The Heavy Photon Search Experiment at Jefferson Lab

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For the HPS Collaboration
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Ample evidence for Dark Matter

Rotation curves of spiral galaxies

Gravitational lensing

Cluster collisions

See SSI-2014 “Shining Light on Dark Matter”
WIMP Dark Matter

- Dark matter is Physics beyond the Standard Model.
  - Only gravitational interaction has been observed.
- WIMP miracle
  - SUSY WIMP with ~100 GeV mass was the most attractive candidate.
  - Dark matter relic density is consistent with the weak interaction scale.
- No experimental evidence
  - Direct DM detector searches
  - No SUSY at ATLAS/CMS
- Other possibilities?
Low Mass Dark Matter and Heavy Photon as a mediator

- Low mass dark matter, MeV \sim GeV.
  - Two PRL papers in the last few weeks: PRL 115, 021301 and 061301 (2015).
- Need low mass mediator
  - To be consistent with the DM relic density.

\[ \Omega_{DM} \approx (\sigma v)^{-1}, \sigma v \propto \frac{m^2}{m_{med}^4} \]

- WIMPless miracle, PRL 101, 231301 (2008)
- HPS searches for the mediator.
Anomalies got the heavy photon business going

- Cosmic positron excess
- Muon (g-2) 3.6σ anomaly
- 16.6 MeV anomaly
  - arXiv: 1504.01527
- Moller scattering
  - arXiv: 1402.3620
Ongoing heavy photon searches

- **Colliders**
  - ATLAS and CMS at LHC
  - BaBar and Belle
  - KLOE at DAΦNE
  - PHENIX at RICH
  - WASA at COSY
- **Fixed target**
  - NA48 at SPS
  - APEX at JLab
  - HPS at JLab
  - DarkLight at JLab
  - A1 at MAMI, Mainz
  - MicroBooNE at FNAL
  - SeaQuest at FNAL (proposal)
Fixed Target Searches

Look for radiated $A'$ decay to $e^+e^-, (\mu^+\mu^-)$

\[ \sigma_{BH} \text{ very large } \gg \sigma_{\text{Rad.}} \]
But kinematically distinct ➔
Use clever trigger to separate.

Bethe-Heitler
Radiative

\[ e^- \quad \gamma \quad e^- \]
\[ e^- \quad Z \quad e^- \]
\[ e^- \quad Z \quad e^- \]

E(e+) [GeV] vs E(e-) [GeV]

Black: BH
Red: Rad.

Very high luminosities:
Intensity Frontier Physics.

P. Schuster, R. Essig et al, Intensity Frontier WS ’11 summary paper.

Bump Hunt:
Look for signal over background.

Bump Hunt + Vertexing:
Look for signal over background, reduce background with vertexing.

HPS Design Choices

• **A’ kinematics** ⇒ very forward production

\[
\begin{align*}
E_A' &\approx E_{\text{beam}} \\
\theta_{A'} &\approx 0 \\
\theta_{\text{decay}} &\approx \frac{m_{A'}}{E_{A'}}
\end{align*}
\]

• **Vertexing** A’ decays requires detectors close to the target. Invariant mass is an essential signature, so good momentum/mass resolution is also required. Vertexing and bump hunting need tracking and a magnet.

  Want \( \Delta m/m \sim 1\% \) for bump hunt
  Want \( \Delta z \sim 1\text{mm} \)

• **Trigger with a high rate, rad hard EM Calorimeter**
  Placed downstream of the magnet, it can ID e⁺ and e⁻.

• **HPS opts for large forward acceptance/moderate currents.** This requires placing sensors as close as possible to the beam.
A' lifetime

\[ \gamma c T \approx 1 \text{ mm} \left( \frac{\gamma}{10} \right) \left( 10^{-8} \frac{\alpha}{\alpha'} \right) \left( \frac{100 \text{ MeV}}{m_{A'}} \right) \]

Lower \( \alpha' \), lower mass \( \rightarrow \) longer lifetime

Background is all prompt \( \rightarrow \) Lower coupling can be reached using vertexing.

\[
\begin{align*}
\frac{\alpha'}{\alpha} &\approx 10^{-4} \\
&\approx 10^{-5} \\
&\approx 10^{-6} \\
&\approx 10^{-7} \\
&\approx 10^{-8} \\
&\approx 10^{-9} \\
&\approx 10^{-10} \\
&\approx 10^{-11}
\end{align*}
\]
Controlling Beam Backgrounds

With sensors close to the beam (just ½ mm for the first Si sensor), background control, radiation damage, and beam stability become critical.

Constraints

• Avoid Multiple Coulomb Scattered (MCS) beam
• Avoid the “sheet of flame”, the beam electrons which have radiated, lost energy, and been deflected in the horizontal plane by the magnet
• Avoid beam gas interactions.
• Avoid errant beam motions.

Design solutions

• Split the detectors top-bottom to avoid the beam and the “sheet of flame.
• Run the tracker in vacuum to eliminate beam gas interaction.
• Tightly collimate the incident beam.

\[ \text{Beam } e^- / \text{month} @ z=10 \text{ cm} \]

\[ 4 \text{ MHz/mm}^2 \]

\[ 8 \times 10^{14} \]

\[ \text{Sheet of flame} \]

\[ \text{photons} \]

\[ \text{MCS beam} \]

\[ \text{“sheet of flame”} \]
High Duty Cycle = CEBAF at JLab

CEBAF - Continuous Electron Beam Accelerator Facility

Simultaneous delivery of electron beam in three Halls. Can be at three different energies and intensities.

Beam at 500 MHz
Beam line in Hall B

Note: neither of new girders are necessary to run beam safely to the electron dump. They are needed to get stable, small size ribbon beam on HPS target.

Quads / correctors for beam steering and focusing
BPMs for beam position monitor and orbit lock
Halo counters and Fast-Shut-Down system
Wire scanners

CLAS12 spectrometer under construction
HPS in Hall B Alcove

3 mm gap protects the SVT

3 mm gap protects the SVT

Wire harp

SVT collimator

Photon beam dump is a lead-brick cave with tungsten insert (was used for the TPE experiment)

The same three magnet chicane and the same magnet power supplies that has been used for the TPE experiment. Analyzing magnet is the Hall-B pair spectrometer magnet with well studied field distribution
HPS Apparatus: SVT

- **SVT Design:**
  - Six layers of Si modules, split top-bottom, each with two sensors: axial and stereo
  - 4x10 cm Hamamatsu microstrip sensor with 60 μm sense pitch.

- **Fast Readout:**
  - CMS APV25 chip, 40 MHz continuous amplitude sampling with 3 μsec latency.
  - Digitizing electronics and power distribution in vacuum.
  - Power and control in/data out through vacuum feedthroughs.
  - Electronics and sensors cooled < 0°C to remove heat and boost radiation hardness.

- **Precision Movers:**
  - Position layers 1-3 close to the beam, do wire scans, and insert targets as needed.
SVT Assembly at SLAC
HPS Apparatus: ECAL

- Top and bottom modules
  - 5 layers each
  - 442 lead-tungstate (PbWO$_4$) crystals in all
- APD readout through custom preamplifiers
- Data recorded with 250 MHz 12 bit FADCs
- A thermal enclosure to keep crystal temperature constant to ~1°F to stabilize gains.

Ecal is downstream of SVT & magnet

PbWO$_4$ crystal with APD and preamp

Crystals are arrayed above and below the Ecal vacuum chamber
A magnet chicane directs the CEBAF 12 electron beam onto a W foil, producing heavy photons. They decay to $e^+e^-$ pairs, which are measured by the Si vertex tracker inside an analyzing magnet. A PbWO$_4$ ECal provides a fast trigger.

https://confluence.slac.stanford.edu/display/hpsg/Heavy+Photon+Search+Experiment
Beam’s Eye View of the SVT
Spring 2015 Engineering Run

Opportunistic run: other Halls had a priority and the 12 GeV work was carried out during week-day day shift.

- Installed SVT end of February
- Commissioned Hall B beamline March-April
  - Calibrated bpms & established orbit locks
  - Set up SVT Protection Collimator
  - Checked beam position stability
- CEBAF down for two weeks after power outage
- Commissioned Trigger and Integrated SVT DAQ late April
- Explore SVT backgrounds as moved SVT closer to beam
- Production running at 1.5 mm started May 1
- Production running at 0.5 mm started May 12
- Run ended May 18th.

Layer 1 silicon sensors are just 0.5 mm above and below beam. Min. opening angle is \( \theta_y = 15 \) mrad.
Proposal: 1 full week of 50 nA beam on target, 30mC
Achieved: ~10 mC with SVT at 1.5 mm, 10 mC at 0.5 mm
Beam Quality

HPS requires a very high quality beam, with very low halo.

\( \sigma_x \sim 300 \text{ to } 500 \ \mu m \) - To spread heat load.

\( \sigma_y \sim 15 \text{ to } 50 \ \mu m \) - To help vertexing & tracking.

The beam also needs to be very stable over time. A Fast Shut-Down stops the beam in <10 ms, if halo counters register above threshold counts.

X, Y and 45 degree beam profiles. May 5th, 2015

Very stable beam on May 12th.
Online data quality

ECal single rates

Total: $3.7 \times 10^5$ Hz

ECAL FADC SCALERS

Total: 372.2 kHz

190.52 kHz

181.66 kHz

Trigger rates

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In good agreement with simulations.
Two Cluster Events

- Momentum/energy calibration
- Mass resolution

\[ S = 2E_{\text{beam}}M_e \]
Tracked Pairs at 1.5 mm

$A'$ candidates have $P(e^+) + P(e^-) \sim P_{\text{beam}} = 1.05$ GeV

Simulation (6 GeV)
Pairs Vertex at the Target

Z-vertex is critical for the experiment.
- Also the hardest @ 15 mrad.
- Requires very good SVT alignment (not yet done!)

Z RMS ~ 8.7 mm

Y RMS ~ 0.3 mm

X RMS ~ 0.7 mm
Pairs Mass Distribution

Tiny fraction of all data.

Very preliminary look!
To do: better calibrations, cuts, more data, ...

### Histogram

- **Entries**: 103668
- **Mean**: 0.02635
- **RMS**: 0.01138
Full HPS Reach

Near term Running (Yellow):
1 week with 50nA @ 1.1 GeV
1 week with 200nA @ 2.2 GeV
2 weeks with 300nA @ 4.4 GeV

Additional Running (Blue):
2 weeks with 200nA @ 2.2 GeV
2 weeks with 300nA @ 4.4 GeV
3 weeks with 450nA @ 6.6 GeV

Times are “PAC” times = Calendar time/2

Opportunistic run Fall 2015
TBD Spring 2016
Summary

- We have roughly 1/3 PAC week with Si at 0.5 mm
  - 15 mrad acceptance
- Beamline, ECal, Trigger and SVT all worked well
  - Beam background and trigger rates are consistent with simulations.
- Lots of work to do ..
  - Check Trident Yield in the data
  - ECal energy calibration
  - SVT alignment
  - Understanding the vertex tails
- But a physics result may be in reach