HEAVY PHOTON DISPLACED VERTEX SEARCH AT 2.3GeV WITH PROSPECTS FOR TRUE MUONIUM DISCOVERY

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DISSERTATION

Submitted to the University of New Hampshire
in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy

in

Physics

September 2019

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Dedication

To my wife, who gives my life any meaning whatsoever:

While this document represents the culmination of the best 10 years of my life, only because I concurrently spent them with you, it has also taken an appreciable amount of time away from you (not to mention some horrible living conditions), and nothing in the universe is worth that. It has been quite the journey, and I can only hope that this represents a fresh chapter of our lives with brighter days ahead.

Acknowledgements

I would like to thank everyone within the HPS collaboration, particularly Matt Graham for teaching me how to manage Monte Carlo production (and then conveniently forgetting how to do it himself). Also, my best friend Matthew Roberson, who I sort of abandoned in New Hampshire to live in a much better part of the world; the best of luck in your own studies! I also couldn't have done this without my adviser Maurik's support and positivity, and Department of Energy grant DE-FG02-88ER40410.

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ABSTRACT

**HEAVY PHOTON DISPLACED VERTEX SEARCH AT 2.3GeV WITH
PROSPECTS FOR TRUE MUONIUM DISCOVERY**

by

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The Heavy Photon Search (HPS) collaboration at Jefferson Lab is searching for a new massive $U(1)$ gauge boson known as the A' , or dark photon, in the sub- GeV regime, which arises from considering an additional symmetry in the Standard Model. Though part of a hidden sector, the A' also kinetically mixes with the photon of electromagnetism, allowing it to have detectable QED decays. The signatures of this new particle in a fixed target experiment include a resonance in the e^+e^- invariant mass spectrum and a displaced vertex of its decay products, which the HPS detector in Hall B at JLab is equipped to detect. HPS is also sensitive to discover True Muonium (TM), an exotic bound state which has never been observed in experiment. In this dissertation, data taken from the 2016 HPS run at 2.3GeV beam energy is analyzed to search for a displaced decay vertex from an A' . The True Muonium yield is also estimated using Monte Carlo simulations, to determine the feasibility for a True Muonium search in future runs at 6.6GeV .

Chapter 1

Introduction

The A' , also called a dark photon or heavy photon, is a proposed massive vector boson similar to the regular massless photon, and arises naturally from modern theories for beyond Standard Model physics involving dark matter interactions. In writing the Lagrangian density for such a theory, which includes a dark sector particle with a simple $U(1)$ symmetry, a kinetic mixing term arises, which couples this new field to the electromagnetic current of the Standard Model. The A' therefore acts as the carrier of a new force, which interacts with both appropriately-charged hidden sector particles, and electrically charged particles (albeit weakly for the latter), effectively making it a “window” into these hidden sectors at relatively low energies.

It should be noted that the hidden sector containing the A' may not necessarily be any version of the “dark sector” in which the dark matter from cosmological evidence resides. The hidden sector particles which are appropriately charged under the A' interaction will still be referred to as “dark matter (DM) particles” for convenience, with the caveat that no specific model of dark matter is being assumed. It should also be stressed that the A' is theoretically well-motivated [1][2][3][4], and its properties are general enough for a search to stand on its own, independent from specific dark matter experiments. Its existence is inferred from a few relatively modest assumptions about the properties of a force carrier that would reside in a sector beyond the Standard Model.

With that said, mechanisms involving the A' would also fit naturally into certain anomalous results of recent experiments, as well as dark matter models which may describe them. For example, an excess of positrons detected by the PAMELA experiment could be explained by interactions of dark matter particles, mediated by a force carrier such as the A' [5][6]. The anomalous magnetic moment of the positive muon, first measured by Brookhaven AGS experiment, has a value much higher than what is predicted by the Standard Model [7][8], which could also be explained by interactions with the dark photon [9]. Loose theoretical constraints from results such as these provide a natural range of A' masses to search for [10].

Among the other experiments attempting to detect heavy photon interactions are the LHCb experiment at CERN [11], BaBar at the Stanford Linear Accelerator Facility (SLAC) [12], and APEX at the Thomas Jefferson National Accelerator Facility (JLab) [13]. The Heavy Photon Search experiment (HPS), also located at JLab, will be the focus of this document.

The A' , and also a new bound state of $\mu^+\mu^-$ called True Muonium (TM), as will be shown, have two characteristic properties to which the HPS experiment is sensitive: a non-zero mass, and lepton decay products having a vertex which appears displaced from that of ordinary massless photon decay. The HPS detector is a compact, large acceptance forward spectrometer capable of resolving precise vertex locations and energies of the decay products produced from particles created from the collision of an electron beam with a fixed tungsten target. Using this setup, evidence for events involving exotic new particles may be discovered, from processes generated by a beam electron scattering off a high-density target. In the next chapter, the theoretical motivation for the A' 's existence will be developed, as well as its extended lifetime and decay kinematics. The HPS setup and subdetector readout will be outlined in chapter 3, as well as the accelerator's beamline. Chapter 4 will detail how the tracks from collected data are reconstructed, and common vertices are fit, forming the

data set on which a displaced decay vertex takes place. The displaced vertex search will be performed in chapter 7, involving events generated from a Monte Carlo simulation procedure described in chapter 5, and mass resolution obtained from reconstructed Møller events from chapter 6. Finally, chapter 8 will explore the potential to discover True Muonium in the HPS experiment, using both calculations of its production cross section and simulations to determine its expected yield. A discussion of the results will follow.

Chapter 2

Heavy Photon Motivation and Theory

In this chapter, the theoretical motivation for the production and decay of the A' will be discussed, as well as the QED backgrounds which must be accounted for in simulations.

2.1 The A' Parameter Space

The A' can be thought of as a “dark” counterpart to the photon of electromagnetism, which transmits the electromagnetic force between electrically charged particles. The A' then carries a new force in a similar way between appropriately-charged particles of dark matter, which couple to the corresponding hidden field strength $F'_{\mu\nu}$ with a coupling constant analogous to the electric charge e . Additional terms in the Lagrangian density of the extended SM allow for the detection of the A' , once the dark sector is included [3][4]:

$$\mathcal{L}_{extended} = \mathcal{L}_{SM} + \varepsilon F^{\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m_{A'}^2 A'^\mu A'_\mu \quad (2.1)$$

Here, $F'_{\mu\nu} = \partial_{[\mu} A'_{\nu]}$ is the dark sector counterpart to the electromagnetic field strength $F_{\mu\nu}$ from the Standard Model, assumed to also obey a $U(1)$ symmetry, and A'_μ is the dark 4-potential. There is also a mass term explicitly stated, because the heavy photon would not necessarily remain massless under electroweak symmetry breaking, as the regular photon does.

The term $\varepsilon F^{\mu\nu} F'_{\mu\nu}$ is an allowed mixing of the Abelian forces of QED and its dark counterpart, with ε as the coupling constant. To provide more clarity on how this would affect detectable interactions, the extended Lagrangian density in eq. 2.1 can be equivalently expressed by removing the mixing term and redefining the QED photon fields as

$$A^\mu \rightarrow A^\mu + \varepsilon A'^\mu \quad (2.2)$$

However, doing so also changes the interaction term for processes within the Standard Model ($\mathcal{L}_{SM}$), which feature electromagnetic currents J^μ :

$$e A_\mu J^\mu \rightarrow e A_\mu J^\mu + \varepsilon e A'_\mu J^\mu \quad (2.3)$$

As a result, calculations of QED interactions from Feynman diagrams would now contain additional terms involving $e \varepsilon A'_\mu J^\mu$ at each vertex, signifying a coupling to the A' . This is how kinetic mixing induces a new interaction between Standard Model particles and the hidden sector.

The dimensionless constant ε therefore determines the relative strength of the A' interaction with electrically-charged particles to the coupling e of the standard photon, with ε constrained through several high-scale mechanisms to be within the range $\sim 10^{-8} - 10^{-2}$ [3][14]. A summary of the A' mass-coupling parameter space and the proposed region for HPS to explore is shown in figure 2-1 [18].

Figure 2-1: Parameter space for the mass-coupling ranges of the A' . The already-explored regions (shaded) are labeled by the corresponding experiments, as well as the proposed $20 - 1000 MeV$ range that HPS will investigate using data from 2015, 2016 and beyond. A bump hunt in the invariant mass spectrum is performed in the upper region (stronger coupling forces a prompt decay), while a displaced vertex search will be more feasible in the more open lower region.

While the possible parameter space of the A' may be larger, the region shown above represents a portion that is currently considered to be well-motivated by theory [17].

2.2 A' Production and Kinematics

In order to detect an event involving an A' , HPS will search for two signatures that will distinguish it from the ordinary background photons produced from bremsstrahlung and other mechanisms: a narrow resonance in the invariant mass spectrum and a displaced decay vertex of the resulting e^+e^- decay products. When an electron beam collides with

a target of atomic nucleus Z , an A' may be produced in a way analogous to an ordinary photon [19].

Figure 2-2: An A' produced by an electron interacting with an atomic nucleus, such as the tungsten target used for the HPS experiment. As depicted, this process (radiative trident) is diagrammatically identical to bremsstrahlung, although the rate of production and kinematics are different for the A' .

For an ordinary bremsstrahlung photon generated by electron collisions on a fixed target (beam energy E_0), the differential cross section can be estimated by the Weizsäcker-Williams approximation [14]. This can be done in a similar way for an A' of energy $E_{A'} = xE_0$ and scattering angle $\theta_{A'}$:

$$\frac{d\sigma}{dx d\cos\theta_{A'}} \approx \frac{8Z^2\alpha^3\varepsilon^2 E_0^2 x}{U^2} \left[\left(1 - x + \frac{x^2}{2}\right) - \frac{x(1-x)m_{A'}^2 E_0^2 x \theta_{A'}^2}{U^2} \right] \tilde{\chi} \quad (2.4)$$

where

$$U = E_0^2 x \theta_{A'}^2 + m_{A'}^2 \frac{(1-x)}{x} + m_e^2 x \quad (2.5)$$

and $\tilde{\chi}$ is an effective photon flux obtained by integrating over a dominant elastic form factor which depends on the mass of the A' considered, as well as the composition of the target. This approximation is valid for A' masses in the range $m_e \ll m_{A'} \ll E_0$ and $x\theta_{A'}^2 \ll 1$. The cross section for ordinary bremsstrahlung photons is recovered when $m_{A'} = 0$, but with a modified $1/x$ factor arising from deeper corrections due to a non-zero mass [20]. Integrating over all angles, the differential cross section becomes

$$\frac{d\sigma}{dx} \approx \frac{8Z^2\alpha^3\varepsilon^2x}{m_{A'}^2} \left(1 + \frac{x^2}{3(1-x)}\right) \tilde{\chi} \quad (2.6)$$

Using the parameters of the experiment, the production cross section for radiative A' s effectively depends on $m_{A'}$ and ε in the following way:

$$\sigma_{A'} \approx 100pb \left(\frac{\varepsilon}{10^{-4}}\right)^2 \left(\frac{100MeV}{m_{A'}}\right)^2 \quad (2.7)$$

Once produced, the A' carries most of the beam energy on average, and has a small cutoff angle in the forward direction:

$$\theta_{A'} \leq \max \left(\frac{\sqrt{m_e m_{A'}}}{E_0}, \frac{m_A'^{3/2}}{E_0^{3/2}} \right) \quad (2.8)$$

and corresponding cutoff energy

$$(1-x) \sim \max \left(\frac{m_e}{m_A'}, \frac{m_A'}{E_0} \right) \quad (2.9)$$

Equations 2.8 and 2.9 come from the breakdown of the approximation, similar to what will be shown to happen to True Muonium, and helps to narrow down the energies and angles considered during analysis [20]. What makes the A' distinguishable in experiment from the background photons produced by the same mechanism is that its non-zero mass allows the A' to be created resonantly, affecting its production rate $\left(\sim \varepsilon^2 \frac{m_e^2}{m_A'^2}\right)$ and kinematics as well.

These kinematic differences manifest themselves in the form of exotic decay signatures, which are the signals that HPS hopes to detect. Some knowledge of the energy and angular ranges to expect can provide a valuable tool for eliminating the oppressive background of standard photons and their resulting lepton pairs. In particular, knowledge of what fraction of the expected background lepton pairs has an energy sum within the same regime as those from the A' signal (near the beam energy) provides a basis for which selection cuts to apply in order to get a cleaner signal. In the next section, the extended lifetime of the A' will be discussed, which gives rise to the displaced vertex to be searched for.

2.3 A' Decay

While the A' and a standard model photon both decay into a lepton pair, their different QED couplings affect their relative lifetimes. Since the mixing parameter ε which governs the coupling strength of the A' is on the order of 10^{-3} times smaller than the electric charge e , the A' will have a longer lifetime than the standard photon, proportional to $1/\varepsilon^2$ [19]:

$$c\tau = \frac{1}{\Gamma} \approx \frac{3}{N_{eff}m_{A'}\alpha\varepsilon^2} \approx \frac{0.8cm}{N_{eff}} \left(\frac{10^{-4}}{\varepsilon}\right)^2 \left(\frac{100MeV}{m_{A'}}\right) \quad (2.10)$$

Here, N_{eff} takes into account the number of possible decay products. If $m_{A'} < 2m_\mu = 211MeV$, then $N_{eff} = 1$, since no decays into a $\mu^+\mu^-$ pair would be possible. This also assumes that there are no low-mass dark matter states that are charged under the A' , which would allow for hidden sector decays [15]. For larger A' masses, $N_{eff} = 2 + R(m_{A'})$, where $R = \sigma_{hadron}/\sigma_{muon}$, the ratio of production cross sections for hadrons and muons at the A' mass. Additional decay channels beyond e^+e^- are possible (figure 2-3) [16], but HPS is only sensitive to A' masses below $\sim 200MeV$, effectively excluding them.

Figure 2-3: Branching ratios for various A' decay channels. Since HPS is only sensitive to A' masses below 200MeV for a beam energy of 2.3GeV , only the e^+e^- decay channel needs to be considered.

The boosted decay length l_0 , as a function of the coupling parameter ε is:

$$l_0 \equiv \gamma c\tau = \frac{0.8\text{cm}}{N_{eff}} \left(\frac{E_0}{10\text{GeV}} \right) \left(\frac{10^{-4}}{\varepsilon} \right)^2 \left(\frac{100\text{MeV}}{m_{A'}} \right)^2 \quad (2.11)$$

If the coupling ε is relatively large, then the decay length in equation 2.11 is small and difficult to resolve from the background tridents, which decay promptly. In this large coupling region, the A' is primarily detectable by considering the invariant mass spectrum of the decay products of the experiment, which should feature a sharp “bump” at the A' mass, wherever it may be within the tail of the background signal. For weaker coupling, the decay length becomes correspondingly large, on the order of tens of centimeters. A summary of the characteristic angles expected for the displaced A' , at a particular mass and beam energy,

is shown in figure 2-4.

Figure 2-4: Characteristic angles for the A' and its leptonic decay products

Both the production cross section and decay length become small for large A' masses ($m_{A'} \approx 1\text{GeV}$), making the mass bump hunt that much more challenging in this regime. Therefore, finding ways to reduce the background during analysis becomes especially important. The work represented in this dissertation will focus on the “small coupling” (larger displacement) region of the parameter space. To summarize the relative difficulty in detecting displaced vertex signals for different A' masses, a region of the parameter space (figure 2-1) is highlighted in figure 2-5 with the expected decay lengths overlain.

Figure 2-5: Highlighted portion of the A' parameter space with the expected decay lengths overlain. For the mass range accessible to HPS, an $\varepsilon^2 \sim 10^{-7}$ will allow the displaced vertex to be resolved and also fall within the detector acceptance ($< 10cm$ from the target).

Another signal with very similar kinematics to the A' , which HPS may have the potential to discover at higher beam energies is True Muonium, motivated and discussed in chapter 8.

Chapter 3

HPS Experimental Setup

The Heavy Photon Search (HPS) experiment is conducted at the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab in Newport News, Virginia. The target and detector setup for HPS are located in an alcove behind the CLAS detector in Hall B. The incident electron beam of 2.3GeV for the 2016 experimental run and 200nA pulsed in 2ns bunches, hits a thin tungsten foil target of $4\mu\text{m}$ ($\sim 0.2\%$ RL), and produces QED products, most of which will be carried along the beamline. A high Z target like tungsten is preferable for its short radiation length that minimizes unwanted hadrons from being produced ($\sigma_{QED}/\sigma_{had} \sim Z^2/A$), and is thin to minimize the beam spread. Tungsten is also preferable for its high melting point, which is especially a concern when using a thin target.

Background photons, and electrons with degraded energy that bend more in the magnetic field, form an intense sheet which necessitates the splitting of the detection hardware to allow passage with minimal damage to the equipment. In order to minimize beam-gas interactions, the beam and the detector regions must also be maintained in a vacuum ($\sim 10^{-6}\text{Torr}$). The HPS detector chain is shown in figure 3-1 [21].

Figure 3-1: The HPS setup. The beam arriving from the left hits the tungsten target, and the resulting charged products are bent by an analyzing dipole magnet, then deposit their energy in the SVT and ECal. The role of the SVT is to help reconstruct tracks from particles which create triggers in the ECal.

Many background tridents are created in the experiment, as well as electrons that have undergone multiple scattering and Møller scattering; understanding and reducing this background without losing potentially exotic decay candidates is a primary challenge for the A'/TM search. Specialized triggers were designed to accept physics events of interest, which can be used to calibrate the detectors and/or search for lepton pairs which came from new physics. The remaining sections in this chapter describe the beamline and detector subsystems, the hardware specs of each, and how the various signals are readout to create a physics event.

3.1 CEBAF beamline

The CEBAF beamline consists of an injector, two linear accelerators, and superconducting magnets which steer the electron beam into a ring, along with RF separators to extract the beam into the different experimental halls.

Figure 3-2: The accelerator ring at the CEBAF, highlighting the recent 12GeV upgrade components. The electron beam is injected with an energy of 123MeV , and two linear accelerators add 2.2GeV during each pass, before the beam is sent to one of four experimental halls.

Figure 3-3: An aerial view of CEBAF, with the locations of the halls (A, B, C, and D) and counting houses that control the experiments.

3.1.1 Beam generation and bunch structure

The continuous wave electron beam that CEBAF accelerates is generated by shining three individual RF-pulsed lasers on gallium-arsenide photocathodes, ejecting 130keV electrons (In the summer after the 2016 running, this was upgraded to four lasers, to accomodate the new experimental hall D) [30]. While the fundamental frequency of these combined electron pulses is 1497MHz , this bunch structure is divided into three subharmonics of 499MHz before injection into the accelerator. This is accomplished by transverse orthogonal magnetic fields rotating the beam, where electrons are passed through slits at 0° , 120° , and 240° [29]. In this way, the beam current (i.e. the number of electrons in a 499MHz bunch) can be

adjusted by tuning the slits and intensity of the laser pulses. The three pulse trains are recombined and accelerated to 123MeV before injection into the accelerator ring.

Figure 3-4: The bunch structure of the electron beam generated at CEBAF. Three separate electron beams with tunable current are combined into a 1497MHz bunch structure before injection, to be accelerated at the CEBAF operating frequency. The beam sent to each experimental hall has 2ns bunches. For the 200nA current used for Hall B, this translates to 2500 electrons per bunch.

In the CEBAF accelerator ring, the three interlaced electron beams match the 1497MHz frequency of the superconducting niobium RF cavities comprising the two linear accelerators. The beam is injected into the ring, and gains up to 1.1GeV from each linac (2.2GeV from each pass), up to five possible passes, and each hall is able to receive the beam from any lower pass as well. Accounting for the energy added to the beam before injection, the maximum beam energy from n passes are $n * 2.2\text{GeV} + 123\text{MeV}$. A 1.056GeV beam was able to

be taken opportunistically during the 2015 running due to a partial failure of the liquid helium cooling system, and the 2016 run used a 2.3GeV beam. RF separators recreate the 2ns bunch structure ultimately seen by the halls. By selecting the pass, and being able to vary the intensity of the photocathode lasers pre-injection, each of the halls are able to individually select their own current and beam energy. For most of the 2016 running, the beam energy was 2.3GeV , and the current was 200nA , although a few low and high-current runs were taken at 50, 100, and 300nA , as well as additional 1.056GeV data to complete some studies from the 2015 engineering run.

Figure 3-5: A high-purity superconducting niobium 7-cell RF cavity used to accelerate the beam, at the 1497MHz accelerator frequency. There are eight RF cavities in each of the 25 cryomodules in a linac.

Figure 3-6: RF separators located behind the experimental halls to phase-separate the 1497MHz beam into its 499MHz components. The 499MHz beams can be individually tuned by each hall to select the current, and may come from any available pass to select the energy.

3.1.2 Hall B beam tuning procedure

Before a generated beam is delivered through a detector in a hall, it must be tuned to be within set stability thresholds. To do this, a very low-current beam ($< 10\text{nA}$) is first sent to a beam dump at the location of the tagger magnet located near the hall entrance (figure 3-7). Harp scans are performed on this beam to establish its profile (figure 3-8), and beam position monitors (BPMs) measure its position (horizontal/vertical) and current. PMTs also monitor photon counts at several locations. When acceptable beam conditions are established (table 3.1), the beam is steered using correctors and quadrupole magnets to a beam dump at the end of Hall B, past the HPS setup [26] [27].

Parameter	Acceptable value
Relative nA BPM positions	$< 0.25mm$
(FC current)/(IPM2C24 current)	0.98 – 1.02
Upstream normalized PMT rates	$< 50Hz/nA$
Current Stability	10% of average current

Table 3.1: Acceptable beam quality parameters at the tagger magnet. Once these are established, the beam can be steered to the Faraday cup at the end of Hall B.

Figure 3-7: The Hall B beamline from the entrance to the hall to the Clas12 detector, which HPS is behind. The beam is first sent to the tagger dump for tuning.

The beamspot width and absolute position is measured by a “harp scan”, in which thin

horizontal and vertical wires are slowly moved across the path of the beam, scattering some of the beam electrons and perturbing the reading on the nearby halo counter. By plotting the counts as a function of motor position of the apparatus, the beam location and profile is determined. The distributions should be roughly Gaussian, whose widths give the horizontal and vertical sizes of the beamspot. In the case of the “2HO2” harp scan station shown in figure 3-9 near the HPS target, a third, diagonal wire is included in the “harp”, so that the beam tilt can be measured as well. An example of a typical beam profile in the 2016 experimental run and apparatus used to measure it is in figure 3-8. The accompanying plots show that the beam profile is Gaussian over 5 orders of magnitude, indicating that the beam halo beyond the core is $< 10^{-5}$ times the beam current. A summary of the beam quality parameters for the 2016 run is in table 3.2.

Figure 3-8: The apparatus used to perform a harp scan to measure the beam profile, and a typical beam profile measured with a 2HO2 harp, located 2.2m upstream from the HPS target. The harp is moved into the beam at a 45° angle, such that the three wires traverse the beam vertically, horizontally, and at 45° to measure the size and obliqueness of the beam at that station.

Parameter	2016 Value
Beam Energy (E)	1.056, 2.300 <i>GeV</i>
$\delta E/E$	10^{-4}
Beam Current	50 – 300 <i>nA</i>
Current Stability	$\sim 5\%$
σ_x	$< 300\mu m$
σ_y	$< 50\mu m$
Position Stability	$< 30\mu m$
Divergence	$< 100\mu rad$
Beam Halo ($> 5\sigma$)	$< 10^{-5}$

Table 3.2: Measured beam quality parameters for the 2016 run.

3.1.3 HPS beamline components

Once a physics-quality beam is achieved, it is steered through the HPS detector region by the first of a two-magnet dipole chicane setup (pole length: 50*cm*, maximum field strength: 1.2*T*), deflected horizontally from the original beamline by 30.5*mrad*. This incident angle must be accounted for in the simulations, discussed in chapter 5. After the target, an analyzing dipole magnet (pole length: 91.44*cm*, maximum field strength: 1.5*T*) separates the charged particles produced in the target, so that they bend through the tracking region and deposit their energy in the electromagnetic calorimeter (ECal). The beam electrons which did not lose energy in the target are then bent by the second chicane magnet back to the original beamline path, where the beam is terminated in a beam dump. The beamspot can be viewed on a monitor downstream of HPS before the beam dump. The beam dump is surrounded by a Faraday cup, which collects the beam charge, and is used to verify the

beam current and normalize the data. The beamline region surrounding the HPS setup is shown in figure 3-9 [31].

Figure 3-9: The HPS enclosure (figure 3-1), in the Hall B alcove. Two chicane magnets steer the electron beam into the target, and then to the Faraday cup to collect the charge. An analyzing spectrometer dipole magnet (maximum field: $1.5T$) bends the charged particles emerging from the target into a very low-curvature helix for track reconstruction to be performed.

The SVT collimator in figure 3-9 is designed to protect the SVT from radiation damage due to its very close proximity to the beam ($0.544mm$) once fully closed. It consists of a $1cm$ thick tungsten plate with a slot opening, so that it will attenuate the beam in the event that the beam is steered too far in the direction of the active SVT silicon. Halo monitors are also present to detect radiation levels in excess of a pre-defined threshold in regions where the levels should not be as high. In the event that this threshold is passed, the electron beam will undergo a fast shutdown (FSD) to avoid damage. Once a stable beam is achieved, BPM values are noted in order to quickly bring the beam back after an FSD trip.

Figure 3-10: Strip charts for BPM positions at various locations along the beamline, and beam current for run 8040 on 04-16-2016. The discontinuities are points where the beam tripped and was brought back. The current stability during good beam was $\sim 5\%$.

The HPS target is an array of different target materials in an aluminum frame [32]. The primary target used for the 2016 A' search is the tungsten target with an average areal density of $0.00782g/cm^2$, which translates to an average target thickness of $4.062\mu m$. Short carbon and polyethylene runs were taken as well ($\sim 30mins.$ each) for more specialized studies.

Figure 3-11: The HPS target mount containing $4\mu\text{m}$ and $8\mu\text{m}$ tungsten, as well as carbon and polyethylene. The $4\mu\text{m}$ tungsten was primarily used in the 2.3GeV 2016 runs.

3.2 Silicon Vertex Tracker (SVT)

To precisely determine the interaction vertex of fermionic decay products produced in the target, a tracking system is needed so that particle tracks may be efficiently reconstructed from hits in the detector, and traced back to their points of origin by a track-fitting algorithm. This is accomplished with a silicon vertex tracker (SVT), consisting of six groups of dual silicon strip sensors that particles may pass through.

3.2.1 SVT Sensor Positions

The first three groups of dual SVT sensors (each of these sensor pairs will hereby be referred to as a “layer”) consist of two sensor strips and hybrid readout board (a “half-module”), and the last three layers consist of two such half-modules glued together. This larger module in layers 4-6 allows for more hits near the end of the tracking region to be captured, where the highly curved tracks are most horizontally-displaced from the beamline, and also more closely matches the wider acceptance of the ECal.[25]. A diagram of the six

SVT layers is shown in figure 3-12 [18], and a photo of a half-module in figure 3-14 [28].

Figure 3-12: The silicon vertex tracker system for HPS. The silicon layers are spaced 10, 20, 30, 50, 70, and 90cm from the target.

A single silicon strip sensor is capable of making a 1D measurement of the hit; its vertical position is defined by which strip was hit, but the horizontal position along the strip is not resolved. Each of the six SVT layers are therefore comprised of a *pair* of sensors to create a 3D measurement out of two 1D hits that are spatially separated by a small amount. The two sensors in a layer are rotated relative to each other by a stereo angle of 50 or 100mrad in order to determine both the horizontal and vertical coordinates, where the strips overlap. The first three groups of sensor pairs have a stereo angle of 100mrad to create an optimal volume with which to reconstruct interaction vertices (figure 3-14). The latter three (dual half-module layers) have a stereo angle of 50mrad for greater pattern recognition [28] [34]. This difference in stereo angles also helps to reduce false tracks made using “ghost hits”, which arise from incorrectly associating 1D hit measurements along a pair of strips which have ambiguity along one axis. An example of how ghost hits occur can be seen in figure

3-13, and details of track finding and reconstruction will be discussed in chapter 4.

Figure 3-13: An example of how ghost hits are created from ambiguous 1D strip sensor measurements.

The top figure in 3-13 shows a pair of 2D hit measurements that were made from intersecting sensor layers, which make the 1D measurements x and u , defined by the strip that was hit. The bottom shows an additional two 2D hits that can be made using the same collection of 1D measurements. Changing the stereo angle between sensors in the final three SVT layers reduces the chance of ghost hits from layers 4-6 creating a track consistent with ghost hits from layers 1-3.

The first three SVT layers (100mrad rotation) have a measurement resolution of $60\mu\text{m}$

in the bend plane, which increases to $120\mu m$ when the stereo angle is halved in the last three layers. Most of the uncertainty in hit position is introduced by multiple scattering in the earlier layers that the particle traverses, which is why the thickness of the silicon is kept to a minimum ($320\mu m$).

Figure 3-14: SVT half-module consisting of silicon sensors and APV25 board (foreground) with the module assembly mounts in the background. These half-modules comprise layers 1-3.

Figure 3-15: Full SVT module (two half-modules glued together). These sensors comprise layers 4-6. The increased acceptance region from combining sensors helps collect the hits from charged particles that have been highly displaced in the magnetic field near the end of the tracking region.

Figure 3-16: SVT layers 4-6, mounted in the aluminum frame.

The top and bottom halves of the SVT are vertically separated to allow for the passage of the full e^- beam and the forward scattered background radiation and electrons. The readout chips begin taking data at a distance of $\pm 1.5mm$ from the beamline, to minimize radiation damage.

3.2.2 SVT readout

Each SVT sensor has 639 strips. Only every other sensor strip is actually readout; the strips in between are capacitively coupled to the readout strips such that any charge deposited on these strips are shared between the adjacent readout strips. The strips are readout by APV25 chips, each with 128 channels, so 5 chips are needed per sensor to readout all the strips [28]. In total, there are 36 sensor layers, which makes 23040 total readout channels (effectively 23004, since one channel per sensor is not used).

Each channel of the APV25 chips is coupled to a pulse shaping amplifier, with pulse shaping time of $50ns$. The channels are sampled continuously at $41MHz$, and written to the analog memory pipeline consisting of 192 cells [33]. The Analog Pulse Shape Processor (APSP) reads out 6 consecutive cells when a trigger signal is received from the ECal (section 3.3.1). The programmable latency, the position in the pipeline between the written pulse and which cell is marked for readout, is adjusted to readout two cells before the hit actually crossed the threshold, and 4 after. This allows for the full signal to be fit properly in the readout window. The pulse is later fit in offline analysis, before tracks are reconstructed (chapter 4).

3.3 Electromagnetic Calorimeter (ECal)

The second subdetector, responsible for triggering on events of interest, is the electromagnetic calorimeter (ECal), located beyond the SVT tracking region. Energetic particles created in the experiment will ultimately deposit their energy in the ECal, which consists of 442 scintillating $PbWO_4$ crystals with avalanche photodiodes (APD) for readout. Like the SVT, the ECal is also split into an upper and lower region beginning at $\pm 15mrad$ from the beamline to prevent radiation damage [28]. Lead tungstate crystals have a relatively short

decay time ($512ns$), which allows it to handle the high event rates in HPS [36].

Figure 3-17: The electromagnetic calorimeter (ECal) as viewed by the beam.

The ECal consists of 442 scintillating $PbWO_4$ crystals (face dimension: $13 \times 13 mm^2$), with APDs ($10 \times 10 mm^2$ each) for readout. To stabilize the light yield in the crystals and APD gains, each half of the ECal is temperature-controlled using a chiller operating at $17^\circ C$, which maintains a stable temperature to within $0.3^\circ C$. The ECal is split by $\pm 15 mrad$ to avoid radiation damage due to the beam passing through the detector. The energy resolution for the ECal is $\sigma_E/E \sim 3.6\%$.

Figure 3-18: An example of the ECal FADC rates for a typical 2016 run ($\sim 20MHz$).

Many particles are produced in the experiment, and deposit energy into the ECal at an extremely high rate (10's of MHz). The hardware and firmware which reads out information about these hits therefore needs an exceedingly fast triggering mechanism. Flash ADC boards (FADCs) sample the analog APD signal from each crystal at a constant $250MHz$ into an $8\mu s$ pipeline. The pulse shape is fit to a 3-pole function with width τ (obtained by averaging over many pulses for each crystal) [35]:

$$ADC(t) = P + \frac{A}{2\tau^2} (t - t_0)^2 e^{-(t-t_0)/\tau} \quad (3.1)$$

Figure 3-19: An APD waveform readout from a single crystal and digitized by FADC boards, fit using eq. 3.1.

The digitized signal with amplitude A and time of threshold crossing t_0 is sent to a trigger processor every $16ns$. This trigger is what decides which hits to register as potential candidates for an exotic decay, and selective cuts in time and energy can then be made to select lepton pairs and reduce background events. Since the ECal is the detector in which the final EM showers of the collected particles are deposited, a complex clustering algorithm and various triggers were designed to accept the particles of interest, and begin rejecting the more obvious backgrounds.

3.3.1 ECal clustering and triggers

When a particle deposits enough energy into the calorimeter to create a signal within the FADC sampling window ($4ns$), its energy is rarely fully contained within a single crystal. Rather, the incident particle showers over several neighboring crystals, and these combined hits (called a “cluster”) are what represent the particle. The energy of the ECal hits (converted from ADC counts) and the time of the threshold crossing is sent to a Global Trigger Processor board (GTP) every $16ns$ (4 FADC samples), and subjected to a clustering algorithm. This algorithm first looks for a “seed hit”, the highest energy hit thought to be the point of impact. It then searches for neighboring hits to capture the showered energy. The “cluster energy” is the total energy of these clustered hits, and represents the energy of the particle. The time of the cluster’s seed hit is considered to be the particle’s time of impact. For a seed hit with an energy greater than $100MeV$ (this threshold roughly scales with beam energy), the GTP looks for up to 8 additional hits around the seed hit in a 3×3 window, which are all within a $16ns$ time window. There are two such GTP boards which perform clustering, one for each half of the ECal, and both report the clusters it found to a single SubSystem Processor (SSP). The SSP is what makes the decision to trigger, using either one or two clusters, if the clusters involved pass certain trigger cuts. These cuts are initially determined by simulations [35]. Once a trigger is registered, 100 samples are stored in $4ns$ intervals for each ECal crystal above threshold, allowing for the entire pulse to be fit in offline processing. A flowchart for the ECal trigger system is shown in figure 3-20.

Figure 3-20: A flowchart of the ECal trigger system. Each FADC is sampled every $4ns$, and signals passing thresholds are sent to the Global Trigger Processing Boards (GTP) where clustering is performed. Clusters from both halves of the ECal are sent to the Subsystem Processor (SSP), where a trigger decision is made. Finally, the triggers are sent to the trigger supervisor (TS), which reads out both subdetectors.

There are several HPS triggers that are used independently while taking data, and are meant for different purposes. For example, the 'pulser' trigger, which is designed to readout a signal at a constant rate, should contain a sample of all physics events without any bias. The 'singles1' trigger accepts single particle clusters, and is useful for extracting full energy electrons which can be used to calibrate the detector. The 'singles0' trigger is similar to 'singles1', but with looser thresholds, and 'pair0' was specially designed to trigger on electron pairs which are most likely Møller pairs.

Of primary importance to the A' search is the 'pair1' trigger configuration, which saves a readout event if two clusters are detected on opposite halves of the ECal within a $12ns$ time window, signaling a coincident electron-positron pair which may have come from an A' (or background trident). The other pair1 trigger thresholds are defined in eqs. 3.2-3.8, and the numerical values used in the 2016 run are listed in table 3.3. An example of a typical pair1 trigger which involves two coincident clusters in the ECal is depicted in figure 3-21 [35].

$$E_{min} \leq E_{1,2} \leq E_{max} \quad (3.2)$$

$$N_{hits} \geq N_{threshold} \quad (3.3)$$

$$ESum_{min} \leq E_1 + E_2 \leq ESum_{max} \quad (3.4)$$

$$EDiff_{min} \leq |E_1 - E_2| \leq EDiff_{max} \quad (3.5)$$

$$|t_1 - t_2| \leq t_{coincidence} \quad (3.6)$$

$$E_{low} + (0.0055 GeV/mm) * r_{low} \leq E_{slope} \quad (3.7)$$

$$|\theta_1 - \theta_2 - 180^\circ| \leq \theta_{coplanarity} \quad (3.8)$$

$E_{1,2}$ are the energies of the two clusters in opposite top/bottom halves of the ECal, which have seed hits within the time window $t_{coincidence}$. N_{hits} is the number of total hits that form a cluster, and must be greater than $N_{threshold}$. r_{low} is the distance of the lower-energy cluster (with energy $E = E_{low}$) from the center of the ECal, where the beam would pass through. This cut is meant to reject particles which are less likely to have come from a lepton pair of interest; a low energy cluster near the beam line is more likely to be either a photon from a wide-angle bremsstrahlung event, or a beam electron which has lost most of its energy. The coplanarity cut is designed to select electron-positron pairs by virtue of momentum conservation, with their scattering angles expected to be 180° from each other. Since the rates seen in data are much higher than the triggers are able to process, prescale factors are

also applied to each type of trigger, which reduce the overall trigger rates by only accepting every 1/prescale event. These prescale factors are also listed in table 3.3.

Figure 3-21: An example of an ECal cluster pair passing the trigger cuts, eqs. 3.2-3.8.

In the example depicted in figure 3-21, two clusters are found within a coincidence window $t_{coincidence}$, in opposite top/bottom halves of the ECal; a seed hit > 100 MeV and the surrounding hits in a 3x3 crystal grid within 16ns of the seed hit form the clusters. The cluster in the top half with energy E_1 has the lower energy, so it is the one used for the E_{slope} calculation. The two clusters are also within 40° of being coplanar, so this event is readout.

Parameter	Single-0	Single-1	Pair-0	Pair-1
E_{min}	$0.100GeV$	$1.300GeV$	$0.150GeV$	$0.150GeV$
E_{max}	$2.700GeV$	$2.600GeV$	$1.400GeV$	$1.400GeV$
$N_{threshold}$	3 hits	3 hits	2 hits	2 hits
$ESum_{min}$	—	—	$0.500GeV$	$0.600GeV$
$ESum_{max}$	—	—	$1.900GeV$	$2.000GeV$
$EDiff_{max}$	—	—	$1.100GeV$	$1.100GeV$
E_{slope}	—	—	$0.400GeV$	$0.600GeV$
$\theta_{coplanarity}$	—	—	—	40°
$t_{coincidence}$	—	—	$8ns$	$12ns$
Prescale	$2^{12} + 1$	$2^{10} + 1$	$2^5 + 1$	1

Table 3.3: The ECal trigger thresholds for the 2016 run ($2.3GeV$ beam energy). For pair triggers, there are cuts involving both 1 and 2 clusters. The prescale helps reduce relative trigger rates by only accepting every “1/prescale” event from each trigger.

Figure 3-22: An example of the ECal trigger rates during a typical 2016 run. The “gated” rate counts the triggers when the DAQ was live, $> 90\%$ of the time on average.

During the 2016 experimental run period, HPS was scheduled to take data on the week-ends during February-April. During this time, $99.332mC$ of total charge was collected, $76.453mC$ of which was found to be “good”: when the SVT was closed to the nominal $0.5mm$ position and not moving, and the bias voltage was turned on (it shuts off during an FSD trip and takes time to ramp back up). From the target parameters, this translates to an integrated luminosity of $12240nb^{-1}$.

HPS Goal: 120 mC on target

Figure 3-23: Charge collected during the 2016 experimental run, providing the data sets from which displaced heavy photon vertices will be searched. Data was only collected during weekends, creating the plateaus.

The triggered events collected from the HPS experiment are then used to reconstruct charged tracks for further analysis. The next sections describe how the digitized tracker hits and clusters created in the subdetectors are converted into track candidates, which are then fit to a common vertex.

Chapter 4

Track Reconstruction

Once all of the triggered events are stored from an experimental run, each event will contain a collection of raw hits from both the SVT and ECal, consisting of the digitized samples from each detector. HPS employs a sophisticated framework whose role is to reconstruct the tracks of charged particles from this information, to be paired with the clusters of particles which most likely created them. The ECal provides the event triggers, while charged tracks are reconstructed entirely using hits found within the SVT layers.

4.1 Creating SVT Hits

The raw SVT hits are fit to a pulse and clustered, similar to what is done for the ECal. The functional form used to fit an SVT pulse for a sensor strip above threshold is

$$f(t) = A \frac{\tau_1^2}{(\tau_1 - \tau_2)^3} \left(e^{-\frac{t-t_0}{\tau_1}} - e^{-\frac{t-t_0}{\tau_2}} \sum_{k=0}^3 \frac{\left(\frac{\tau_1 - \tau_2}{\tau_1 \tau_2} (t - t_0) \right)^k}{k!} \right) \quad (4.1)$$

This allows the time of the threshold crossing, t_0 , and amplitude (ADC counts), A , to be extracted. τ_1 and τ_2 are time constants obtained from the APV25 response, the pedestal and shaping time respectively. The fit is done assuming both a single pulse and the sum of two pulses, and the fit with the lowest χ^2 is the one used. A typical pulse shape is shown in figure 4-1 [34].

Figure 4-1: A waveform readout containing 6 APV25 samples in $24ns$ intervals. A few samples are saved before the trigger time, so that the entire pulse can be fit and the time of threshold crossing (t_0) extracted.

Once the amplitude and time of threshold crossing are obtained from fitting the pulse, the SVT hits are subjected to a clustering algorithm to determine if multiple hits came from a single particle. Any hit in a strip sensor with an amplitude greater than 4x the noise level of the channel is considered to be a “seed hit”, and additional neighboring strip hits with an amplitude greater than 3x the noise level, and a t_0 within $8ns$ of the seed hit, are added to the cluster. The position of the cluster is defined by the centroid of the hit positions which make up the cluster, weighted by their amplitudes.

Clusters in either sensor of an SVT layer are defined as “1D” hits. A 3D hit (also called

a “stereo hit”) is made from two 1D strip clusters. The hits are recorded in local strip coordinates $[u, v, w]$. In this coordinate system, u is the direction defined by different sensor strips (the coordinate measured by the sensors that were hit), v is the direction along the sensor strips (the unmeasured coordinate), and w is perpendicular to the sensor layer. For a stereo hit to be made, thresholds must be passed to make sure that the 1D hits are in adjacent sensor planes (part of an axial/stereo pair), and that the clusters in the two sensors overlap:

$$\text{sensor separation} = |u_1 \hat{u}_1 - u_2 \hat{u}_2| \cdot \hat{w}_1 < 20mm \quad (4.2)$$

$$\text{stereo angle} \sim |\hat{v}_1 \cdot \hat{u}_2| > 0.01rad \quad (4.3)$$

$$\text{perpendicularity} \sim |\hat{w}_1 \times \hat{w}_2| < 0.013rad \quad (4.4)$$

If an axial/stereo pair satisfies these criteria, and are also within 12ns of each other, then a stereo hit is created at their intersection.

Figure 4-2: How a stereo hit is created in an SVT layer.

In figure 4-2, clusters are made from 1D hits found within multiple strips (encapsulated in the green SVT sensor layers), where the cluster centroid is weighted by the amplitudes of the individual hits. A 3D stereo hit is created at the intersection of the strip hits, and used in a helical track fit.

4.2 SeedTracker

The track finding algorithm that HPS uses is called “SeedTracker”, which is within the LCSim (“Linear Collider Simulation”) software package, originally developed for the silicon detector (SiD) used by the International Linear Collider [37][38][39]. Although the SiD detector geometry is fundamentally different from HPS, in that the silicon layers form con-

centric rings around the interaction vertex instead of a linear design, the framework is general enough for the classes used for the track reconstruction to be successfully repurposed. Seed-Tracker works by using the “seed-confirm-extend” philosophy of track finding. It makes 3D hits from the 1D hits in the axial and stereo layers of the SVT that are contained within the triggered event, and first fits a helix to all possible combinations of the hits found in 3 adjacent layers (the “seed” step). It next considers all the hits from another set of layers (usually only a single layer), picks up any hits whose position falls within a certain χ^2 threshold, and refits (the “confirm” step). If a hit is found in the confirm step, it looks for more hits in the remaining layers (the “extend” step). A defined set of seed/confirm/extend layers on which to perform this algorithm is referred to as a “tracking strategy”. Several such strategies are used in parallel during HPS track reconstruction, since some tracks may not contain hits in a particular layer and would otherwise be discarded. A track only needs to have hits in five layers; besides not gaining much from having six hits, many otherwise good tracks could be missing a hit in one of the layers. In each step of seed-confirm-extend, the stereo hits in the layers involved are fit to a helix, which is the path that a forward-scattered charged particle would take in a constant magnetic field. This is approximately still the case within the tracking region before the fringe field affects the trajectory, and serves as a first approximation to the path of the particle. The track is eventually extrapolated through the inhomogeneous region of the field to obtain the endpoint at the ECal, but the initial track finding and fitting is done entirely within the tracking region, ending at SVT layer 6, located 90cm from the target.

4.2.1 Helical Track Parameters

The helical fit is parameterized by the 5 quantities depicted in figures 4-3 and 4-4. Three parameters (d_0, ϕ_0, Ω) are defined in an (x, y, z) coordinate system, where $+z$ is the direction

of the magnetic field vector, and $+x$ is along the beamline. These parameters are best visualized when the helix is projected into the $x - y$ (equivalently “ $r - \phi$ ”) plane, the plane in which the particles bend.

Figure 4-3: The 3 track parameters which describe the track in the x, y, z coordinate system: distance of closest approach (d_0) of the reference point P^r to the track, the curvature ($1/R$) based on the radius from track to center of the arc (P^c) in the $x - y$ projection of the track, and the azimuthal angle (ϕ_0) of the track momentum at P^0

Another two parameters ($z_0, \tan \lambda$) come from projecting the helix into an “(s, z)” coordinate system, where s is the arc length of the track in the $x - y$ plane. The quantity “ λ ” in this coordinate system is the complement to the polar angle θ between z and the $x - y$ plane. In a homogeneous field, the track slope $\frac{ds}{dz} = \tan \lambda$ is a straight line, and therefore a constant for a given track [40].

Figure 4-4: The 2 track parameters which describe the track in the s, z coordinate system: the distance of closest approach (z_0) of the reference point P_z^r to the track, and the track slope $\tan \lambda$, constant for a given track.

A helix is fit to the 3D space points where stereo hits were made in two steps: first, a circle fit is performed on the three seed hits in the $x - y$ global coordinates, and the covariance is obtained for d_0 , ϕ_0 , and Ω . Then a line is fit to the $s - z$ coordinates, to get the covariance of z_0 and $\tan \lambda$. These are then combined into a single covariance matrix for the helical track fit. The free choice of the reference point P^r allows the track parameters to be obtained from any point along a track. In particular, the parameters are saved at the point in the tracking region just before the track is extrapolated to the ECal to be matched to a cluster.

Once a helical fit is performed, the momentum of the track in GeV/c can be extracted for the determined track parameters (called a “track state”)[40]:

$$p = a \left| \frac{B_z}{\Omega} \right| \sqrt{1 + \tan^2 \lambda} \quad (4.5)$$

where $a = c \times 10^{-15}$, c is the vacuum speed of light in mm/s, and the track curvature Ω is in mm^{-1} . The units imply that each track has a fundamental charge $\pm e$, the sign of which is obtained by

$$q = \text{sgn} \left(\frac{B_z}{\Omega} \right) \quad (4.6)$$

The helical tracks found using SeedTracker serve as first estimates to the tracks created by particles in the experiment. These tracks are then refit by a more elaborate framework, to estimate the scattered hit positions in each SVT layer.

4.3 General Broken Lines (GBL)

In SeedTracker, energy loss and multiple scattering are largely neglected, except in the form of adding errors in hit position each time the helix intersects a scatter point (SVT layer). The multiple scattering errors are added to the hit resolution error for each hit in quadrature, which decreases the weight of the hits in the later layers that are used in the fit. So while SeedTracker acknowledges that multiple scattering would have increased the hit residual errors, allowing hits downstream to drift further from their expected positions, the change in the helical trajectory due to scattering is not actually applied at each scatter point.

A better track fit is made after SeedTracker, using a software package called “General Broken Lines” (GBL), whose method for fitting tracks is mathematically equivalent to that of a Kalman filter [41]. Instead of treating three track hits simply as uncorrelated hit positions that a helical track should intercept, GBL begins with a track found using SeedTracker, and treats each hit on the track as a measurement subject to multiple scattering (MS) within the silicon layers. The track is refit while considering the contribution of MS to each consecutive hit position in the layers, which are connected by a track segment (the “broken line”). GBL

refits existing hits that have previously been fit to a helix and by SeedTracker. It adds a correction to the hit positions and track parameters, by minimizing a least squares function based on the variances of the estimated scattering angles.

The way that GBL parameterizes MS is by “kink angles” (β_i), the angles which adjust the particle’s trajectory as a result of MS within each layer. These kink angles are defined in terms of the deflection angle θ upon exiting the silicon, and incident angle ψ , shown in figure 4-5 [42].

Figure 4-5: Multiple scattering which occurs within an SVT layer. Δy is the residual of the measurement, and Δs is the thickness of the silicon, $\sim 300\mu m$. The variance of a “kink” angle between hits in adjacent layers (equation 4.8) defines the net result of MS through a layer.

The measured residuals y_i in figure 4-6 are where the input helix, found from SeedTracker, intersects a GBL scattering plane, in this case the position of an SVT layer (s_i). The objective of GBL is to find the actual trajectory of a particle influenced by MS, starting with these helical track hits. It does this by minimizing a least squares fit involving the kink angles β_i at each u_i , depicted in figure 4-7 [42].

Figure 4-6: A hypothetical path (red) of a particle undergoing multiple scattering. The intersection of the helical fit from SeedTracker with the SVT layer positions are labeled y_i , along with the measurement errors. The white circles are where the particle's trajectory should actually intersect the layers, once MS is taken into account. The residual between y_i and this position (u_i) is one term in the function that GBL tries to minimize.

Figure 4-7: The kink angles β_i at the fitted estimates of the scattered hit positions u_i , which are obtained from minimizing equation 4.9.

The kink angle β_i at each track segment between layer positions s_i and s_{i+1} is approximated by

$$\beta_i = \left[\frac{u_{i-1}}{(s_i - s_{i-1})} - \left(\frac{u_i}{(s_i - s_{i-1})} + \frac{u_i}{(s_{i+1} - s_i)} \right) + \frac{u_{i+1}}{(s_{i+1} - s_i)} \right] \quad (4.7)$$

Physically, β_i is defined as the difference between the angles $(\theta - \psi)_{i-1} \equiv \psi_{left}$ and $\psi_i \equiv \psi_{right}$ in layer i (defined in figure 4-5). The β distribution is approximated to be Gaussian by the Highland equation (4.8), where the scattering material is fully characterized by the radiation length X_0 [43]. The mean expectation value of β_i is 0; the variance which forms a cone around $\beta_i = 0$ determines the scattering behavior. The variance of β_i is the sum of $Var[\psi_{left}]$ and $Var[\psi_{right}]$, and also depends on the track momentum p (velocity v) at each layer, initially estimated with SeedTracker:

$$Var[\beta_i] \equiv \sigma_{\beta,i}^2 = \left(\frac{13.6 MeV}{pv} \right)^2 \frac{\Delta s}{X_0} \left[1 + 0.038 \ln \left(\frac{\Delta s}{X_0} \right) \right]^2 \quad (4.8)$$

where Δs is the thickness of the silicon, and X_0 is the radiation length ($21.82 g * cm^{-2}$ for silicon). Using equations 4.7 and 4.8, the least squares fit that GBL performs to estimate the scattered hit positions $(u_1, \dots, u_i, \dots, u_n)$ for n SVT layers and $n - 1$ track segments minimizes the hit residuals and kinks through the quantity

$$S(\vec{u}) = \sum_{i=1}^n \frac{(y_i - u_i)^2}{\sigma_i^2} + \sum_{i=2}^{n-1} \frac{\beta_i^2}{\sigma_{\beta,i}^2} \quad (4.9)$$

Both the track collection found with SeedTracker as well as the refit GBL tracks are kept in the event, but the GBL tracks will be the collection analyzed in this document, unless explicitly stated otherwise.

4.4 Track-Cluster Matching

After the GBL refit, an attempt is made to pair tracks in an event with clusters from the same event. Since the magnetic field is no longer constant in the region just before layer 6 (figure 4-8), a track is first extrapolated from its position in SVT layer 5 ($\sim 70\text{cm}$ from the target) to the ECal assuming a constant field.

Figure 4-8: The magnetic field strength as a function of z -position. The fringe field begins just before layer 6, with the near-constant value dropping $\sim 16\%$ by the time it gets to the layer 6 position.

A generated 3D magnetic fieldmap is then used to propagate the tracks through the fringe region. The track is first swum from the start position to a point safely before the constant field region ends, at the position of layer 5 (70cm from the target), where the initial momentum is calculated. The track is then extrapolated in 5mm step sizes to new positions within the fringe field, where the track parameters are updated each time. The position where the track intersects the face of the ECal (1.393m from the target) is where

the matching is determined.

Figure 4-9: A track being extrapolated to the face of the ECal. The track is first extrapolated to layer 5 ($\sim 70cm$ from the target) assuming a constant B-field, just before the end of the tracking region (S_1). It is then swum through the fringe field (S_2) in $5mm$ steps, using a 3D fieldmap generated from a magnet survey, in order to find where the track endpoint should intersect the ECal.

Distributions of the difference in x -positions for the cluster and track, as a function

of cluster energy, are made separately for top/bottom and positive/negative tracks. Each distribution is divided into many energy slices, and each slice is fit to a Gaussian. The functional form of the resulting means and sigmas is parameterized by a 5th-degree polynomial to quantify the match at a specific cluster energy. An example of this for negative tracks is shown in figure 4-10. Similar distributions are made for positrons and the top ECal half, to extract matching parameters in the form of energy-dependent Gaussian fits.

Figure 4-10: The horizontal difference in cluster-track positions for electrons in the bottom half of the ECal. The red lines are the parameterized Gaussian mean for each energy $\pm 3\sigma$.

The track-cluster matching is quantified by the parameter n_σ , defined by the Gaussian parameters at the cluster energy:

$$n_\sigma = \sqrt{n_{\sigma_x}^2 + n_{\sigma_y}^2} \quad (4.10)$$

where $n_{\sigma(x,y)}$ for each coordinate (x, y) is

$$n_{\sigma(x,y)} = \frac{(x, y)_{cluster} - (x, y)_{track} - \mu_{(x,y)}}{\sigma_{(x,y)}} \quad (4.11)$$

Figure 4-11: The n_{σ} value for all clusters and tracks in the same Ecal half, multiplied by the sign of the track (arbitrary units). During reconstruction, a track is matched to a cluster if n_{σ} is less than 30. This value is deliberately left very loose, so that matching can be selectively tightened during offline analyses by further cuts on the n_{σ} variable.

A track is associated to a cluster during recon if the n_{σ} for a track-cluster pair is less than 30, and they are both found within the same ECal half (the sign of the track slope 'tan λ ' defines a top/bottom track). This matching cut is a first estimate and deliberately left loose; final matching criteria are meant to be applied during individual analyses.

4.5 Vertexing

Once the track reconstruction is performed, pairs of GBL tracks are fit to a common vertex, forming the collection in which detached vertices may be searched for, which could signal an A' candidate. The vertex fit is performed using a fast global method by Billoir [44] [45]. The vertex fit algorithm takes as input two (or in general, n) tracks, in the form of their parameters $q_{i,j}$ and covariance matrix C_i at a reference point. The goal is to find a vertex position V and associated track momenta at that position by way of a least squares fit.

Figure 4-12: The inputs and outputs of a vertex fit. The track parameters at a reference point (translated to a “perigee” coordinate system, figure 4-13) are fit to a vertex V by minimizing equation 4.17. While this technique can handle any number of tracks in principle, HPS vertexes only two tracks at a time.

To fit vertices near the region of interest ($z = 0$ to $z \sim 2\text{cm}$), the track parameters are translated to “perigee” coordinates, where the “perigee” P is the point on the track closest to the beam axis, and used as the reference point with parameters q_i in figure 4-12. The track parameters in perigee coordinates at this point now take the form $q = q(\varepsilon, z_p, \theta, \phi_p, \rho)$, and those at the vertex V which define the momentum are $p = p(\theta, \phi_v, \rho)$, where θ and ρ are the polar angle and curvature of the track as previously defined in figures 4-3 and 4-4. The rest of the perigee parameters are shown in figure 4-13.

Figure 4-13: The perigee parameters used in the vertex fit. The derivatives of the vertex position and momentum with respect to the perigee parameters ε , z_p (defined below), and ϕ_p are used to do the fit.

The relationship between the perigee track parameters q at reference point P and vertex parameters p at vertex $V = V(x_v, y_v, z_v)$ is

$$\varepsilon = x_v \sin \phi_v - y_v \cos \phi_v - \frac{\rho}{2} (x_v \cos \phi_v + y_v \sin \phi_v)^2 \quad (4.12)$$

$$z_p = z_v - (x_v \cos \phi_v + y_v \sin \phi_v) [1 + \rho (x_v \sin \phi_v - y_v \cos \phi_v)] \cot \theta \quad (4.13)$$

$$\phi_p = \phi_v - \rho (x_v \cos \phi_v + y_v \sin \phi_v) \quad (4.14)$$

For the matrices of partial derivatives

$$D_{i,j} = \left(\frac{\partial(\varepsilon, z_p, \phi_p)}{\partial(x_v, y_v, z_v)} \right)_{i,j} \quad (4.15)$$

$$E_{i,j} = \left(\frac{\partial(\varepsilon, z_p, \phi_p)}{\partial(\theta, \phi_v, \rho)} \right)_{i,j} \quad (4.16)$$

the χ^2 to be minimized in the vertex fit for n tracks with covariance matrices C_i is

$$\chi^2 = \sum_{i=1}^n (\delta q_i - D_i \delta V - E_i \delta p_i)^T C_i^{-1} (\delta q_i - D_i \delta V - E_i \delta p_i) \quad (4.17)$$

The vertex position and refit momenta are obtained from equation 4.17 by solving for δV and δp_i , with initial fit estimates $\delta V = (0, 0, 0)$ and $\delta q_i = q_i$, under the minimization condition

$$\partial \chi^2 / \partial V = \partial \chi^2 / \partial p_i = 0 \quad (4.18)$$

The function minimization is performed using the Minuit algorithm, developed at CERN [46]. A beamspot constraint can also be added to the vertex fit by including the additional term

$$(V - b)^T C_b^{-1} (V - b) \tag{4.19}$$

to equation 4.17, where $b = (x_b, y_b, z_b)$ is the beamspot position, and a target-constrained fit can be performed by projecting the unconstrained tracks back to the target. The Gaussian widths of the beamspot used in the covariance C_b^{-1} is estimated to be $130\mu\text{m}$ in x and $50\mu\text{m}$ y , based on harp scans performed during the experiment (section 3.1.2). In HPS recon, the unconstrained, beamspot-constrained, and target-constrained vertex fits are performed for pairs of charged tracks which were refit using GBL. This is done separately for positive/negative tracks, which form the collections of trident and A' candidates, as well as negative/negative tracks, which capture Møller electron candidates. All of these collections are saved in the final recon output for analysis.

Chapter 5

Monte Carlo Simulation Chain

In order to confidently analyze the reconstructed tracks and vertexed particle candidates in data, as well as acceptances and efficiencies, realistic Monte Carlo simulations must be made, which describe the signal and backgrounds that the experiment will encounter. To do this, a robust set of software packages are used. The full process includes simulating the various physics signals and backgrounds using Monte Carlo techniques, propagating these events through a simulated detector geometry, and then accepting and reconstructing these events in a manner as identically as possible to how raw data is handled. This section describes the steps involved.

5.1 Event Generation with EGS and MadGraph

The first step of the Monte Carlo simulation chain is to produce the various physics events that will ultimately be accepted in the detectors and analyzed. These events are generated using two software packages: EGS5 [47] and MadGraph [48]. Background processes and signals are generated separately using one or both of these packages, and then mixed before being propagated through the rest of the simulated geometry of the HPS experiment, using Geant4 (described in the next section). Note that a 'generated event' can be somewhat ambiguously-defined within this context, since the events come from different sources, but it will always apply to one of two scenarios. A generated event can be either the collection of

particles (IDs, positions, momenta) which exist after a defined number of beam electrons are propagated through a target material, and all interactions accounted for in the simulation are applied (e.g. an 'egs5 event'), or this same notion of a collection of particles after a *single* process is simulated (e.g. trident or A' signal using MadGraph), where no HPS target parameters are yet assumed to account for multiple scattering. In other words, scattered events generated using EGS is a single-step process, while MadGraph takes two steps; generated events are later simulated through the target, adding the additional multiple scattering that they would have undergone.

The primary HPS Monte Carlo background structure is comprised of the scattered beam events produced by EGS5, and includes elastic and quasielastic scattering, Møller scattering, and pair production. An 'event' in this context is defined as the collection of particles produced after sending a $2ns$ bunch of beam electrons through the target material ($4\mu mW$), and therefore depends on the beam current to be simulated (e.g. 2500 electrons/bunch translates to $200nA$). Specialized signal events (A' , True Muonium) and certain other background processes (tridents, wide-angle bremsstrahlung) are also needed, but neither egs5 or Geant4 are able to produce them accurately or efficiently (~ 2.3 tridents would be produced naturally for each pulse of 1000 electrons hitting the target). These events are therefore generated using MadGraph and then processed using EGS5 to simulate additional scattering processes that could affect them at random points throughout the target material. They are then mixed with the primary scattered beam background, according to the cross sections of the individual processes.

5.2 Background Mixing Procedure

Once each individual process is generated, an optional step is to create a full physics background by merging these processed MadGraph events with the scattered beam back-

ground. This is done by sampling events from each generated process according to a Poisson distribution, weighted according to the integrated cross section of the process calculated by MadGraph:

$$\# \text{ of sampled events} = \text{random integer sampled from } \frac{\mu^r e^{-\mu}}{r!} \quad (5.1)$$

where r is a positive pseudo-random integer and μ is the mean number of signal events to be used, calculated from the generated cross section of the events and the luminosity of the experiment:

$$\begin{aligned} \mu &\equiv \text{mean } \# \text{ of events} = \mathcal{L}\sigma \\ &= (\text{target density})(\text{target thickness})(\text{beam bunch size})\sigma \\ &= (6.30610^{-2} \text{ atoms/cm/barns})(0.0004375\text{cm})(\#e_{beam}^- \text{ per } 2\text{ns})\sigma \end{aligned} \quad (5.2)$$

The size of the beam bunch ($\#$ of beam electrons per 2ns) depends on the beam current to be simulated. For example, there are 625 electrons/bunch for 50nA , which scales to 2500 for 200nA , etc. Once these events are sampled, they are then merged into events that have been sampled from a scattered beam background file ($500k$ total events per file). An example of how mixing tridents and wide-angle bremsstrahlung into the scattered beam background creates the kinematics of the final background particles is shown in figure 5-1.

Figure 5-1: A schematic of the mixing procedure for Monte Carlo backgrounds. Shown are distributions of the polar scattering angle vs. energy of photons, electrons, and positrons from the scattered beam background (top-left), wide-angle-bremsstrahlung (top right), and background tridents (bottom-left). The bottom-right distribution is of the full Monte-Carlo background after sampling/mixing is performed.

After mixing occurs, an 'event' is then defined to be the collection of particles which exist after sending a $2ns$ bunch of beam electrons through the entire length of target material, which includes a luminosity-weighted number of tridents and wide-angle bremsstrahlung in

realistic proportions. To account for the angle between the Hall B beamline and the HPS target (section 3.1.3), the momentum vectors of generated events are also rotated horizontally by 30.5mrad from $\theta_x = 0$. All of these events still exist at $z = 0$ (just after the target), to be propagated through the detector geometry by the software described in the following section.

5.3 Event Propagation using SLIC

Once the physics events are generated in the target and the beam angle offset is applied, the next step is to simulate their passage through the entire HPS detector geometry, so that the readout of the detectors may be simulated and handled in the same way as it is for raw data. This is accomplished with SLIC (Simulator for the LInear Collider), a program that uses the GEANT4 library to simulate the detector and create secondary particles from the generated events as they pass through it [49][50]. GEANT4 (for GEometry ANd Tracking), is a C++ based platform for the simulation of the passage of particles through matter, and allows for a customized linear collider detector description (LCDD) to be defined in an XML format using a multitude of available materials through which particles may pass. In order to match data, it is crucial at this stage to account for all materials present in the experiment, by creating them within the simulated detector geometry. For example, many wide-angle bremsstrahlung events artificially create e^+e^- pairs from the photon converting in extraneous material, such as an aluminum support frame. All of these things should ideally be accounted for to minimize discrepancies between data and MC. A visualization of an e^+e^- pair traveling through the simulated detector geometry can be seen in figure 5-2.

Figure 5-2: An electron-positron pair traveling through a simulated detector geometry, as visualized using the WIRED plugin in the Java Analysis Studio 3 (JAS3) software package.

Simulated hits are generated where the particles intersect the SVT layers and ECal crystals defined by the geometry, in the form of time stamps and energy depositions. These simulated hits are digitized and converted into raw hits to be reconstructed the same way as for hits found in data.

5.4 MC Readout and Recon

Once the MC events are propagated through the detector geometry with SLIC, all MC particles that had been originally generated will then have start and endpoints within the entire volume, and any SVT sensor plane that the particle crosses will contain information about the time of crossing and energy deposition, based on the simulated material it passes through. This information is stored in a collection of “SimHits” which is unique to Monte

Carlo, since the common hits created by a single particle are known with certainty and can be associated. These simulated detector hits are then converted into “raw hits”, which are meant to simulate the actual response of each subdetector, including digitization and event readout (chapter 3).

Once simulated readout is performed to get an event structure that would have been collected in the experiment, the track reconstruction and vertexing works the same way as it does for data; a key difference being that each hit can now be traced back to the particle which created it, allowing the reconstructed quantities (e.g. momentum) to be compared with those that were simulated. An example of how the Monte Carlo agrees with data, and how the individual components contribute to the full background, is shown in figure 5-3.

Figure 5-3: A comparison of the momentum sum from reconstructed $e + e^-$ events, from mixed Monte Carlo background and the data it represents. The primary background components (tridents and wide-angle bremsstrahlung) are also shown.

Monte Carlo simulations are used to understand and recreate the various backgrounds and resolutions seen in data, and to discover cuts for extracting particular signals, including A' 's and TM. This is the subject of the remaining sections, including the search for displaced A' vertices.

In particular, the mass residual ($|m_{\text{simulated}} - m_{\text{reconstructed}}|$) can be calculated for the reconstructed A' events, providing one axis of the space where the displaced vertex search is performed (chapter 7), and the mass resolution calibrated using other simulated events (Møllers) which are also found in data.

Chapter 6

Møller Event Selection and Mass resolution

While the majority of the physics processes from the experiment includes interaction with the nucleus, a fraction of the collected events come from electron-electron (Møller) scattering. This is a useful process to understand, because Møller electrons have a simple mathematical relationship linking their momentum and incident scattering angle θ . In addition to finding discrepancies in track momentum, Møllers also provide a valuable data point in the mass resolution for a vertex at the target, which should be consistent with the vertex of an A' with similar mass ($\sim 50MeV$ for $2.3GeV$ beam) when extrapolated back to the target position. This is an important quantity to know, since the mass resolution defines how many events are let into a search window for the vertexing analysis (chapter 7). Møller events were simulated with a beam energy of $2.3GeV$, using a subroutine in EGS5 which only keeps the Møller events produced from the scattered beam. The agreement between the differential cross section and generated Møller energy is shown in figure 6-1 [51].

Figure 6-1: Generated energy of simulated 2.3 GeV Moller electrons at the target. The calculated cross section is overlain. The beam current used was $200nA$, along with the target parameters defined in chapter 5.

As seen in figure 6-1, Møllers are mostly produced at the two extremes of the energy spectrum. The high-energy beam electrons are scattered very little when interacting with electrons in the target, which in turn ejects the target electrons with very low momentum (wide scattering angle). Unfortunately, the HPS pair triggers largely reject these two peaks because the higher-energy electrons miss the calorimeter, which prevents electrons from the low-energy peak from being paired with them. As a result, most of the vertexed Møllers are

near the center of the energy range ($E_1 \sim E_2 \sim E_{beam}/2$) where the yield is quite low.

6.1 Kinematic Interdependence of Møller Electrons

The relationship between the energy E of a Møller electron and its scattering angle θ is

$$E(\theta) = \frac{E_{beam}}{1 + \frac{2E_{beam}}{m_e} \sin^2(\theta/2)} \quad (6.1)$$

In the case of the 2016 experimental run, $E_{beam} = 2.3GeV$. Equation 6.1 (overlain in figure 6-2) provides an excellent check of how closely a Møller candidate selected from a collection of vertexed electrons follows the expected elastic scattering model.

Figure 6-2: Scattering angle θ vs. energy E of simulated 2.3GeV Moller electrons at the target, before being propagated through the detector geometry. The distribution matches equation 6.1, the overlain curve.

The kinematics of the electron pair also depend on one another. To minimize accidentals, the primary Moller cuts imposed should then involve both electrons selected from a vertexed e^-e^- pair rather than individual electrons. Møllers in the HPS experiment should primarily come from a beam electron ($E = E_{beam} = 2.3\text{GeV}$) that has been scattered from a target electron initially approximated to be at rest. In this case, the energies of the detected Moller

pair should always add to the beam energy:

$$E_2(E_1) = E_{beam} - E_1 \quad (6.2)$$

Plugging this energy sum constraint into equation 6.1, a relationship between the Møller scattering angles θ_1 and θ_2 can be also obtained:

$$\theta_2(\theta_1) = 2 \sin^{-1} \left(\frac{m_e}{2E_{beam}} \csc \frac{\theta_1}{2} \right) \quad (6.3)$$

Selecting cuts based on these relationships after data reconstruction, particularly the ones with inter-electron dependence (energy-energy, theta-theta) is a reliable way to select a clean Møller sample.

Figure 6-3: The scattering angles θ_1 vs. θ_2 of reconstructed 2.3GeV Moller electrons in data. The distribution matches the yellow curve, equation 6.3. The red lines indicate the bounds of the theta sum cut, which account for the wider resolution from using reconstructed tracks.

Møller track selection cuts	
beamspot-constr. Møller candidates	singles0 trigger
Track time coincidence	$ t_{track1} - t_{track2} < 2ns$
Opposite ECal volumes	$\tan\lambda_1 * \tan\lambda_2 < 0$
Isolation cut	(equation 7.3)
L1/L1 cut	Both e^- tracks have L1 hits
Momentum sum	$0.75 * E_{beam} < p_{pair} < 1.15 * E_{beam}$
Scattering angle sum	$40mrad < \theta_1 + \theta_2 < 48mrad$

Table 6.1: Møller selection cuts used to extract Møller scattering events from a data sample.

6.2 Møller Event Selection

The vertexing procedure in chapter 4 was tuned to vertex only pairs of electrons, instead of e^+e^- , creating a collection of Møller candidates. Based on the Monte Carlo, the selection cuts in table 6.1 were used to extract Møller electron pairs from this collection. Since effectively half of the Møller electrons are full-energy electrons, which either create partial clusters in the ECal or miss it completely, the very loose singles0 trigger configuration (table 3.3) was used to accept enough events for a Møller mass resolution. While the pair0 trigger was initially developed to be the “Møller trigger”, it ultimately did not collect enough Møller candidates in data to analyze.

The Møller invariant mass is fit using a Crystal Ball function, which models the shape of a signal which has undergone energy loss [52]:

$$f(x; \mu, \sigma, \alpha, n) = N \cdot \begin{cases} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right), & \text{if } \frac{x-\mu}{\sigma} > -\alpha \\ A\left(B - \frac{x-\mu}{\sigma}\right)^{-n}, & \text{if } \frac{x-\mu}{\sigma} \leq -\alpha \end{cases} \quad (6.4)$$

where

$$N = \frac{1}{\sigma} \left[\frac{n}{|\alpha|} \cdot \frac{1}{n-1} \cdot \exp\left(-\frac{|\alpha|^2}{2}\right) + \sqrt{\frac{\pi}{2}} \left(1 + \operatorname{erf}\left(\frac{|\alpha|}{\sqrt{2}}\right)\right) \right]^{-1}$$

$$A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right)$$

$$B = \frac{n}{|\alpha|} - |\alpha|$$

Figure 6-4: Møller candidate events from data, fit using a crystal ball function, equation 6.4.

The Møller invariant mass resolution is 1.7MeV for Monte Carlo, and 2.3GeV for data. The ratio of these masses will be used to scale the A' mass resolution used in the vertex search (figure 7-17).

Chapter 7

A' Displaced Vertex Search

In order to search for displaced vertices, the signal for small QED-coupled (low- ε) A' events, the expected backgrounds and various resolutions of the experiment must be well-understood. The following sections detail how the various efficiencies needed to estimate the detectable A' yield are extracted from Monte Carlo simulations, followed by the search for displaced vertices.

7.1 Detectable A' Yield in 2016 Data

The expected number of A' events produced in the radiative fraction of the trident kinematic region is

$$N_{A'} = \frac{3\pi\varepsilon^2}{2N_{eff}\alpha} \left(\frac{N_{rad}}{N_{tot}} N_{bin} \right) \frac{m_{A'}}{\delta m} \quad (7.1)$$

Equation 7.1 is effectively the ratio of the A' cross section to the trident cross section (equation 3 in [19]) for a single mass hypothesis $m_{A'}$, scaled by other parameters of the experiment which must be obtained from Monte Carlo. In particular, N_{rad}/N_{tot} is the fraction of accepted radiative trident events to the full background, which estimates how much of the accepted background events come from the kinematic region where an A' would be found. The bin width δm is defined by the mass resolution (equation 7.6), N_{bin} is the number of events found in this bin, α is the fine structure constant, and $N_{eff} = 1$, because only e^+e^-

decays are expected (section 2.3). The actual detectable A' yield for an HPS vertex search is further scaled by an integral involving the z -cut and vertex-dependent efficiency, up to the end of the A' vertex acceptance, $z_{acceptance}$ (found from MC to be $< 80mm$, Appendix B.1):

$$N_{A'}(z_{cut}) = N_{A'} * \int_{z_{cut}}^{z_{acceptance}} \frac{e^{\frac{-(z-z_{target})}{\gamma c\tau}}}{\gamma c\tau} \epsilon_{vtx} \epsilon_{cut} dz \quad (7.2)$$

The vertex efficiency ϵ_{vtx} is the z -dependent fraction of simulated A' events which are accepted by HPS (obtained for each simulated mass), the mass cut efficiency ϵ_{cut} is 0.838 for events passing the z -cut (0 otherwise), corresponding to a bin width of $1.4 * \sigma_{mass}$, and $\gamma c\tau$ is the A' decay length (equation 2.11). Using Møller electrons from MC and data, the target position z_{target} was discovered to be $-4.3mm$ from the nominal position of $z = 0$. The vertex cut z_{cut} for each mass bin will be the topic of section 7.2.

7.1.1 A' Selection Cuts and Cut Efficiency

A vertex search is performed by finding the smallest possible vertex cut on the data such that the various prompt background events expected from the Monte Carlo are effectively eliminated, and a significance is assigned to any excess events. Before that however, other types of selection cuts are made to reduce contamination from high- z events, while preserving as many events as possible within the radiative region of accepted events, where an A' would be found. The events surviving these cuts are used to calculate the radiative fraction of these background events as a function of mass (figure 7-10), to be used in determining the expected yield for each A' mass-coupling hypothesis. The selection cuts used in the 2016 vertex search are in table 7.1. They were initially obtained by optimizing a cumulative distribution function of the signal-to-noise ratio $S/\sqrt{S+B}$, found using reconstructed e^+e^- pairs in Monte Carlo, where the signal is represented by radiative trident events, and the background is the combination of Bethe-Heitler tridents and wide-angle bremsstrahlung events. The

reasoning behind this strategy is to find where to place a cut beyond which there would be more background than signal found in the distribution.

These cuts were tuned using a 5% subset of the blinded data used for this analysis. Plotting each quantity to be cut as a function of z -vertex, and isolating mass regions where high- z events are found, reasonable track quality cuts were placed to eliminate high- z events arising from very low-momentum or poorly-fit tracks, which contaminate the vertex vs. mass distribution (figure 7-15) where the displaced vertex search is performed.

Accidental pair and FEE/elastic cuts	
Cluster coincidence	$ t_{clust1} - t_{clust2} < 1.5ns$
Opposite ECal volumes	$\tan\lambda_1 * \tan\lambda_2 < 0$
Isolation cut	(equation 7.3)
Elastic/FEE rejection	$p_{el} < 1.4GeV$
Radiative cut	$p_{el} + p_{pos} > 1.8$
Track quality/matching cuts	
Track fit χ^2	$\min(\chi_{track,el}^2, \chi_{track,pos}^2) < 15$
Track χ^2 sum	$\chi_{track,el}^2 + \chi_{track,pos}^2 < 30$
Cluster-track match n_{sigma}	$\min(n_{sigma,el}, n_{sigma,pos}) < 3$
Match sum	$n_{sigma,el} + n_{sigma,pos} < 6$
Poor low-momentum tracks	$p_{el} > 0.6GeV, p_{pos} > 0.8GeV$
WAB rejection cuts	
L1/L1 and L2/L2	e^- and e^+ tracks have L1 and L2 hits
Momentum Asymmetry	$-0.6 < (p_{el} - p_{pos})/(p_{el} + p_{pos}) < 0.6$
Beamspot-unconstrained vertex fit difference	$\chi_{bsc}^2 - \chi_{unc}^2 < 5.5$

Table 7.1: The A' event selection cuts used in the 2016 A' vertex search.

The **isolation cut** is designed to exclude poorly-reconstructed events which result from a track being incorrectly associated to the wrong SVT hit. If a particle scatters in layer 1, then its trajectory will be influenced such that a line fit may incorrectly associate its hits in later layers with a neighboring hit in layer 1. If such a track is used in vertexing, then it will pull the vertex downstream of the target, potentially creating a false A' candidate with a displaced z -vertex. This type of situation is shown in figure 7-1.

Figure 7-1: The situation that the isolation cut tries to prevent. If the true trajectory of a scattered charged particle creates hits denoted by the black circles, then a nearby L1 hit (red circle) may result in a better linear fit, and such a fit will be used to create the track. This would pull the fit vertex downstream, and potentially create a false positive in a vertex search.

An mishit like the one seen in figure 7-1 should influence the track parameters from the resulting fit in a quantifiable way, and so a cut can be defined to reduce these types of events. In particular, the tracks from a scattering event such as this should see an increased vertical

distance of closest approach at the target by roughly twice the distance between the hit used for the fit and the correct one (apparent from figure 7-1). Therefore, the isolation cut is designed to reject any track which an unusually large vertical drift. Equation 7.3 is the explicit form of the isolation cut in table 7.1.

$$(\text{track vertical DOCA at the target}) - 2 * (\text{distance between L1 hits}) < 0 \quad (7.3)$$

The WAB rejection cuts, which include the **L1/L1 and L2/L2 cuts**, are designed to cut out events which likely came from an e^+e^- pair originating from a photon converting in a silicon layer, where the positron from such a conversion paired with a beam electron, rather than both particles originating near the target (figure 7-2). In such a case, at least one track in the pair should not have intersected the first SVT layer, so requiring that both tracks do is an efficient way to eliminate WAB contamination. **The momentum asymmetry cut** exploits the difference in momenta between the electron and positron in the pair created from a WAB event, since the momenta from a pair produced in an actual A' decay would be roughly equal.

Figure 7-2: How a wide-angle-bremsstrahlung event creates a false vertex. The photon from the event converts into an e^+e^- pair from interacting with the silicon, and the positron may be paired with an electron which originates from the target. When fit, the vertex itself will be consistent with a displaced A' vertex, contaminating the data. Requiring that each track has hits in layer 1 eliminates $\sim 60\%$ of these types of events.

The beamspot-unconstrained χ^2 difference cut: If both particles originated from the same location, whether from the target or a decay from a displaced particle which originated from the target (e.g. an A'), then the reconstructed vertex (the position and e^+e^- momenta) should project back to the beamspot on the target reasonably well, where the original particle was produced. While the χ^2 of the unconstrained vertex fit (equation 4.17) only encapsulates how well the tracks intersect at a common vertex, the beamspot-constrained χ^2 (equation 4.19) does this and also quantifies how likely both tracks originated from an event created in the target, if the tracks are extrapolated back to the position of the target. Cutting on the beamspot-unconstrained χ^2 difference is therefore designed to eliminate events involving layer 1 scattering, such as wabs, where one particle would have originated from the target, and one would have originated much further downstream, worsening the beamspot-constrained χ^2 . The z -vertex distribution as a function of this

difference is shown in figure 7-3, and the effect of applying this cut on the vertex vs. mass distribution (where the vertex search is performed) is shown in figures 7-4 and 7-5.

Figure 7-3: The z -vertex distribution as a function of beamspot-constrained minus unconstrained χ^2 in 2016 data. Highly-displaced events consistent with wide-angle bremsstrahlung appear in the tails of the data where this quantity becomes large (figure 7-4), so a cut (red line) is placed to ensure that they do not contaminate the full data set.

Figure 7-4: The z -vertex distribution as a function of invariant mass for simulated wide-angle bremsstrahlung events, with and without the beamspot-unconstrained χ^2 difference cut. This cut eliminates high- z events involving SVT layer 1 scatters, which would contaminate the data.

Figure 7-5: The z -vertex distribution as a function of invariant mass for the 2016 data set used in this analysis, with and without the beamspot-unconstrained χ^2 difference cut. The cut eliminates high- z events involving layer 1 scatters, which would contaminate the data. Displaced A' events are mostly retained when including this cut, as seen in figure 7-8.

The beamspot-constrained minus unconstrained χ^2 cut is unable to eliminate events with a displaced vertex coming from *two* particles scattering in layer 1, however. While this type of event is similar to a false displaced vertex created from a converted wide-angle bremsstrahlung event (figure 7-2), a double Coulomb scatter would be immune to any cut which relies on the beamspot constraint χ^2 , since both particles would have originated from the beamspot when the tracks are projected back to the target position.

Figure 7-6: A double Coulomb scattering event, which would create a false displaced vertex downstream of the target. While these events are rare, there is currently no way to eliminate them in a vertex search.

Since there is currently no way to distinguish these events in simulation, double Coulomb scattering events like the one in figure 7-6 are likely candidates for any background event which survives the vertex cut (section 7.2). The placement of the remaining cuts is discussed in Appendix A. Figures 7-7 and 7-8 show the effect on the high- z events in data when applying each cut, compared with displaced A' events.

Unconstrained Vertex-z Cut Flow (Data)

Figure 7-7: The effect on the vertex distribution from applying each vertexing cuts to data.

The high- z tails are significantly reduced.

Unconstrained Vertex-z Cut Flow (Displaced A's)

Figure 7-8: The effect on the vertex distribution from applying each selection cut to fully reconstructed displaced A' events from pure A' Monte Carlo (mass hypotheses: $50-175\text{MeV}$). None of the cuts after the L1L1 cut (to reduce WAB contamination) have a significant effect on the highly-displaced A' events, although they do reduce the statistics.

The efficiency of these selection cuts on the reconstructed 125MeV A' pairs from MC (which have the highest acceptance for an equal number of generated events) is 40%. For comparison, only about 6% of wide-angle bremsstrahlung events pass these cuts, mostly rejected by requiring hits in SVT layer 1, and 20% of trident events pass.

7.1.2 Fraction of radiative background events

To get the fraction of radiative events where an A' search is conducted ($\frac{N_{rad}}{N_{tot}}$ in equation 7.1), the vertexing cuts in table 7.1 are applied to each type of the simulated background events individually. This background includes both radiative and Bethe-Heitler tridents, as well as events which came from the photons in a wide-angle bremsstrahlung event converting into an e^+e^- pair within a silicon layer. The ratio of the radiative to non-radiative background events gives the expected fraction of events which overlap with the A' kinematics, and factors into the expected yield of generated A' events which pass acceptance (equation 7.2).

Figure 7-9: The invariant mass spectrum of the various background events from MC, normalized by cross section. The radiative fraction is obtained by dividing the radiative trident events (red) by the non-radiatives combined with wab events (black).

Figure 7-10: The radiative fraction of reconstructed and cut background events as a function of invariant mass. In the flat region where the vertex search is conducted ($50\text{MeV} - 140\text{MeV}$), the radiative fraction is 17.8%. Fit function: $0.181948 - 1.27696 \exp[-x/0.0124404]$.

From figure 7-10, 17.8% of accepted background events in the constant region of the mass range are from the radiative events.

7.1.3 A' Efficiency vs. Decay Vertex

The selection cuts in the previous section only serve to reduce much of the known backgrounds that are expected in the data. In order to fully account for the expected efficiency of accepted A' events in a vertex search, the efficiency as a function of vertex displacement along the beamline must be determined for each of the generated A' masses; this is the ϵ_{vtx}

in equation 7.2. This efficiency must include the effects of all the cuts in table 7.1 (described in the previous sections), as well as the geometric acceptance of the detector.

The decay vertices for the simulated A' samples in this analysis were displaced by $c\tau = 10\text{mm}$. After the boost is applied, the spectrum of vertices along the beamline fill the entire detector region before the first SVT layer (figure 7-11).

Figure 7-11: The spectrum of displaced A' vertices that were generated (100MeV mass), before detector acceptance and reconstruction. The linear fit shows the decrease in statistics over the range from the target to the 1st SVT layer (10cm).

For each A' mass generated and reconstructed in the simulation chain, the corresponding vertex distribution after reconstruction and event selection cuts is divided by the total distribution before acceptance, to get the vertex-dependent efficiency curve ϵ_{vtx} . The functional

form of this curve, fit to each mass (example in figure 7-12), is

$$\frac{\epsilon_{recon}(m_{A'}, z)}{\epsilon_{generated}(m_{A'}, z)} \equiv \epsilon_{vtx}(m_{A'}, z) = e^{p_0 + p_1 z + p_2 z^2 + p_3 z^3} \quad (7.4)$$

where each coefficient p_i depends on the A' mass, $m_{A'}$.

Figure 7-12: Acceptance and cut efficiency as a function of displaced vertex, for 50MeV A' 's.

The complete set of efficiency plots for the simulated A' masses, like the one in figure 7-12, can be found in Appendix B.1.

7.2 Vertex Cut

The search for displaced decay vertices will take place on the vertex vs. mass histogram of reconstructed events, after the selection cuts are made. However, there is still a large amount of background in these events, as seen in figure 7-9. While a mass resonance search would keep this background and search for a small “bump” in the invariant mass spectrum on top of it, a vertex search is performed by designing a cut on the z -coordinates of the vertices using Monte Carlo, such that this background is effectively eliminated. The search for excess displaced events then takes place beyond this z -cut. Events from the simulated background tridents are shown in figure 7-13, and will be used to determine the shape of the background for each mass bin, and where the tails of the z -vertex distribution for each mass begins.

Figure 7-13: The background trident MC vertex z vs. mass distribution from which the background shapes from each mass bin are determined. Resolution-limited mass slices are created to represent each mass bin to be searched in data, and the background shape modeled by equation 7.5.

7.2.1 Background model and tail fits

In order to find an optimal vertex z -cut to reject background events, first the background must be modeled and the tails parameterized. To do this, the mass axis of figure 7-13 is divided into 100 slices between 50MeV and 140MeV (which overlap since the resolution-limited bin size is larger than the 0.9MeV between the slices). Vertex distributions are then created from each slice and fit, to estimate the background model. Beyond this range, there are too few events for the tails to be fit effectively. The background is modeled by a Gaussian core and a Gaussian + exponential tail, by the piecewise function

$$B(z; \bar{z}, \sigma, b, l) = \begin{cases} Ae^{-\frac{(z-\bar{z})^2}{2\sigma^2}} & \text{if } z \leq \bar{z} + b \\ Ae^{-\frac{(z-\bar{z})^2}{2\sigma^2} - (z-\bar{z}-b)/l} & \text{if } z \geq \bar{z} + b \end{cases} \quad (7.5)$$

The b parameter in equation 7.5 defines the z -position where the tail begins for each mass slice, and l defines the length of the tail. An example of a mass slice from figure 7-13 and resulting background fit to the vertex distribution is in figure 7-14.

Figure 7-14: The mass slice for the 100MeV center-of-mass bin (width: 3.95MeV) and resulting vertex distribution to which equation 7.5 is fit. Two high- z events exist past the tail in this particular slice.

The size of each mass slice is a function of the mass resolution (equation 7.6), and also defines the widths of the mass bins used in the vertex search. The complete set of these background fits and their parameters can be found in Appendix B.2.

7.2.2 Mass resolution and z -cut

Once the backgrounds are fit for each mass slice using Monte Carlo, a z -cut can be calculated for each mass bin in data such that the expected background should be effectively eliminated beyond the cut. Figure 7-15 shows the vertex vs. mass histogram for the data set on which the vertex search will be performed. For this analysis, a blinded 10% subset of the full data set was used (~ 2 million vertexed e^+e^- pairs).

Figure 7-15: The cut vertex z vs. mass distribution on which the vertex search is performed. A mass-dependent vertex cut is determined to effectively eliminate all of the remaining background in each mass bin.

The vertex cut, z_{cut} , is the lower bound of the integral in the calculated A' yield (equation 7.2). It is obtained by counting how many background events are contained in each mass bin, within a resolution-limited window of size δm :

$$\delta m = |m - m_{bin}| < 1.4 * \sigma_m \quad (7.6)$$

The mass resolution σ_m is obtained by simulating displaced A' events with a spectrum of masses through the experiment, reconstructing and vertexing them to get their invariant mass spectra, and fitting each residual ($|m_{generated} - m_{reconstructed}|$) to a linear fit as a function of mass. These fits for each A' mass that was simulated can be found in Appendix B.3

(example in figure 7-16).

Figure 7-16: The mass residual $|m_{\text{generated}} - m_{\text{reconstructed}}|$ as a function of vertex- z for $125\text{MeV } A'$ s (top), and the fit of the mass resolution as a function of vertex- z (bottom). This is performed for each of the generated A' masses, and the constant values are used to estimate the resolution at each mass point (figure 7-17).

Figure 7-17: The constant values for the linear mass resolution fits at the decay vertex, for the full spectrum of generated A' masses. The overall linear fit provides the mass-dependent resolution σ_m . The pink point is the Møller mass resolution obtained from Monte Carlo, and the red point is the Møller mass resolution from data. This discrepancy suggests a systematic shift of $\sigma_{data}/\sigma_{MC} = 1.35$, which will scale the A' mass resolution.

Using σ_m for the A' s in figure 7-17 scaled by $\sigma_{Møller,data}/\sigma_{Møller,MC}$ to define the size of each mass window, and the fit background model (equation 7.5), a cumulative distribution function (cdf) can be made for each slice. A z -cut can then be defined such that 0.5 events are expected to pass the cut for each mass bin.

Figure 7-18: The vertex cut as a function of invariant mass, such that a resolution-limited mass slice will contain 0.5 background events. The range $50 - 140 \text{ MeV}$ was used for the calculation. The background tails contain approximately zero events beyond 140 MeV , and can no longer be effectively fit.

7.3 A' candidate events in 2016 data

Once the vertex cut is applied to reject all known background based on the model, any event which survives can be further examined. Figure 7-19 shows the 2016 data set with the z -cut (figure 7-18) overlain.

Figure 7-19: The selected events from 2016 data with the z -cut overlain in red. The events past this cut are A' candidates, which will be assigned significance.

Since the excess events are counted at each mass slice, and there are far more mass slices than excess events, there will be repeated instances of these events which show up in overlapping slices. The increased signal significance which results from this will be corrected for in section 7.3.3.

Figure 7-20: The A' candidate events from 2016 data which pass the z -cut. The number of these events (422) is overestimated due to overlapping mass slices, and will bias the significance if this is not taken into account.

7.3.1 Signal significance

The surviving A' candidates are each assigned a significance which characterizes the probability of finding an excess background event beyond the expectation of the known physics from the simulations. Not accounted for in simulation, for example, is the possibility of a “double scattering” event, where two electrons from the target each undergo symmetric Coulomb scattering in the first SVT layer, and a false vertex is created downstream from the target from the result (figure 7-6), and these are therefore likely candidates for the excess events in the vertex search. Assuming that the background events beyond the z -cut follow a Poisson distribution with mean b , the probability of finding a number of signal events s in

excess of the expected background in each slice is $b^s e^{-b}/s!$ [53]. Signal significance can then be quantified by a “ p -value”, which gives the probability that a background-only hypothesis will produce at least a given number of false signal events beyond the z -cut:

$$p(s, b) = e^{-b} \sum_{k=s}^{\infty} \frac{b^k}{k!} \quad (7.7)$$

A large p -value indicates that known physics processes likely caused the excess, excluding the possibility of an A' event. A small p -value, however, indicates that finding a certain number of signal events would be highly unlikely, and either there was a background or other contamination that had not been accounted for in simulation, or a potential discovery has been made. The threshold for significance of a discovery is somewhat arbitrary, but a typical value is $p = 0.05$, or “a 5% probability that the background-only hypothesis produced the signal”, and thus a 95% probability of a discovery.

7.3.2 Background estimate and local p -value

In order to count the number of background events for a given mass slice, the candidate events in figure 7-20 are first removed from that slice. The remaining events at all other masses are assumed to be background (which implicitly assumes that an A' would exist at a single mass in this range), and fit to a cubic function. This is done for each mass slice, and the value of the signal-excluded background fit at the center of each mass slice estimates the background count for that slice. An example of such a background fit is shown in figure 7-21.

Figure 7-21: A background fit for a mass slice, with the events in the slice removed. A background fit is performed to estimate the number of background events in each mass bin.

Figure 7-22: The estimated number of background events at each mass bin, from fitting the background in all mass slices as in figure 7-21.

Using the number of estimated background events in each mass slice as the ' b ' parameter, and the actual number of events in the bin as the ' s ' parameter, the p -value can be calculated for each slice using equation 7.8.

Figure 7-23: The calculated p -value at each mass, which gives the significance of the excess events for each mass slice. The most significant p -value is 0.0886, for a mass hypothesis of 80.5 MeV .

However, these p -values are artificially low (significant), since the signal counts are artificially high due to overlapping slices, and what is known as the “look-elsewhere” effect.

7.3.3 “Look-elsewhere” correction and global p -value

Since the size of each mass bin is very small compared to the full range that was searched, there will be a higher probability of a false positive signal simply due to statistical fluctuations within a small sample. The p -values in figure 7-23 were calculated for individual mass bins (“local” p -values), but once the most significant local p -value is found, it must be weighed against the entire mass range, rather than a single bin, since a single bin will always have

a higher (local) significance. Furthermore, if one does not know *a priori* at which mass the signal is expected to be, then an excess of events anywhere would be considered equally probable, artificially raising the significance of any signal that is found. This is known as the “look-elsewhere effect” [54].

To account for this, a global p -value was calculated for the most-significant local p -value, 0.0886 in figure 7-23. This does not take into account any less-significant A' events that could be located at different masses in this range, but assumes that the A' would have a single mass resonance, if it exists. Figure 7-20 was fit to a cubic function and used as the model the signal distribution, and the cubic fit from figure 7-21 (the candidate distribution with the events from the most significant mass bin removed), was used to model the background for the mass slice containing the most significant local p -value. A total of 10,000 distributions were randomly populated based on these model estimates (using the same number of excess events found in figure 7-20), the same analysis from the previous section was performed on each distribution, and the most significant local p -value was recorded for each one. In this way, a spectrum of local p -values which could have been produced from assuming the most significant mass hypothesis from this analysis is produced, and from it, a mapping between a particular local p -value and its probability of occurring through many repeated trials (ideally infinite) is obtained.

Figure 7-24: The probability of obtaining a particular p -value, after 10,000 simulations of the background-only hypothesis using the background estimate for the most significant local p -value in figure 7-23. The most significant local p -value for a single mass bin was 0.0886, but correcting for the look-elsewhere effect, this translates to a most significant p -value of 0.68 for all of the mass bins.

The mapping of local-to-global p -values in figure 7-24 suggests that if the background-only model (the null hypothesis) randomly produced the signal found at 80.5MeV in figure 7-23, and if this was the mass hypothesis assumed from the beginning (so no “look-elsewhere effect”), and if the same number of excess events that were found in the overlapping mass slices were used to get this value (accounting for a potentially worse “look-elsewhere effect” from incorrectly choosing an ideal number of mass bins, causing them to overlap too much) then the corrected global p -value would be 0.68, well below the threshold for significance.

7.4 Sources of systematic uncertainty

There are several sources of systematic uncertainty introduced to this analysis which should be discussed, which involves changing parameters to which this vertex search may be sensitive, and see how it affects the significance of each mass hypothesis.

7.4.1 Uncertainty in the background fits

One potential systematic error to account for in this analysis is the background fit. That is, if the cubic function used to model the background was not correct, since the shape of the high- z background in a region of very low background is largely uncertain, then how would it affect the result? To answer this, lower-order polynomials were also used to estimate the background spectrum of events surviving the z -cut (figure 7-20), and the analysis repeated to obtain the significance of the excess events. A quadratic, linear, and constant functions were used to do this.

Figure 7-25: The events passing the z -cut, and calculated p -value for each mass slice, using a quadratic function to fit the background.

Figure 7-26: The calculated p -value for each mass slice, using a linear function to fit the background.

Figure 7-27: The events passing the z -cut, and calculated p -value for each mass slice, assuming a constant background.

From figures 7-25, 7-26, and 7-27, changing the order of the polynomial fit function used

to calculate the p -values does not increase the significance of the peaks found in figure 7-23, and actually decreases the significance of the most significant mass hypothesis (80MeV) to roughly $1/4$ of what it was when using a cubic function to fit the background. It also decreases the next most significant mass hypothesis ($\sim 70\text{MeV}$) by roughly half. Therefore, the conclusion that no A 's were found in this vertex search holds for high- z background assumptions that are modeled with up to a 3rd-degree polynomial.

7.4.2 Uncertainty in the mass resolution

Another source of systematic error comes from the mass resolution. Since Møller electrons are used to scale the expected invariant mass resolution for the A 's in MC to match the data (which defines the bin width and z -cut), and the Møller statistics tend to be low for the 2.3GeV beam energy, the error bars on the masses are quite large. To see what effect underestimating the data/MC discrepancy would have on the final result, the mass resolution was assumed to be at the high end of the error bar for the Møllers collected from data in figure 7-17, 2.7MeV , instead of the mean value of 2.3MeV , to increase this discrepancy. Using a cubic fit for the background, the resulting candidates and p -values are shown in figure 7-28.

Figure 7-28: The events passing the z -cut, and calculated p -value for each mass slice, assuming a larger mass resolution of 2.7MeV for data, rather than 2.3MeV .

From figure 7-28, increasing the MC/data mass resolution discrepancy to within the limits of the error bars reduces the significance of the previously most-significant mass hypothesis by over half of what it was from the original analysis, and leaves the next most significant peak largely unchanged. To carry this further, the discrepancy of the mass resolution was doubled, which goes well beyond the original $\sigma_{data}/\sigma_{MC}$ discrepancy of 35%.

Figure 7-29: The events passing the z -cut, and calculated p -value for each mass slice, assuming a 2x larger mass resolution in data than for MC.

From figure 7-28, increasing the resolution discrepancy between MC and data will only worsen the significance, as more background (averaging $\sim 5 - 6$ events per bin) is let into each mass slice.

7.4.3 Uncertainty in the number of mass bins

Since the decision to use 100 mass bins in the vertex search was not optimized in any way, it may be the case that this was too many, creating an excessive number of A' candidates that may influence the fits and affect the significance. To check, the analysis was repeated using 50 mass bins, for both the MC tail fits and the vertex search on the data. Using half as many bins reduces the number of background events at the 68.4MeV slice just enough to make this the most significant mass in the data, with a local p -value of 0.113.

Figure 7-30: The events passing the z -cut, and calculated p -value for each mass slice, using 50 mass bins.

Once the “look-elsewhere” correction is applied to the peak at 68.4MeV , using the background fit and mass resolution for that bin as was done in the previous vertex search, the global p -value for this mass hypothesis is 0.692.

Figure 7-31: The local p -values for the data set using 50 mass bins instead of 100 (left), and the local-to-global correction using the fits to the signal and background (right)

This demonstrates that, while the background fits are sensitive enough to the mass bin density to influence which of two mass hypotheses (sufficiently close in significance) is the most significant, none of the peaks in the examined mass range fell below the 5% significance threshold for the background-only hypothesis using half as many bins, even before correcting for the look-elsewhere effect.

7.5 Reach estimate

When a signal is not detected in a particular data set, it is customary to report the upper limit, which is the maximum rate that the signal can be produced, and still be consistent with the data within some confidence threshold. This answers the question of whether there are enough signal events expected in the data set for a search to be conclusive, within the parameters used in the search. In other words, it determines if a search on a particular data set excludes any region of the mass-coupling parameter space seen in figure 2-1.

A method by Steven Yellin called the “optimum interval” method was used to put an upper limit for A' production in the data subset that was analyzed [55] [56]. The confidence threshold used was 90%, which says that if an A' exists at a particular rate, then this limit would incorrectly exclude that rate 10% of the time. Therefore, for a region of mass-coupling parameter space to be excluded with the same confidence, the expected number of events in the data must be at least as high as this upper limit.

Figure 7-32: The expected number of A' events produced from equation 7.2, assuming an A' exists at each mass and ε in the data analyzed. The distribution was generated by performing the integral in equation 7.2 starting at the z -cut, and includes the vertex-dependent acceptance. The highest expected number of events for 10% of the data is 1.038.

The expected number of A' events in figure 7-32 was found for each mass and ε hypothesis

by calculating the integral in equation 7.2 beginning at the z -cut from figure 7-18, and including the numerical values for the z -cut, efficiency, mass resolution, and radiative fraction as functions of mass. Since the z -cut is a function of the background fit parameters in equation 7.5, and the amplitude A of the background distribution scales with statistics, the z -cut should increase roughly with more data as

$$z_2 = z_1 + l * \ln(A_2/A_1) \quad (7.8)$$

where l is the tail length parameter from the background fits, with a value of $\sim 1 - 2mm$ for this search (Appendix B), so the full data set ($A_2/A_1 \sim 10$) should increase the z -cut by $\sim 2.3mm - 4.6mm$. The highest expected number of A' events in figure 7-32 (10% of the full data set) is 1.038, at a mass of $70MeV$ and $\varepsilon^2 = 4 * 10^{-8}$. Dividing the upper limit by the number of events expected in this data set (figure 7-32) gives a convenient ratio that determines whether or not exclusion is possible.

Figure 7-33: The ratio of the upper limit of A' events produced, to the expected number of events (equation 7.2). In order for an exclusion to be possible at a 90% confidence limit, the expected number of A' events must reach the upper limit threshold, and so this ratio must be ≤ 1 . For 10% of the 2016 data set, the lowest point is 4.495.

In order for a data set to exclude any region of parameter space with a 90% confidence limit, the expected number of events in the data that was analyzed must be greater than the upper limit threshold, or equivalently, the lowest point in figure 7-33 must be ≤ 1 . Since the lowest point is 4.495, no exclusion can be made for 10% of the 2016 data.

Chapter 8

Potential for True Muonium

Discovery at 6.6GeV

While HPS was designed to search for the heavy photon, another tantalizing signal that can be searched for using the HPS detector setup is True Muonium (TM). True Muonium, or dimuonium, is an exotic hydrogen-like atom governed by QED, much like positronium, a (e^+e^-) bound state, and muonium (μ^+e^-) . What is known as *True* Muonium, however, is a bound state consisting of a $(\mu^+\mu^-)$ pair, and has not yet been discovered in experiment as the other two have. While the signal may be very small, True Muonium is well worth searching for. Not only would it complete the collection of known lepton bound states observed in experiment, it also has the potential to put strong constraints on any beyond standard model physics that affects the muon sector. [57]. The following sections will motivate why HPS is an ideal experimental setup to trigger on a particular TM state with similar production and decay characteristics as the A' , and the feasibility of the experiment producing enough TM to search for in higher energy runs.

8.1 Motivation and Theory

Like similar exotic atoms, TM can exist in atomic orbitals reminiscent of hydrogen, and since it is composed of two spin-1/2 particles (doublets, with spin $\pm 1/2$) with four spin basis

states ($\uparrow\uparrow, \uparrow\downarrow, \downarrow\uparrow, \downarrow\downarrow$) when measured on a given axis, the total spin of TM can be either 0 or 1 once properly added. TM with spin-0 exists as a singlet (para-dimuonium or PM), and decays into a pair of photons which are difficult to resolve from the background, with the lowest energy state decaying within only 0.602 ps [22]. Of interest to HPS is the spin-1 TM in the triplet states (ortho-dimuonium or OM), because it instead decays into an e^+e^- pair and has a longer lifetime as well ($\sim 5 - 15ps$). OM can therefore be detected in a similar way as the A' by tuning the analysis to search for its invariant mass, known precisely to be $2m_\mu = 211MeV$, and the displaced vertex of its decay products, which depends on the characteristic lifetime of the orbital state [21]. The triplet states that HPS will be most sensitive to discover are the 1^3S_1 , 2^3S_1 , and 2^3P_2 states, due to their (relatively) higher yields in the experiment. However, only the 1^3S_1 state survives until after the target without a high probability of dissociating. Since the relative probabilities of the various states being produced go as $\sim 1/n^3$ (eq. 13-14), the higher states may be neglected. These states are shown in the level diagram of figure 8-1, along with their decay products and lifetimes [22].

Figure 8-1: Orbital states and corresponding lifetimes of TM. HPS is sensitive to the first two triplet or 'ortho-' states (n^3S_1) which decay into lepton pairs.

The lifetimes of the OM n^3S_1 states (which also apply to all "true fermionium"), are [22]

$$\tau(n^3S_1 \rightarrow e^+e^-) = \frac{6\hbar n^3}{a^5 m c^2} \quad (8.1)$$

Equation 8.1 can be used in simulations to calculate the corresponding decay length at each energy produced. As it turns out, $\gamma c\tau \sim 1.7 \text{ cm}$ for the 1S state at a 6.6 GeV beam energy, which falls comfortably within HPS's vertex acceptance.

8.2 True Muonium Production and Kinematics

There are two primary production mechanisms for OM which will be considered in HPS: a 1-photon mechanism analogous to bremsstrahlung (figure 8-2), and a 3-photon mechanism (figure 8-3) [23] [24].

Figure 8-2: The one-photon (radiative) mechanism for TM production. This diagram is identical to that of the A' , and HPS should therefore be able to detect the decay products.

Figure 8-3: The three-photon mechanism for TM production. This and figure 8-2 will be the primary modes of production for the 1^3S_1 TM state. The 3-photon diagram will dominate the signal due to the high Z target used in HPS. However, this signal will be obscured by the oppressive background which the experiment is designed to reject.

The cross sections for the single photon mechanism, analogous to (eq. 5) for the A' , and the three-photon mechanism respectively are [23]

$$\left(\frac{d\sigma}{dx}\right)_{1\gamma} = \frac{1}{4n^3} \frac{Z^2 \alpha^7}{m_\mu^2} \frac{x(1-x)(1-x+\frac{1}{3}x^2)}{[1-x+(m_e/2m_\mu)^2]^2} \left[\ln \left(\frac{(E_0/m_\mu)^2 (1-x)^2}{[1-x+(m_e/2m_\mu)^2]^2} \right) - 1 \right] \quad (8.2)$$

$$\left(\frac{d\sigma}{dx}\right)_{3\gamma} = \frac{1}{4n^3} \frac{Z^2 \alpha^7}{m_\mu^2} \left(\frac{Z\alpha\Lambda}{m_\mu} \right)^2 \frac{4B}{x} \left[\left(1-x+\frac{1}{2}x^2 \right) \ln \left(\frac{(1-x)m_\mu^2}{x^2 m_e^2} \right) - 1 + x \right] \quad (8.3)$$

The energy ratio $x = E_{TM}/E_0$ is analogous to that of equation 2.6, where E_{TM} is the energy of the True Muonium. In eq. 8.3, $B = 0.85$, and $\Lambda = 405/A^{1/3}$ is a parameter that takes the screening effect of the target material into account, with A being its atomic mass (183.84u for tungsten), and is related to the mean square radius r of the charge distribution

of the nucleus by $\Lambda^2 = 6/\langle r^2 \rangle$. The relative importance of these two primary production mechanisms depends strongly on the energy ratio x , as seen in figure 8-4

Figure 8-4: Differential cross sections as a function of $x = E_{TM}/E_0$ for the 1γ and 3γ mechanisms of TM production, using a tungsten target and 6.6GeV beam energy. for a large Z target, bremsstrahlung dominates production at higher x , and 3γ at lower x .

Also note that the 3-photon mechanism (eq. 8.3) contains an extra Z^2 dependence relative to that of the single photon one, making this mechanism the dominant one for high Z targets like tungsten. Production of individual states of interest will be discussed in the following section.

Just as the A' has very different kinematics from the photon, allowing for choices of cuts to be made during analysis to optimize the signal to background ratio, the kinematics of the products from the two primary OM production mechanisms are very different as well, suggested by figure 8-4. Since the single-photon mechanism is essentially the same as for the radiative A' , the resulting OM and decay products will be carried at a small forward angle relative to the beamline. In contrast, the 3-photon mechanism, whose amplitude depends strongly on the transverse momenta and properties of the target, will be scattered at a much larger angle. The resulting scattering angles go as

$$\theta_{1\gamma} \sim \frac{m_\mu}{E_0} \quad (8.4)$$

$$\theta_{3\gamma} \sim \frac{\Lambda}{xE_0} \quad (8.5)$$

The 1^3S_1 OM state is produced predominately by these primary production mechanisms. The cross sections for the production of the $2S$ and $2P$ states are an order of magnitude lower than for the $1S$ states, and their dissociation inside the target is higher, making their yields after the target negligible [24].

The single-photon (radiative) mechanism will therefore be of primary interest for an HPS search, since its kinematics are very similar to A' production, and can be analyzed using the same methods used to detect a signal in the displaced vertex and invariant mass spectra of the e^+e^- pair. The portion of the True Muonium signal produced by the 3-photon mechanism, although larger, falls within the oppressive Bethe-Heitler background that HPS is designed to reject. The simulation and analysis of True Muonium will therefore be focused toward the radiative $1S$ mechanism.

A very large caveat here is that the radiative TM cross section (eq. 8.2) is positive only for $E_0 \geq 3.2\text{GeV}$. This is because the radiative cross section for True Muonium is estimated using the Weizsäcker-Williams approximation for bremsstrahlung-like processes [58], and this approximation breaks down at the energy fraction $x \approx E_e/E_0$, where $\frac{d\sigma}{dx} = 0$. Therefore, for any analysis, the differential cross section must only be integrated up to $x \approx 1 - m_e/E_0$. For $E_0 = 6.6\text{GeV}$, this breakdown occurs for $x \geq 0.999298$ however, which is a very small exclusion. Because of the limits of this approximation, as well as an unfeasibly small yield at lower energies, the earliest that TM may be plausibly searched for using HPS, is from a future run at 6.6GeV beam energy.

As with the A' , the way that radiatively-produced TM will be detected is by collecting and identifying its e^+e^- decay products, allowing for its invariant mass and decay vertex to be determined. In the following sections, the expected TM yield after the target will be calculated, and the feasibility of a discovery discussed, using True Muonium events simulated and reconstructed within the confines of the HPS experiment.

8.3 Expected True Muonium Production Rate

Even if HPS is calibrated to only distinguish the radiatively-produced $1S$ state from the background, the total $1S$ yield must be obtained from finding the expected number of events produced from not only the $1S$ primary production mechanism, but also the $2S$ and $2P$ states transitioning into additional $1S$ states, rather than dissociating in the target. Therefore, in order to get the expected number of True Muonium events produced in a fixed target experiment like HPS (and which also survive the target), both the production and dissociation cross sections for these various states must be calculated.

The primary production cross sections are found from integrating equations 8.2 and 8.3:

$$\begin{aligned}\sigma_{prod}^{1S} &= 1.27455pb \\ \sigma_{prod}^{2S,2P} &= 0.15931pb\end{aligned}\tag{8.6}$$

The 2S and 2P states are lower than the 1S state by a simple factor of 8, from the $1/n^3$ dependence. The dissociation cross sections can be obtained from following the procedure in [23] for a tungsten target, in which the transition cross sections for higher states (up to $n = 12$ for this estimate) are subtracted from the transition+dissociation cross sections:

$$d\sigma_{diss}^{nl} = d\sigma_{tot}^{nl} - d\sigma_{trans}^{nl}\tag{8.7}$$

where the total (transition+ dissociation) and transition-only cross sections are

$$d\sigma_{tot}^{nl} = Z^2 \frac{\alpha^2}{\pi a^2} (1 - F^{n,l,0,n',l',0}(q)) |\Delta(q, Z)|^2 q dq\tag{8.8}$$

and

$$d\sigma_{trans}^{nl} = (1 - (-1)^{l-l'}) Z^2 \frac{\alpha^2}{\pi a^2} |\Delta(q, Z) F^{n,l,0,n',l',0}(q/2)|^2 q dq\tag{8.9}$$

The transfer matrix elements $F^{n,l,m,n',l',0}(q)$ for a hydrogen-like wavefunction $\psi^{n,l,m}(x, \theta, \phi)$ are

$$\begin{aligned}F^{n,l,m,n',l',0}(q) \\ = \int_0^\infty \int_0^\pi \int_0^{2\pi} x^2 \sin(\theta) e^{iqx \cos(\theta)} \psi^{n',l',m'}(x, \theta, \phi)^* \psi^{n,l,m}(x, \theta, \phi) d\phi d\theta dx\end{aligned}\tag{8.10}$$

and a numerical approximation of the Thomas-Fermi-Molière form factor is used:

$$\Delta(q, Z) = 4\pi \sum_{i=1}^3 \frac{\alpha_i}{q^2 + \beta_i^2}$$

$$\text{where } \beta_i = \frac{m_e b_i}{121} Z^{1/3} \quad (8.11)$$

$$\alpha_1 = 0.10, \alpha_2 = 0.55, \alpha_3 = 0.35$$

$$b_1 = 6.0, b_2 = 1.2, b_3 = 0.3$$

The resulting dissociation cross sections for the True Muonium states under consideration are then

$$\begin{aligned} \sigma_{diss}^{1S} &= 5.67936 * 10^{16} pb \\ \sigma_{diss}^{2S} &= 4.90741 * 10^{17} pb \\ \sigma_{diss}^{2S} &= 6.30545 * 10^{17} pb \end{aligned} \quad (8.12)$$

Note that the $2S$ and $2P$ dissociations are an order of magnitude greater than for the $1S$ state, and the production is nearly an order of magnitude lower. More importantly, the dissociation cross sections are higher than the production cross sections by at least 16 orders of magnitude! This is primarily what makes the True Muonium search so challenging.

The system of coupled differential equations which gives the number of TM events pro-

duced for each state, per number of incident electrons N_e is

$$\begin{aligned}
\frac{dN_{1S}}{dz} &= \frac{1}{\sigma_{diss}^{1S}} \left[N_e \sigma_{prod}^{1S} + N_{2P} \sigma_{trans}^{1S,2P} \right] - N_{1S} \\
\frac{dN_{2S}}{dz} &= \frac{1}{\sigma_{diss}^{1S}} \left[N_e \sigma_{prod}^{2S} + N_{2P} \sigma_{trans}^{2P,2S} - N_{2S} \sigma_{diss}^{2S} \right] \\
\frac{dN_{2P}}{dz} &= \frac{1}{\sigma_{diss}^{1S}} \left[N_e \sigma_{prod}^{2P} + N_{1S} \sigma_{trans}^{1S,2P} + N_{2S} \sigma_{trans}^{2S,2P} - N_{2P} \sigma_{diss}^{2P} \right]
\end{aligned} \tag{8.13}$$

where $z = l/l_{diss}$ is the ratio of the target thickness l to the dissociation length l_{diss} , the average distance traveled in the target before breakup. Using the values above, and the atomic density of tungsten, $l_{diss} = 2.792\mu m$, making the proposed HPS target ~ 3 dissociation lengths.

Solving this system analytically with Mathematica 9.0, plugging in the various calculated cross sections, and assuming a current of $450nA$ and target thickness of $8.750\mu m$ proposed for the $6.6GeV$ run, the expected number of True Muonium events produced in one month for each state is

$$\begin{aligned}
N_{1S} &= 168.36 \\
N_{2S} &= 9.46 \\
N_{2P} &= 15.36
\end{aligned} \tag{8.14}$$

These are the most optimistic numbers, since they include both the radiative and 3-photon processes. If HPS is only equipped to search for states that were radiatively produced, then the number of expected 1S states N_{1S} drops to 33.13 per month. Probing the kinematic region where the oppressive Bethe-Heitler background resides would therefore greatly improve the chance for a True Muonium discovery. Also, the above estimate does not take detector or vertexing acceptance into consideration; this must be done by generating Monte Carlo events

to find the expected efficiency, just as what was done for the A' search in chapter 7.

8.4 True Muonium Event Simulation and Efficiency

To estimate the fraction of expected True Muonium events that would be accepted by the HPS detector and vertexed, simulated events were generated to match the True Muonium mass ($211MeV$) and unboosted decay length calculated from the lifetime of the $1S$ state ($c\tau = 0.5426mm$). The detector geometry that was used to simulate event reconstruction had a magnetic fieldmap tuned to a $6.6GeV$ beam energy (maximum field strength: $B_y = -1.5T$), and was updated to include a new SVT layer $z = 5mm$ downstream from the target. While this layer was not present for the 2016 run (nor used for the A' search in this document), the sensors for it have already been constructed and currently in use for the $4.4GeV$ 2019 run. This layer will therefore be present for a future $6.6GeV$ run as well, and was included in the the True Muonium simulation to give the best yield estimate. The True Muonium was generated at a mass of $211MeV$, with no variance before resolution effects (figure 8-5). After the decay products were propagated through the detector geometry and vertexed, the reconstructed invariant mass of the e^+e^- pairs were fit to a Crystal Ball function (equation 6.4), and the resolution found to be $3.877MeV$ (1.8%). The trigger thresholds were based on the 2016 pair1 trigger configuration (eqs. 3.2-3.8), with scaled-up energy thresholds.

Figure 8-5: The mass of the generated True Muonium, before any resolution spreading from the experiment.

Figure 8-6: The invariant mass of the reconstructed e^+e^- pairs, which came from 1S True Muonium decays.

The generated z -vertex distribution of the True Muonium decays, and the reconstructed vertices as a function of invariant mass are shown in figures 8-7 and 8-8.

Figure 8-7: The generated True Muonium vertices, before acceptance. These decays occur before the first SVT layer (10cm), and are well-within HPS acceptance.

Figure 8-8: The accepted True Muonium decay vertices as a function of invariant mass. Once 6.6GeV data is collected, the TM search window will be much smaller than for an A' of unknown mass (figure 7-13).

A total of 470000 True Muonium events were generated, and 19.43% of these were accepted by the pair1 trigger. The total number of events which were also vertexed (and therefore analyzable) was 56004, or 11.91%. Based on this value, 3.94 True Muonium events can be expected during 1 month of continuous beam time, if HPS is only sensitive to the radiative $1S$ state. If the 3-photon mechanism is able to be resolved from the Bethe-Heitler background with some additional work (assuming a similar acceptance), then this number

increases significantly to ~ 20.06 events per month. This assumption of a similar acceptance is a very rough estimate, however, because the 3-photon mechanism has very different kinematics.

True Muonium Generated (450nA)

Figure 8-9: The number of True Muonium events generated per month vs. target thickness, for each state and diagram, for a fixed current of $450nA$. While the search is feasible if only considering the radiative mechanism, accepting the low-energy 3-photon events would drastically increase the expected yield.

Assuming the 3-photon events are unable to be collected, due either to the inability to simulate them properly while also accounting for the $1S$ conversions, or being unable to resolve them from the oppressive low-momentum background, the yield can also be increased by changing the run parameters. In particular, consider the effect of scaling up the current

I by an amount N , while decreasing the target thickness l by the same amount to keep the luminosity constant. The radiative $1S$ yield Y_{rad1S} is used for this example without the dependence on the other states, since it is the process that can more confidently be simulated and detected, and its dependence on current is a simple linear relationship. While the radiative $1S$ state only produces 33 events per month at nominal settings, running with a thinner target and higher current could potentially double this amount.

Rad. $1S$ generated per month

$$N * 450nA * Y_{rad1S}(8.75\mu m/N)$$

Figure 8-10: The number of radiative $1S$ TM events generated per month vs. N , where the current $I \rightarrow N * I$ and target thickness $l \rightarrow l/N$ to keep the luminosity $\sim I * l$ constant.

From figure 8-10, the amount of readily detectable True Muonium events from the radiative $1S$ state increases approximately 2-fold if the target thickness is decreased by a factor of 3, and the experiment can be run with a microamp beam current. To ease one of these

constraints, a series of thinner targets may be set up instead of a single one, allowing for an equivalent luminosity to be produced with a lower current. This yield improves 10-fold if the 3-photon production mechanism is included:

Figure 8-11: The number of 1S TM events generated per month vs. parameter N , for both the radiative and 3-photon production mechanisms.

Figure 8-11 shows the expected 1S True Muonium yield if the low-momentum region where the 3-photon production mechanism peaks can be probed, but this is currently unavailable for an HPS-like analysis. Again, the very large caveat here is that these yields assume the same acceptance as for radiative 1S events, but this will surely not be the case. In order to determine the actual acceptance, as well as the other parameters needed for a bump hunt or displaced vertex search, new event generators for this process must be made.

Chapter 9

Summary

The HPS experiment had successful engineering runs in 2015 and 2016, and the detectors performed within expectations with a stable beam (table 3.2). A displaced vertex search was performed on a blinded 10% of the full 2016 data set (2.3GeV beam energy), and no A' was found in the $50 - 140\text{MeV}$ mass range. No exclusion in mass-coupling phase space was made either, but the limit obtained from this subset bodes well for a search on the full data set, if the result scales.

HPS is well-equipped to search for True Muonium events at higher beam energies, and a yield for the radiative $1S$ production mechanism at 6.6GeV was estimated using Monte Carlo. While there are only 33 radiative TM events expected per month of beam for the proposed nominal 6.6GeV luminosity, this can be increased two-fold by simple adjustments to the target and current, and more drastically (10x) if the 3-photon region can be probed to search for events with a low-momentum sum. This is currently unexplored (and tricky) territory as it falls within the Bethe-Heitler region, where the A' search has not been tuned, and simulations will need to be developed from the ground up, which would likely need to include taking into account secondary production within the target.

HPS has cut its teeth analyzing and performing heavy photon searches on the 2015 and 2016 engineering runs, and at the time of this writing, the 2019 physics run is underway. Using what was learned from previous runs, HPS has become a mature experiment capable of conducting exciting dark matter searches and look for other exotic decays in the future.

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Appendix A

Placement of Selection Cuts

This appendix motivates the event selection cuts in table 7.1, used to eliminate the trident and wab backgrounds in the data set, while keeping as many radiative events that would be consistent with an A' decay as possible.

A.1 Accidental pair and FEE cuts

Cuts that eliminate accidental pair events were primarily based on maximizing the signal-to-noise ratio $S/\sqrt{S+B}$ of vertexed e^+e^- pairs. This strategy is designed to eliminate regions where the background (non-radiative events) becomes more significant than the estimated signal (radiative events). Since this did not work in defining the radiative region where the $p_{el} + p_{pos}$ cut should be placed, because the composite trident + wab background happens to add up to a roughly constant “noise” distribution as a function of momentum sum (figure A-1 left), the $S/\sqrt{S+B}$ was not used for the radiative cut. Instead, a reasonable radiative cut was placed at 1.8GeV in order to cut out the obvious Bethe-Heitler region at low-momentum, while letting in enough radiative events to fully capture their tails. Then the other cuts were tuned to both optimize the radiative signal in this region and reject high- z events consistent with scattering events or poorly-fit tracks.

Figure A-1: The radiative cut $p_{pos} + p_{ele} > 1.8 \text{ GeV}$. Since $S/\sqrt{S+B}$ yielded an inconclusive radiative cut because of a flat $\sqrt{S+B}$ noise distribution throughout (left), it was decided to define a reasonable radiative region and tune the other cuts to optimize the signal significance.

Figure A-2: The positron low-momentum cut, $p_{pos} > 0.6\text{GeV}$ and FEE cut, $p_{ele} < 1.4\text{GeV}$ in the radiative region where $p_{pos} + p_{ele} > 1.8\text{GeV}$. These cuts eliminate events where $S/\sqrt{S+B} < 1$, where the non-radiative background becomes more significant than the radiative events.

Figure A-3: The cluster coincidence cut, $|t_{clust1} - t_{clust2}| < 1.5ns$. This cut attempts to maximize the signal significance $S/\sqrt{S+B}$ from MC. On the left is the cumulative distribution of the signal significance $S/\sqrt{S+B}$, where there is a region of “diminishing returns” beyond $\pm 1.5ns$; including the statistics beyond that cut adds little to the radiative yield. The cut is loose enough to not cut into the signal region in data, shown as a function of vertex- z on the right.

Figure A-4: The isolation cut, from 7.1.1. Plotted is the “isolation value”, the left-hand side of equation 7.3, which shows that > 0 is indeed the optimal value at which to place the cut.

A.2 Track quality/matching cuts

Since the the track fit χ^2 and track-cluster matching n_{sigma} value (equation 4.10) are not sensitive to cutting on signal significance, these cuts were set based on how well they reduced problematic high- z events due to poor tracks, making sure not to exclude too many simulated A' events (figure 7-8), or core events in the data.

Figure A-5: The track χ^2 sum cut, designed to enforce a reasonable track quality criteria: tight enough to cut out excess high- z events seen in the distributions, while minimizing the loss of events near the core. Shown on the right is the vertex- z distribution vs. χ^2 sum for background MC, including which high- z events they eliminate from the vertex vs. mass distribution on the left.

Figure A-6: The track-cluster matching n_{σ} cuts, shown as a function of vertex- z . This cut was designed to enforce a reasonable track-cluster matching criteria, tight enough to cut out excess high- z events seen in the distributions, while minimizing the loss of events near the core. Shown on the right is the vertex- z distribution vs. matching n_{σ} sum, and the left is the cut on individual tracks (the minimum n_{σ} among the electron and positron).

Figure A-7: The electron low-momentum cut, $p_{ele} > 0.8 GeV$. This cut was found to be the most reasonable way to eliminate high- z events found in both MC and data at low-mass, that could not be eliminated by any other cut.

Figure A-8: The momentum asymmetry cut, $-0.6 < (p_{ele} - p_{pos})/(p_{ele} + p_{pos}) < 0.6$, was initially set very loose in the cut tuning process, to be refined later. However, after all of the other cuts were applied (included in the plots), this became unnecessary, as there was no reasonable place to put it. The tails ended in the same place for each of the MC backgrounds (left), no high- z events could be eliminated using it without sacrificing too many core events, and the entire (10%) data set used for the vertex search (right) has the same resolution as the MC in this variable, so it never actually needed to be loose. While it does effectively nothing, the cut was still included to avoid bias, because this conclusion was not drawn until checked against the full data set that was used for the vertex search.

Appendix B

Fit Curves and Values

This appendix keeps track of the parameter values from the various fits made for the vertex search, and their accompanying plots.

B.1 A' recon/slic efficiency curves (section 7.1.3)

Figure B-1: A' Acceptance and cut efficiency: 50MeV and 55MeV

Figure B-2: A' Acceptance and cut efficiency: 60MeV and 65MeV

Figure B-3: A' Acceptance and cut efficiency: 70MeV and 75MeV

Figure B-4: A' Acceptance and cut efficiency: 80MeV and 85MeV

Figure B-5: A' Acceptance and cut efficiency: 90MeV and 95MeV

Figure B-6: A' Acceptance and cut efficiency: 100MeV and 125MeV

Figure B-7: A' Acceptance and cut efficiency: 150MeV and 175MeV

mass \ coeff.	p0	p1	p2	p3
$50MeV$	1.069e-08	-0.02648	0.0004883	-0.0001368
$55MeV$	2.782e-07	-0.01846	-0.0008714	-5.071e-05
$60MeV$	1.626e-08	-0.03366	0.001087	-7.153e-05
$65MeV$	1.529e-08	-0.02158	0.0008897	-5.216e-05
$70MeV$	-1.206e-07	-0.01253	0.0004132	-3.99e-05
$75MeV$	1.483e-08	-0.02413	0.001218	-4.69e-05
$80MeV$	-2.069e-07	-0.02039	0.001102	-4.003e-05
$85MeV$	2.834e-08	-0.02039	0.001082	-3.566e-05
$90MeV$	-7.548e-06	-0.01869	0.001114	-3.477e-05
$95MeV$	5.832e-07	-0.0163	0.001059	-3.231e-05
$100MeV$	-1.137e-07	-0.02271	0.001334	-3.247e-05
$125MeV$	1.916e-08	-0.02134	0.001171	-2.446e-05
$150MeV$	2.863e-09	-0.01934	0.001237	-2.484e-05
$175MeV$	5.465e-07	-0.01001	0.0006682	-1.778e-05

Table B.1: Coefficients of the cubic A' efficiency fits (reconstructed/SLIC) for each A' mass.

B.2 Background tail fits (section 7.2.1)

Figure B-8: The mass slices and fits used to model the background MC distributions (equation 7.5), for mass slices 1-20.

mass \ param.	A	$\bar{z}$	σ	b	l
0.0500000000000	90.28	-4.146	2.976	9.006	1.942
0.0509090909091	91.91	-4.102	2.94	6.294	1.373
0.0518181818182	96.38	-4.031	2.887	6.601	1.336
0.0527272727273	98.93	-4.082	2.871	6.522	1.443
0.0536363636364	104.3	-4.068	2.861	8.499	1.659
0.0545454545455	108.8	-4.048	2.802	9.522	1.777
0.0554545454545	114.1	-4.033	2.717	8.200	1.438
0.0563636363636	119.4	-3.981	2.621	8.348	1.604
0.0572727272727	121.5	-4.007	2.59	6.99	1.290
0.0581818181818	124.7	-3.948	2.557	8.948	2.19e-07
0.0590909090909	125.9	-3.97	2.509	6.901	1.454
0.0600000000000	124.7	-3.945	2.518	6.862	1.377
0.0609090909091	124.2	-3.974	2.506	6.81	1.393
0.0618181818182	125	-4.05	2.544	8.553	2.052
0.0627272727273	126.8	-4.08	2.52	7.093	1.368
0.0636363636364	124.4	-4.096	2.507	7.089	1.443
0.0645454545455	124.9	-4.138	2.525	87.31	-1.108e+04
0.0654545454545	126.8	-4.18	2.479	7.091	0.9893
0.0663636363636	126.2	-4.183	2.474	5.641	1.084
0.0672727272727	130.3	-4.097	2.389	5.353	1.089

Table B.2: The coefficients for the background tail fits, mass bins 1-20 (figure B-8). “mass” defines the center of the mass bin (GeV), and the fit parameters are defined in equation 7.5

Figure B-9: The mass slices and fits used to model the background MC distributions (equation 7.5), for mass slices 21-40.

mass \ param.	A	$\bar{z}$	σ	b	l
0.0681818181818	130.1	-4.147	2.381	5.443	1.127
0.0690909090909	131.8	-4.147	2.339	5.418	1.251
0.0700000000000	135.6	-4.166	2.265	3.922	1.308
0.0709090909091	137.8	-4.186	2.164	3.348	1.398
0.0718181818182	136.6	-4.185	2.182	3.526	1.351
0.0727272727273	136.8	-4.158	2.182	3.683	1.292
0.0736363636364	133.7	-4.169	2.208	3.900	1.250
0.0745454545455	133.3	-4.134	2.161	3.577	1.305
0.0754545454545	132.2	-4.122	2.164	4.074	1.15
0.0763636363636	131.5	-4.162	2.113	3.533	1.264
0.0772727272727	130.6	-4.141	2.136	3.923	1.163
0.0781818181818	128.3	-4.148	2.139	4.214	1.086
0.0790909090909	127.5	-4.187	2.111	3.929	1.134
0.0800000000000	124.8	-4.135	2.092	4.160	1.052
0.0809090909091	123.6	-4.136	2.067	4.957	1.100
0.0818181818182	121.1	-4.084	2.065	5.171	1.151
0.0827272727273	121.1	-4.06	2.031	5.199	1.478
0.0836363636364	116.8	-4.093	2.052	5.435	1.501
0.0845454545455	117.4	-4.083	2.014	5.393	1.55
0.0854545454545	115.4	-4.079	1.989	5.184	1.394

Table B.3: The coefficients for the background tail fits, mass bins 21-40 (figure B-9). “mass” defines the center of the mass bin (GeV), and the fit parameters are defined in equation 7.5

Figure B-10: The mass slices and fits used to model the background MC distributions (equation 7.5), for mass slices 41-60.

mass \ param.	A	$\bar{z}$	σ	b	l
0.0863636363636	117.1	-4.042	1.899	4.674	1.436
0.0872727272727	115.3	-4.073	1.873	4.171	1.344
0.0881818181818	110.7	-4.095	1.893	4.209	1.347
0.0890909090909	112.3	-4.119	1.841	4.259	1.306
0.0900000000000	108.5	-4.128	1.829	4.094	1.083
0.0909090909091	107.8	-4.141	1.795	4.13	1.089
0.0918181818182	102.9	-4.18	1.787	3.806	1.072
0.0927272727273	101.4	-4.19	1.774	3.611	1.069
0.0936363636364	99.79	-4.205	1.777	3.824	1.167
0.0945454545455	98.56	-4.163	1.799	5.462	1.926
0.0954545454545	96.53	-4.146	1.768	7.053	29.99
0.0963636363636	93.11	-4.161	1.783	7.092	28.71
0.0972727272727	91.14	-4.191	1.779	7.092	56.56
0.0981818181818	87.18	-4.219	1.811	6.075	2.916
0.0990909090909	89.05	-4.196	1.71	4.214	1.426
0.1000000000000	87.38	-4.17	1.73	4.463	1.468
0.100909090909	81.8	-4.17	1.745	3.923	1.112
0.101818181818	78.7	-4.17	1.763	3.38	1.006
0.102727272727	76.53	-4.173	1.783	3.409	1.046
0.103636363636	70.89	-4.224	1.858	4.624	1.209

Table B.4: The coefficients for the background tail fits, mass bins 41-60 (figure B-10). “mass” defines the center of the mass bin (GeV), and the fit parameters are defined in equation 7.5

Figure B-11: The mass slices and fits used to model the background MC distributions (equation 7.5), for mass slices 61-80.

mass \ param.	A	$\bar{z}$	σ	b	l
0.104545454545	69.84	-4.172	1.847	4.423	1.166
0.105454545455	67.96	-4.142	1.811	4.161	1.165
0.106363636364	65.43	-4.073	1.792	5.235	0.9801
0.107272727273	63.6	-4.038	1.763	4.544	0.9105
0.108181818182	62.26	-4.09	1.765	4.471	1.038
0.109090909091	61.82	-4.082	1.719	4.482	1.058
0.110000000000	58.74	-4.11	1.705	4.557	1.1200
0.110909090909	55.69	-4.127	1.719	4.609	0.9905
0.111818181818	55.89	-4.064	1.677	4.298	0.9842
0.112727272727	54.19	-4.103	1.63	4.128	0.8941
0.113636363636	52.27	-4.118	1.634	4.222	0.8531
0.114545454545	50.79	-4.087	1.637	4.211	0.8432
0.115454545455	48.78	-4.126	1.655	4.554	0.8124
0.116363636364	46.83	-4.176	1.666	4.578	0.8396
0.117272727273	45.41	-4.176	1.636	5.276	0.0001453
0.118181818182	44.36	-4.168	1.629	4.26	0.6829
0.119090909091	46.84	-4.179	1.428	2.068	0.9858
0.120000000000	43.77	-4.183	1.449	2.685	0.9494
0.120909090909	42.62	-4.209	1.425	2.325	0.9696
0.121818181818	41.82	-4.21	1.419	1.97	1.023

Table B.5: The coefficients for the background tail fits, mass bins 61-80 (figure B-11). “mass” defines the center of the mass bin (GeV), and the fit parameters are defined in equation 7.5

Figure B-12: The mass slices and fits used to model the background MC distributions (equation 7.5), for mass slices 81-100.

mass \ param.	A	$\bar{z}$	σ	b	l
0.122727272727	52.7	-2.72	2.148	-0.9083	1.096
0.123636363636	41.34	-4.206	1.353	2.626	1.141
0.124545454545	38.3	-4.162	1.36	2.614	1.084
0.125454545455	38.45	-4.142	1.322	2.626	1.085
0.126363636364	36.47	-4.101	1.341	2.64	1.083
0.127272727273	35.47	-4.14	1.332	2.7	1.083
0.128181818182	33.88	-4.098	1.305	2.652	1.109
0.129090909091	33.39	-4.096	1.29	2.539	1.039
0.130000000000	31.31	-4.138	1.313	2.589	0.9777
0.130909090909	30.53	-4.112	1.278	2.51	0.8804
0.131818181818	29.91	-4.097	1.282	2.252	0.935
0.132727272727	33.65	-2.831	2.025	-0.5158	0.8881
0.133636363636	26.85	-4.047	1.24	2.275	0.9978
0.134545454545	26.2	-4.059	1.21	2.259	1.063
0.135454545455	24.89	-4.023	1.199	2.145	1.066
0.136363636364	24.03	-4.082	1.201	2.02	1.104
0.137272727273	22.15	-4.136	1.243	2.165	1.099
0.138181818182	22.09	-4.184	1.238	2.2	1.119
0.139090909091	21.74	-4.131	1.246	2.261	1.073
0.140000000000	21.13	-4.074	1.182	2.176	1.084

Table B.6: The coefficients for the background tail fits, mass bins 81-100 (figure B-12). “mass” defines the center of the mass bin (GeV), and the fit parameters are defined in equation 7.5

B.3 A' mass resolutions (section 7.2.2)

Figure B-13: The mass residuals $|m_{generated} - m_{reconstructed}|$ as a function of vertex- z for 50 MeV and 55 MeV A' s (top), and the fits of the mass resolution as a function of vertex- z (bottom).

Figure B-14: The mass residuals $|m_{\text{generated}} - m_{\text{reconstructed}}|$ as a function of vertex- z for 60MeV and 65MeV A's (top), and the fits of the mass resolution as a function of vertex- z (bottom).

Figure B-15: The mass residuals $|m_{\text{generated}} - m_{\text{reconstructed}}|$ as a function of vertex- z for 70MeV and 75MeV A's (top), and the fits of the mass resolution as a function of vertex- z (bottom).

Figure B-16: The mass residuals $|m_{generated} - m_{reconstructed}|$ as a function of vertex- z for 80MeV and 85MeV A 's (top), and the fits of the mass resolution as a function of vertex- z (bottom).

Figure B-17: The mass residuals $|m_{generated} - m_{reconstructed}|$ as a function of vertex- z for 90MeV and 95MeV A 's (top), and the fits of the mass resolution as a function of vertex- z (bottom).

Figure B-18: The mass residuals $|m_{generated} - m_{reconstructed}|$ as a function of vertex- z for 100MeV and 125MeV A 's (top), and the fits of the mass resolution as a function of vertex- z (bottom).

Figure B-19: The mass residuals $|m_{generated} - m_{reconstructed}|$ as a function of vertex- z for 150MeV and 175MeV A 's (top), and the fits of the mass resolution as a function of vertex- z (bottom).

mass \ coeff.	p0(<i>GeV</i>)	p1(<i>GeV/mm</i>)
50 <i>MeV</i>	0.00174	1.689e-05
55 <i>MeV</i>	0.001854	-1.294e-05
60 <i>MeV</i>	0.00202	-6.356e-06
65 <i>MeV</i>	0.002154	-8.593e-06
70 <i>MeV</i>	0.002209	-1.147e-05
75 <i>MeV</i>	0.002283	-9.275e-06
80 <i>MeV</i>	0.002449	-8.987e-06
85 <i>MeV</i>	0.00246	-5.102e-06
90 <i>MeV</i>	0.002573	-5.322e-06
95 <i>MeV</i>	0.002675	-5.402e-06
100 <i>MeV</i>	0.002763	-8.869e-06
125 <i>MeV</i>	0.003301	-7.122e-06
150 <i>MeV</i>	0.004078	-1.678e-05
175 <i>MeV</i>	0.004426	-4.243e-06

Table B.7: Coefficients used for the linear A' mass resolution fits vs. vertex- z .