Searching for a Heavy Photon and Hidden Sectors with the Heavy Photon Search Experiment

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Abstract

In recent years, astrophysical anomalies have led to new theories to extend the Standard Model to include an additional gauge boson called the heavy photon (or $A'$), which would mediate a new force between dark matter particles and explain these anomalies. In addition to dark matter, it is possible that there exists an entire hidden sector of particles that interact with this heavy photon, which could have gone undetected thus far. As a new experiment called the Heavy Photon Search (HPS) is currently being constructed and optimized to search for $A'$ decays to two leptons, we thought it would be the perfect opportunity to also search for $A'$ decays to two unstable hidden sector particles, which would result in a total of four leptons in the final state. Using simulations of the HPS detector, we have tried to optimize this $A'$ to multilepton search, and see in which scenarios it may be possible for us to detect these hidden sector particles and the $A'$ itself through this channel when HPS runs in the next few years. Ultimately, we feel it will be worthwhile for HPS to look at a multilepton channel in addition to the standard dilepton channel, as this increases the physics motivation of the experiment, and could potentially lead to the discovery of a new light hidden sector of particle physics.

1 Introduction

The Heavy Photon Search (HPS) is a fixed target experiment that aims to directly search for new physics at low energies using the high intensity electron beam delivered by the Continuous Electron Beam Accelerator Facility (CEBAF) accelerator at Jefferson Lab (JLab) in Newport News, Virginia. As CEBAF is currently shut down for upgrades through 2014, HPS hopes to run in 2014-2015, with future upgrades to the detector to follow. Although accelerators such as the Large Hadron Collider are pushing the boundaries of the Energy Frontier by colliding protons at up to 14 TeV—and successfully doing so, as we know with the recent discovery of the Higgs boson—there may still be new physics to be found in the GeV range that has thus far gone undetected. Thus, HPS hopes to use the Intensity Frontier to look for light particles that weakly couple to the Standard Model (SM), as there is plenty of unexplored parameter space for weakly coupled particles, even at low energies. In particular, HPS is interested in
searching for a new low mass U(1) gauge boson called the heavy photon (denoted $A'$ and also commonly referred to as a dark photon, among other names), which would weakly couple to electrically charged particles, and thus serve as a way for the Standard Model to interact with an undiscovered hidden sector of particle physics (also referred to as a hidden valley or dark sector at times) [1].

1.1 Motivation

In addition to the fact that there are no Standard Model measurements that have been made thus far to rule out the existence of a heavy photon or hidden sectors, there is also plenty of physical motivation for their existence. Satellites including PAMELA [2] and Fermi [3], among others, have observed an excess of cosmic ray electrons and positrons at high energies (as shown in Figure 1), which could be explained if you assume that dark matter exists, and that the heavy photon mediates interactions between these dark matter particles [4]. This would allow for dark matter annihilation to heavy photons, which each decay to an electron and positron, as discussed in further detail in Section 1.2. Furthermore, if the heavy photon exists, then it is very possible that it directly interacts with not just the dark matter particles, but instead with an entire class of particles in a new hidden sector [1]. As hidden sectors naturally arise in many grand unified and string theories, it is certainly worthwhile to explore the possibility of discovering a hidden sector with HPS, and in fact, the heavy photon and a hidden sector could even exist without the dark matter phenomenology being as described above.

1.2 Theory of Heavy Photons

The heavy photon interacts with the Standard Model through kinetic mixing with the SM photon [4], in which the photon can oscillate into a heavy photon and vice-versa, as shown
in Figure 2. As the heavy photon is a gauge boson mediating a new force, it has a coupling constant $\alpha'$, analogous to the electromagnetic fine structure constant $\alpha$, so we can represent the coupling strength of the heavy photon with respect to the photon as $\alpha'/\alpha$, where $\alpha' < \alpha$ [1]. Thus, given a sufficiently energetic photon, a heavy photon can be spontaneously produced through kinetic mixing, but the probability for doing so goes as $\sqrt{\alpha/\alpha}$, which is small, hence the need for a more intense beam to produce and detect more $A'$ events.

As briefly mentioned in Section 1.1, the simplest scenario for an $A'$ is the one in which we just have an $A'$ and heavy dark matter in addition to the Standard Model. In this case, a light $A'$ will exclusively decay into an $e^+e^-$ pair (via the kinetic mixing with the photon), thus explaining the excesses observed by PAMELA, Fermi, and others. This also means the primary search being done by HPS is relatively simple, as HPS just needs to look for $e^+e^-$ pairs that are distinguishable from Standard Model backgrounds through various signatures that are unique to the $A'$ [1]. Of course, if the $A'$ is massive enough, it will also decay into muons (or other fermion pairs for an even more massive $A'$), providing an additional search channel for HPS.

1.3 Theory of Hidden Sectors

In a more complex scenario, the hidden sector can also contain particles that are lighter than the $A'$, in which case the $A'$ could additionally decay into hidden sector particles. The specific properties of the hidden sector particles can widely vary, but for the purposes of our study, we assumed that at least one component of the hidden sector included a hidden SU(n) force similar to the strong force, resulting in hidden mesons called $\pi_V$ [5]. We assumed that these $\pi_V$’s couple directly to the $A'$, and that they instantly decay to pairs of SM leptons, just as the $A'$ does in the main HPS search. This allows for the possibility for the $A'$ to decay into two $\pi_V$’s, which each decay into an $e^+e^-$ pair, resulting in four leptons in the final state, which could be an additional search channel for HPS [1].

2 Experimental Setup and Reach

The HPS detector, when fully complete, will consist of a tungsten target, a silicon vertex tracker (SVT), an electromagnetic calorimeter (ECal), and a muon detector, as shown in Figure 3. For a detailed description of the HPS detector, one should refer to the HPS Proposal [1], but I will briefly describe it here for the reader.
In HPS, heavy photon production occurs when CEBAF’s electron beam interacts with the nucleus of a tungsten target, resulting in bremsstrahlung where the photon then undergoes kinetic mixing into the heavy photon, as shown in Figure 4. As HPS is optimized for heavy photon decay into an $e^+e^-$ pair, the target is followed by a silicon vertex tracker, which consists of six double layer planes both below and above the beamline. The main purpose of the SVT is to detect and track electrons, in addition to determining the vertex from which the particle came, which is useful for searching for the $A'$. The beam gap between the silicon planes is necessary to protect the silicon from radiation damage by CEBAF’s electron beam, and allows the SVT to function for a longer period of time, as well as avoiding backgrounds that would result from the incoming beam. The SVT is then followed by an ECal made of lead tungstate crystals, which are also arranged in an upper and lower section due to the beam gap, and the main purpose of the ECal is to determine the energy of both leptons and photons passing through the detector. Finally, the muon detector is the last component of HPS, and it consists of alternating layers of iron absorbers and scintillator hodoscopes for the purpose of identifying muons and pions. Of course, the muon detector is also divided into an upper and lower section to allow for the beam gap as well [1].

As both the mass and coupling strength of the $A'$ are free parameters up to various theoretical and experimental constraints, a two dimensional plot with $\alpha'/\alpha$ on one axis and $A'$ mass on the other axis can be used to look at the regions of parameter space that other experiments have already searched for heavy photons, as well as looking at the reach HPS may have. This plot is shown in Figure 5. The reach HPS may have in terms of searches for other hidden sector particles, however, is less well-defined, as there are so many different scenarios to consider.
Figure 4: Production of the heavy photon through bremsstrahlung, where $A'$ is the heavy photon, $e^-$ is the beam electron, $Z$ is a tungsten nucleus, and $\gamma$ is an exchanged photon [1].

Figure 5: Expected reach in the parameter space of coupling strength vs. $A'$ mass for full 2014-2015 running of HPS (solid red). The red line contours correspond to 1 week of beam time at 1.1 GeV, and 3 weeks each of beam time at 2.2 GeV and 6.6 GeV. The green shaded region is a particularly well motivated region in which the heavy photon can also explain the anomalous magnetic moment of the muon, while the other shaded regions are mass and coupling configurations that have already been ruled out by previous experiments [1].
Figure 6: Feynman diagram for production of $A'$ and subsequent cascade through the hidden sector and back to the Standard Model.

3 Analysis

While the main search channel for HPS is $A' \rightarrow e^+e^-$, we have begun to explore the possibility of looking for $A' \rightarrow \pi_V\pi_V \rightarrow e^+e^-e^+e^-$ through the hidden sector decays discussed in Section 1.3, and shown in Figure 6. To do so, we have generated events of this type (using a beam energy of 2.2 GeV and input parameters of $m_{A'} = 300$ MeV and $m_{\pi_V} = 100$ MeV, as these are both free parameters) with the Monte Carlo software MadGraph, and we then ran them through the HPS detector simulation and reconstruction software in order to see how sensitive HPS may be to these hidden sector, multilepton events. Using the tracks reconstructed by the HPS tracking algorithm, we have made several observations for different types of events from this Monte Carlo sample of 25000 events.

3.1 Two Track Events

As the $A'$ in our scenario is decaying to four leptons in the final state, events with just two reconstructed tracks cannot be used to reconstruct the $A'$ mass. However, as $\pi_V$ decays to two leptons, we can take any event with two or more tracks and plot the invariant mass of $e^+e^-$ pairs to attempt reconstruction of the $\pi_V$ mass. This plot is shown in Figure 7(left), where it is clear that the reconstructed $\pi_V$ mass is a relatively sharp peak at the correct mass, while the noise surrounding this peak can largely be attributed to three and four track events, where I matched every possible combination of $e^+e^-$ pairs instead of attempting to find the correct one, though this can be done in principle. For our purposes, however, we are simply looking to see that this reconstruction can be done with HPS, so further optimization of the $\pi_V$ reconstruction is not necessary at this time, as it is clear that it is both possible and has a well-defined peak.
Figure 7: Left: Reconstruction of invariant mass for $e^+e^-$ pairs. The peak of this distribution is located at the correct $\pi^+\pi^-$ mass of 100 MeV. Right: Reconstruction of invariant mass for four track events. The peak of this distribution is located at 200 MeV, while the generated $A'$ mass is 300 MeV, so some of the tracks used in these events were likely misreconstructed.

3.2 Four Track Events

Using events in which four tracks are reconstructed, it may also be possible for us to reconstruct the $A'$ mass in this hidden sector scenario. However, far fewer events have four tracks, and those which do often contain misreconstructed tracks, as we saw reconstructed momenta greater than our input beam energy, which is non-physical. Nonetheless, we can take all of the events with four correctly charged tracks, and plot the invariant mass to see how well our $A'$ can be reconstructed in this channel. Figure 7(right) shows this plot, and it is clear that the efficiency for HPS to detect such events is not very good—as there are only 24 four track events of the 25000 events that were generated. However, using a previous incarnation of the detector simulation, in which the acceptance was just slightly larger, there were four times as many four track events, which shows that the dilepton $A'$ channel is a very different optimization problem from the multilepton $A'$ search that we are conducting here. In any case, even with this few of four track events, it may still be possible to discover the $A'$ and hidden sector decays through this channel, as will be discussed in the following section.

3.3 Backgrounds

The primary backgrounds for the main HPS search for $A' \rightarrow e^+e^-$ are the Bethe-Heitler and radiative trident, shown in Figure 8. Of course, these trident backgrounds have much higher cross sections than the $A'$ signal events, but there are some distinguishing characteristics that help HPS in the search for the $A'$. For instance, when the $A'$ is produced, it takes most of the beam energy, whereas in the trident events, the beam electron retains most of the beam energy.
In our multilepton analysis, meanwhile, reconstruction of $\pi_V$’s will still compete with the trident backgrounds. Although we have much better efficiencies for $\pi_V$ reconstruction than $A'$ reconstruction, it may still be a challenge to overcome the backgrounds, as we can see by looking at Figure 9(left), which shows the two track reconstructed mass of 250000 Monte Carlo trident events that were passed through our HPS detector simulation. We have not yet done extensive work to distinguish $\pi_V$’s from the background, but one potentially useful part of the hidden sector phenomenology is that hidden sector particles are often long lived, which would lead to displaced vertices for $\pi_V$ decays. For the purposes of our analysis, we let the $\pi_V$ particles instantly decay to leptons, but in reality, the displaced vertices that would result from lifetime effects could make it much easier to discover the $\pi_V$ and distinguish them from the trident backgrounds. Further simulation studies using the more phenomenologically complicated, but experimentally simpler scenarios where the $\pi_V$ is long lived may be carried out in the future.

The four track events, on the other hand, have fewer trident events to compete with, as the probability of two trident events happening simultaneously is smaller (but certainly nonzero). To see how the four track background looks, we used the same trident sample as before but instead took all events with four tracks and found the reconstructed mass of these events, as seen in Figure 9(right). As the low efficiency for four track $A'$ events works against the possibility of discovering the $A'$ in this channel, we decided to attempt to reduce this background by cutting out all events of both the signal and background which had a total momenta greater than our beam energy (those containing poorly reconstructed tracks). Furthermore, as the generated $A'$ events decayed to $\pi_V$’s, we made cuts on the resultant two track masses for these events; that is, if we had four tracks in the final state, but no combination of tracks would give accurate or precise $\pi_V$ masses, we rejected the event. This resulted in the plots shown in Figure 10, which plot four track momenta as a function of four track mass for both signal and background events. It is important to note that our $A'$ signal events here all fall around 200 MeV rather than the correct mass of 300 MeV, so we may still have some misreconstructed tracks present among these signal events. Furthermore, we have not yet mentioned anything about normalizing the
Figure 9: Left: Two track reconstructed mass from 250000 Monte Carlo trident events, acting as background on $\pi V$ reconstruction. Right: Four track reconstructed mass from the same trident events, which act as background on $A'$ reconstruction in the four lepton channel.

signal to the background, and it turns out that for each entry on the histogram for the trident background, there would be approximately 4000 such events observed by HPS in the 2014-2015 running time. However, due to the small statistics present, this could still be a fluctuation, so further studies must be done to clarify this.

4 Future Work

Going forward, we intend to continue and expand this study to better understand how HPS could detect signatures from a hidden sector. Although not yet mentioned here, we have also previously used three track events to reconstruct the $A'$ using the missing transverse energy (under the assumption that the $A'$ has small transverse momentum). However, this was in a previous incarnation of the HPS detector simulation, and we have yet to transfer this analysis to the current version, so this will be done in the near future. It is also important to note that we have only detailed one type of hidden sector scenario here, with one particular set of $A'$ and $\pi V$ masses, along with just looking at one beam energy. Preliminary studies using different mass configurations, as well as the higher energy 6.6 GeV beam are currently ongoing, and it is possible that we will observe more four track events in these studies, as a higher energy beam or lighter particles may result in fewer of the soft leptons that were outside of our detector acceptance. Furthermore, since the detector acceptance seems to be the primary reason for our poor efficiency, we have begun building a toy model of the HPS detector through which we can run our Monte Carlo files and attempt to understand the acceptance issues in a simpler manner, without issues such as multiple scattering, pair production from radiated photons, etc.
Figure 10: Four track momenta vs. four track mass for signal events (left) and trident events (right) after our cuts on the two track invariant masses. Note that these are not normalized, and each entry on the trident histogram corresponds to approximately 4000 such events over the course of six weeks. Also note that the $A'$ events that pass our cuts are not well reconstructed here, as they peak at the wrong mass.

Another promising route for us to investigate is to instead impose cuts on the momenta of our individual tracks in the four track events. The reason for doing this is to ensure that soft, poorly reconstructed tracks are ignored, allowing for a more accurate reconstructed $A'$ mass. In Figure 11 we did just that, along with separately plotting the momenta spectra of all tracks and MC particles for the purpose of better understanding what may and may not be reconstructed in the end, but our future acceptance studies for these multilepton events should also help with this.

5 Conclusions

Although there is still plenty of simulation work to be done to improve this analysis and further explore the possibility for HPS to discover the $A'$ through a hidden sector channel, it seems at this point that such a search would be worthwhile. Searching for hidden sector particles can significantly increase the physics potential of the experiment, as an $A'$ and hidden sector can interact independently of or simultaneously with dark matter, which means HPS can search for several different new physics scenarios at the same time.

This “Coupling Frontier” is a great complement to the Energy Frontier being pursued by the LHC and other high energy collider experiments, and HPS will make a significant impact on the future of high energy physics, no matter the results of the 2014-2015 and other future HPS runs. If a heavy photon is discovered, the impact on the high energy physics community
Figure 11: Top left: Momenta spectrum of reconstructed tracks from $A'$ signal events. Bottom left: Momenta spectrum of generated MC leptons from signal events. Top right: Four track mass for signal events, after imposing the cut that all tracks must have momentum greater than 250 MeV. This results in a more accurate reconstructed $A'$ mass than before, which is promising.

is quite obvious. But even if the $A'$ is not discovered, HPS will be helping to guide future experiments in where to search for new physics, and will ultimately lead to either more answers or more questions—which is an excellent thing in either case.

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References


