First Results from the Heavy Photon Search Experiment

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SLAC

On behalf of the Heavy Photon Search Experiment
Light Dark Matter

There is strong evidence for the existence of Dark Matter (DM), but its nature continues to elude us.

- Weakly Interacting Massive Particle (WIMP) Dark Matter are a motivated candidate but searches for them in the most favorable areas have yielded nothing... will be ruled out or found by next gen experiments (e.g. SuperCDMS, LUX/LZ) in the coming years.
- **Light Dark Matter** (i.e. sub-GeV range) is a reasonable candidate but requires a new force to achieve the correct thermal relic (WIMP’s limited by Lee-Weinberg Bound to 2 GeV).  

Consider the case where DM interacts via a vector mediator (dark/heavy photon, $A'$)

\[
\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{\varepsilon}{2} F_{\gamma \mu \nu} F'_{\mu \nu} + \frac{1}{4} F''_{\mu \nu} F''_{\mu \nu} + m_{A'}^2 A'_{\mu} A'^{\mu} 
\]

kinetic mixing between SM photon and the dark photon \(\rightarrow\) induces weak coupling to electric charge

$\Phi \rightarrow e^+ e^-$

$e^+ \rightarrow \gamma^* \rightarrow e^+ e^-$

$A' \rightarrow A' + \varepsilon A'$

Equivalent

$A' \rightarrow e^+ e^-$

$\varepsilon e$
Fixed Target Kinematics

Since dark photons couple to electric charge, they will be produced through a process analogous to bremsstrahlung off heavy targets subsequently decaying to $l^+l^-$.

$$e^- \rightarrow A' \rightarrow l^+ + l^-$$

Energy = $E$

Kinematics are very different from bremsstrahlung:
- Production is sharply peaked at $x \approx 1 \rightarrow A'$ takes most of the beam energy
- $A'$ decay products opening angle, $m_{A'}/E_{beam}$

The HPS experiment was designed to make use of such a production mechanism to search for a heavy photon using two methods:

**Resonance Search (Bump Hunt)**

Look for an excess above the large QED background → Large signal required so limited to large coupling.

**Displaced Vertex + Bump Hunt**

Long lived $A'$ will have a displaced vertex → Will help cut down prompt backgrounds but limited to small coupling.

See Matt Solt's talk tomorrow July 6 at 2:00pm in Room 203.
HPS Reach

HPS will have sensitivity to territory motivated by thermal dark matter!

Cosmic Visions Whitepaper [arXiv:1707.04591]
The HPS Apparatus

- **Pair Spectrometer**
  B = .25 T

- **Electromagnetic Calorimeter**
  Used for triggering and particle ID

- **Linear Shift Motion System**
  Allows adjustment of deadzone between SVT volumes

- **High intensity e⁻ beam**
  Courtesy of CEBAF @ JLab

- **Silicon Vertex Tracker (SVT)**
  Split into two volumes to avoid intense flux of scattered beam electrons. Used for precise momentum and vertex determination

- **SVT Vacuum Chamber**
  Si tracker placed in vacuum in order to avoid backgrounds due to beam-gas interactions

- **SVT + ECal DAQ capable of 50 kHz**

- **~10⁻³ X₀ Tungsten Target**
  Thin target to reduce multiple scattering

- **Tungsten Target**

- **Installed within the Hall B alcove at Jefferson Lab upstream of the CLAS12 detector**

- **Emitted Electrons**
  Courtesy of CEBAF @ JLab
HPS Engineering Runs

Two successful JLab engineering runs

- **Spring 2015**: 50 nA, 1.056 GeV electron beam (night and weekend running)
- **Spring 2016**: 200 nA, 2.3 GeV electron beam (weekend running)

**Goal**: Understand the performance of the detector and take physics data.

- For the 2015 run, data was taken with the Silicon Vertex Tracker (SVT) in two configurations: inactive edge at 1.5 mm and 0.5 mm from the beam plane
- **2015**: 10 mC with the SVT at 1.5 mm and 10 mC (**1.7 PAC days**) at 0.5 mm
- **2016**: 92.5 mC (**5.4 PAC days**) with the SVT at 0.5 mm

The results shown in this talk used the full 0.5 mm 2015 Engineering run dataset.
The 2015 engineering run has demonstrated that HPS is ready to do a meaningful search for heavy photons:

- Hall B beamline was capable of delivering a small beam spot, low beam halo with high stability → allowed placing tracker 0.5 mm from the beam
- Excellent Ecal time and energy resolution allows for the efficient selection of true e+e- pairs
- Vertex resolution was as expected and sufficient to conduct a search for a displaced $A'$

**Beam Position Stability**

- $X$ - position
- $Y$ - position

**Vertex Resolution vs Mass**

**Ecal time resolution vs Energy**

- $\chi^2 / ndf = 3620 / 19$
- $p0 = 0.07485 \pm 0.000135$
- $p1 = 0.1124 \pm 0.001021$

\[
\frac{p_0}{E} + p_1
\]
Backgrounds

The search for an $A'$ involves looking for a narrow resonance in the $e^+e^-$ invariant mass spectrum on top of a large, continuous background composed of several components.

Physics Backgrounds

- **Bethe-Heitler**
  - Dominant, but most lies below the $A'$ signal region.

- **Radiative**
  - Irreducible. Kinematically identical to $A'$ but can be used to understand expected $A'$ rates.

- **Accidentals**
  - True $e^+e^-$ pairs will have time-coincident clusters in the calorimeter. Can be suppressed using time cuts and cuts used to remove scattered beam electrons.

- **Wide Angle Bremsstrahlung (WAB)**
  - Conversions of photons produced in the target and first few layers of the SVT can mimic a trident $e^+e^-$ pair.

\[
\frac{d\sigma(e^-Z \rightarrow e^- Z(A' \rightarrow l^+ l^-))}{d\sigma(e^-Z \rightarrow e^- Z(\gamma^* \rightarrow l^+ l^-))} = \frac{3\pi e^2}{2N_{eff} \alpha \delta m} \frac{m_{A'}}{m_{A'}}
\]
Bump Hunt Event Selection

Apply kinematic and goodness of track and vertex fit cuts to clean up accidentals. Reduces contamination from accidentals to < 1%.

Requiring the sum of the $e^+e^-$ pair momentum to be $0.8E_{beam} < p(e^+e^-) < 1.2E_{beam}$ GeV and greatly reduces the number of Bethe-Heitler background in our final sample.

Requiring a layer 1 hit removes 68% of WABS from final event sample. Additional cuts on the distance of closest approach and $p_t$ asymmetry rejects WAB's by > 80% of WABs.
Bump Hunt Event Selection

Apply kinematic and goodness of fit cuts to reduce Bethe-Heitler background. Reduces contamination from accidentals. Requires the sum of the positron and electron pair momentum to be $0.8 \, E_{\text{beam}} < p(e^+e^-) < 1.2 \, E_{\text{beam}}$ GeV and greatly reduces the number of Bethe-Heitler background in our final sample.

Requiring a layer 1 hit removes 68% of WABS from final event sample. Additional cuts on the distance of closest approach and $p_t$ asymmetry reject WABs.

Apply kinematic and goodness of track and vertex fit cuts to clean up accidentals. Reduces contamination from accidentals to < 1%.

Does Positron Track Have a Layer 1 Hit?

- NO
- YES

mc

Entries 2.145228e+07
$e^+e^-$ Mass Resolution

- Determined the resolution as a function of mass using $A'$ and Möller Monte Carlo
- From data, use the Möller invariant mass distribution to measure the mass resolution
- Scale the MC mass resolution parameterization to match the data observation.

Discrepancy between data and Möller Monte Carlo is due to mismatch of momentum resolutions.
Search for a resonance within a window in the mass range between 19 MeV and 81 MeV by scanning the $e^+e^-$ invariant mass spectrum in 0.5 MeV step sizes.

Maximize the Poisson likelihood within the range using a composite model with the signal described as a Gaussian and an exponential of a Chebychev polynomial to model the background.

- Mass < 39 MeV: exp(5th order), window size: $14\sigma_{mass}$
- Mass >= 39 MeV: exp(3rd order), window size: $13\sigma_{mass}$

Use Likelihood ratio to quantify significance of any excess i.e. “bump”

Determine the 2σ signal upper limit at each mass hypothesis by inverting the likelihood ratio

Translate the signal upper limit into the coupling-mass phase space
No significant bump was found!

Fit Results

Establishing whether the signal+background model is significantly different from the background-only model is typically done using the profile likelihood ratio and test statistic $q_0$

$$q_0 = \begin{cases} -2 \ln \frac{L(\lambda, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})} & \hat{\mu} > 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

$$p = \int_{q_{0, obs}}^{\infty} f(q_0 | 0) dq_0$$

Use toy MC to determine the look-elsewhere correction

$p$-value @ 37.7 MeV = 0.0016

1σ global

2σ global

Global p-value vs. Local p-value

$A'$ Mass (GeV)

0.02 0.03 0.04 0.05 0.06 0.07 0.08

0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08

10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7
2σ Upper Limit on $\varepsilon$

2015 Engineering Run
1.7 PAC days @ 1.05 GeV

2018-2020 Physics Run
4 Weeks @ 2.2 GeV
4 Weeks @ 4.4 GeV
Summary and Outlook

The Heavy Photon Search has successfully completed engineering runs in 2015 and 2016:
- Detector performance was found to be as expected
- An additional source of background (WAB's) was found and mitigated
- HPS is now fully approved for its full time

Publication of the 2015 bump hunt analysis is imminent!

Several analyses are ongoing:
- 2016 Bump hunt analysis and 2015/16 Vertex analysis are ongoing

Upgrades to trigger and SVT are being built and will be installed Jan '19:
- Will significantly extend the reach of HPS

Next run planned for summer of 2019 at 4.4 GeV
Backup
Radiative Fraction

Translating the signal upper limit into the mass-coupling phase space requires knowledge of the fraction of radiative events in our event sample → use Monte Carlo to parametrize the radiative fraction as a function of mass.

\[ \epsilon^2 = \left( \frac{S_{\text{max}}/m_{\mathcal{N}}}{f \cdot \Delta B/\Delta m} \right) \times \left( \frac{2N_{\text{eff}}\alpha}{3\pi} \right) \]

Constant at 8.5% for now. More WAB’s are needed to get a better parametrization.
HPS Upgrades

Vertex reach is worse than we had projected → No vertex reach expected using 1.7 days of data

- Vertex decay efficiency assumed constant out to 10 cm
- MC used to make initial projections did not use the correct acceptance

Modest upgrades will allow recovery of reach for future runs

- The layers of the SVT will be moved closer to the beam → Increase acceptance
- Add an additional thin layer to the SVT at 5 cm → Improves vertex resolution and vertex efficiency
- Implement a positron only trigger → Will allow recovery of some of the reach lost due to the ECal hole.
Silicon Vertex Tracker

- Six layers of pairs of Si microstrip sensors → One axial and the other at small angle stereo (50 & 100)
  - Layer 1-3: single sensor
  - Layer 4-6: double width coverage to better match Ecal acceptance
- 36 sensors
- 180 APV25 chips
- 23,004 channels

<table>
<thead>
<tr>
<th>Layer</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z$ position from target (cm)</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>70</td>
<td>90</td>
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<tr>
<td>Stereo angle (mrad)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>50</td>
<td>50</td>
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<tr>
<td>Bend plane resolution ($\mu$m)</td>
<td>$\approx$6</td>
<td>$\approx$6</td>
<td>$\approx$6</td>
<td>$\approx$6</td>
<td>$\approx$6</td>
<td>$\approx$6</td>
</tr>
<tr>
<td>Non-bend plane resolution ($\mu$m)</td>
<td>$\approx$60</td>
<td>$\approx$60</td>
<td>$\approx$60</td>
<td>$\approx$120</td>
<td>$\approx$120</td>
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<tr>
<td>Nominal dead zone in $y$ (mm)</td>
<td>$\pm$1.5</td>
<td>$\pm$3.0</td>
<td>$\pm$4.5</td>
<td>$\pm$7.5</td>
<td>$\pm$10.5</td>
<td>$\pm$13.5</td>
</tr>
<tr>
<td>Material budget</td>
<td>7%</td>
<td>7%</td>
<td>7%</td>
<td>7%</td>
<td>7%</td>
<td>7%</td>
</tr>
</tbody>
</table>
Silicon Microstrip Sensors

Developed for D0 RunIIb upgrade
- Radiation tolerant: expect fluence of $4.8 \times 10^{15}$ e$^-$ in 6 months of running
- Breakdown voltage: $\sim 1000$ V
- $< 1 \% X_0$ per layer

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Cut dimensions ($L \times W$)</td>
<td>100 mm x 40.34 mm</td>
</tr>
<tr>
<td>Active area ($L \times W$)</td>
<td>98.33 mm x 38.34 mm</td>
</tr>
<tr>
<td>Readout (Sense) pitch</td>
<td>60 (30) $\mu$m</td>
</tr>
<tr>
<td># Readout (Sense) strips</td>
<td>639 (1277)</td>
</tr>
<tr>
<td>Breakdown voltage</td>
<td>$&gt; 1000$ V</td>
</tr>
<tr>
<td>Depletion voltage</td>
<td>$&gt; 130$ V</td>
</tr>
<tr>
<td>Bias Resistor Value</td>
<td>$0.8 \pm 0.3$ M$\Omega$</td>
</tr>
<tr>
<td>AC Coupling Capacitance</td>
<td>$&gt; 12$ pF/cm</td>
</tr>
<tr>
<td>Total Interstrip Capacitance</td>
<td>$&lt; 1.2$ pF/cm</td>
</tr>
<tr>
<td>Defective Channels</td>
<td>$&lt; 1%$</td>
</tr>
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</table>
Readout Electronics: APV25

Originally developed for CMS
- Radiation tolerant
- Low noise (S/N>25)
- 40 MHz “Multi-peak” 6 sample readout allows for shaper output reconstruction
- 2 ns resolution

<table>
<thead>
<tr>
<th># Readout Channels</th>
<th>128</th>
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<tbody>
<tr>
<td>Input Pitch</td>
<td>44/μ</td>
</tr>
<tr>
<td>Shaping Time</td>
<td>50 ns nom. (adjustable)</td>
</tr>
<tr>
<td>Output Format</td>
<td>multiplexed analog</td>
</tr>
<tr>
<td>Noise Performance</td>
<td>270 + 36 x C(pF) e⁻</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>345 mW</td>
</tr>
</tbody>
</table>
SVT DAQ

Hybrid
- APV25
  - Clocking & Control

Front End Board
- Amp
- ADC
- ADC RX

RCE Platform
- Sample Framing
- Data Reduction
- Data Buffer
- Timing & Trigger
- Event Building
- ECal TDAQ
- ROC Application

High density vacuum penetration
Electromagnetic Calorimeter

- Comprised of 442 PbWO₄ crystals coupled to avalanche photodiode readout
- FADC readout at 250 MHz → allows for a narrow trigger window (8ns)
- Trigger and DAQ capable of a rate > 50 kHz
Trigger

Crate Trigger Processor
Contains cluster finding algorithm. Searches for clusters in every 3x3 array of crystals. If sum exceeds threshold and is isolated, amplitude, position, time and hit are reported to SSP.

Sub-System Processor
Searches for pairs that within an 8 ns window and applies a topological selection

Flash ADC
Samples Ecal crystal APD’s @ 250 MHz. If signal crosses threshold, integrated amplitude and crossing time is sent to CTP

Trigger Supervisor
Generates trigger signal

HPS Calorimeter

FADC
221 Channels

CTP

SSP

TS