Searching for Heavy Photons in Hall B

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Overview

• Motivation
• Heavy Photon Search experiment
• Experiment performance
• Preliminary results
• What’s next
Nature is described well by Standard Model, but we are missing something...

Galaxy rotational velocities

Strong evidence for dark matter!

Gravitational Lensing

Cosmic Microwave Background structure

3.5 keV emission “line” at galactic centers

Bulbul et al.
Exploring the Dark Sector

**Standard Model:**

\[ U(1)_Y \times SU(2)_W \times SU(3)_S \]

- **EM** Weak Strong

**Dark Sector:**

\[ U(1)_D \times \ldots \]

- Dark Forces?
- Neutral under SM forces

**Dark Matter theories**

**Weakly Interacting Massive Particle (WIMP)s:**
- 10s-100s GeV mass range
- Lots of searches, not detected so far

**Light Dark Matter:**
- MeV-GeV mass range
- Requires new force for correct relic abundance

**Strongly Interacting Massive Particles (SIMPs):**
- MeV-GeV mass range
- Strongly interacts with itself
Exploring the Dark Sector

**Standard Model:**

\[ U(1)_Y \times SU(2)_W \times SU(3)_S \]

- EM
- Weak
- Strong

**Dark Sector:**

\[ U(1)_D \times \ldots \]

- Dark Forces?
- Neutral under SM forces

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**Standard Model**

- \( g, W^\pm, Z, \gamma \)

**Dark Sector**

- Forces + particles
- Dark matter?

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- MeV-GeV mass range
- Requires new force for correct relic abundance

**Strongly Interacting Massive Particles (SIMPs):**

- MeV-GeV mass range
- Strongly interacts with itself
Extra Abelian U(1) gauge symmetry $\rightarrow$ new gauge boson!

Holdom, Phys Lett. B166, 1986

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'_{\mu\nu} F'_{\mu\nu} + m_{A'}^2 A'_{\mu} A'_{\mu}$$

Heavy Photon  
(aka: dark photon, $A'$, U-boson...)

Kinetic mixing induces a small coupling $\varepsilon e$ to electric charge

Simplest case:
loop-level interaction

$$\varepsilon \sim \frac{g_Y g_D}{16\pi^2} \ln \left( \frac{m_\Phi}{m_{\Phi'}} \right) \sim 10^{-3} - 10^{-1}$$

Grand Unified Theory:
two-loop interactions and higher

$$\varepsilon \sim 10^{-6} - 10^{-3}$$

Mass of heavy photon is less constrained
Methods of heavy photon production

“Wherever there are photons (and sufficient phase space), there are dark photons.”
—Philip Schuster

(Z here is atomic number of nucleus)

- Bremsstrahlung
  \[ e^-Z \rightarrow e^-ZA' \]

- e+e- annihilation
  \[ e^-e^+ \rightarrow \gamma A' \]

- pZ \rightarrow X + meson
  \[ \pi^0 \rightarrow \gamma A' \]
  \[ \eta \rightarrow \gamma A' \]
  \[ \phi \rightarrow \gamma A' \]

- Drell-Yan
  \[ q\bar{q} \rightarrow \gamma A' \]

Wherever there are photons (and sufficient phase space), there are dark photons.

Decay Branching Fractions:
Methods of heavy photon detection

Visible decays:

Invariant mass bump hunt:
- Large coupling, prompt decays, lots of background

Displaced vertex:
- Small coupling, long-lived decays, little/no background

Invisible decays:

Missing mass bump hunt, allows for decay to Dark Sector
Experiments

Electron fixed target

\[ \sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \]

Nucleus \( \bigotimes \)

A1 at Mainz (2011)
APEX in Hall A (2010)

HPS first to vertex

DarkLight (Jlab, LERF)
APEX in Hall A (2018)
MAGIX (Mainz) (2019+)

Beam dump (long lived A')

E141 and E137 at SLAC, E774 at FNL, Orsay

Fixed target experiments complement collider measurements
high luminosity → sensitive to small couplings
Experiments

Proton fixed target $\sigma \sim \epsilon^2$

NA48/2 at CERN SPS

$K^\pm$ beam $\rightarrow \pi^\pm A'(\rightarrow e^- e^+)$

NA48/2 (2015)
HADES (2013)
U70 proton beam dump

SeaQuest (FNAL):
$\mu^+ \mu^-$ from p beam dump
Bump hunt and vertex
Test run this year

SHiP (CERN) (2026+):
CERN SPS, visible & long decay lengths
Facilities to generate heavy photons

Collider

\[ \sigma \sim \frac{\alpha^2 \varepsilon^2}{E_{CM}^2} \]

Good for missing mass searches

BaBar (e+e-), \( \Upsilon \rightarrow \gamma A' \) (2009)
WASA (pp), \( \pi^0 \rightarrow \gamma A' \) (2013)

LHCb (pp), 2021+:
Triggerless operation
Rare, heavy quark decays
\( D^* \rightarrow D^0 A' (e^+ e^-) \)
\( B \rightarrow K^* A' (\mu^+ \mu^-) \)

Complements fixed target searches
Higher center of mass energy \( \rightarrow \) higher \( A' \) masses
Looking for radiated $A' \rightarrow \ell^+ \ell^-$

Bremsstrahlung-like reaction

- $A'$ carries most of the beam energy
- Very small angles
- Rate suppressed by $\sim \epsilon^2 \frac{m_e^2}{m_{A'}^2}$

$$\frac{d\sigma(e^- Z \rightarrow e^- Z (A' \rightarrow \ell^+ \ell^-))}{d\sigma(e^- Z \rightarrow e^- Z (\gamma^* \rightarrow \ell^+ \ell^-))} = \frac{3\pi \epsilon^2}{2N_{eff} \alpha \delta m} \frac{m_{A'}}{m_{A'}}$$

Decay length

$$l_0 \equiv \frac{\gamma \epsilon}{T} \approx 0.8 \text{ cm} \left( \frac{E_{beam}}{10 \text{ GeV}} \right) \left( \frac{10^{-4}}{\epsilon} \right)^2 \left( \frac{100 \text{ MeV}}{m_{A'}} \right)^2$$

$$E_A \sim E - m_A$$

$$E_e \sim m_A$$
Physics Backgrounds: tridents

Bethe-Heitler

- Dominant background
- Kinematically different

Radiatives

- Irreducible background
- Kinematics identical to heavy photon
Existing Constraints

Large $\epsilon$ coupling
$\rightarrow$ prompt decay

Small $\epsilon$ coupling
$\rightarrow$ $A'$ long-lived

$A'$ to explain muon $g-2$

Constraint from electron $g-2$

$\epsilon^2$ coupling

$A'$ mass (GeV)

$10^{-8}$

$10^{-7}$

$10^{-6}$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$10^0$
Existing Constraints

- Large $\epsilon$ coupling $\rightarrow$ prompt decay
- Small $\epsilon$ coupling $\rightarrow$ $A'$ long-lived

- Bump Hunt
- Displaced Vertex

Proposed regions of interest for HPS search

$\epsilon^2$ coupling

Beam dump

$A'$ mass (GeV)
HPS in Hall B

Jefferson Lab, CEBAF

CEBAF max energy 2.2 GeV/pass (max 5 pass)
Simultaneously deliver beam to 4 halls
HPS Detector

- **Electromagnetic Calorimeter (Ecal)**:
  - Triggers events
  - Measures particle energy
  - Resolution: 4%/√E

- **Silicon Vertex Tracker (SVT)**:
  - Measures particle trajectories
  - Momentum and vertex

- **0.125% W target**

- **Analyzing Magnet**: B

- **e- beam**: 0.5 mm from beam!
HPS Experimental Goals and Considerations

HPS is sensitive to heavy photons with both prompt and displaced decay vertices
→ Small mass resolution for bump hunt to fight backgrounds
→ Small vertex resolution and minimal tracking material to reduce scattering

Maximize acceptance for low mass $A'$ decays
→ Close to the beam

HPS approved to run for 180 beam days

Actual HPS sensitivity depends on beam time and energy
Silicon Vertex Tracker

- Six layers of Si microstrip sensors (axial and stereo)

- Layers 1-3: single sensor, 100 mrad stereo

- Layers 4-6: double sensor wide, 50 mrad stereo
- 36 total sensors
- 180 APV25 chips
- 23,004 channels
Electromagnetic Calorimeter

- 442 PbWO₄ scintillating crystals re-used from CLAS Inner Calorimeter
- Large Area Avalanche Photo Diodes (APD) for readout (10x10 mm²)
- Light Monitoring System
- Gap between top and bottom half to allow for “sheet of flame”
Triggering events

HPS Calorimeter (442 Channels):

Flash ADC
- Samples Ecal crystals at 250 MHz
- If threshold crossing, reports integrated amplitude and time to GTP

General Trigger Processor
- Builds 3x3 clusters
- Reports time, energy, and position to TP

Consider topologies and optimize for heavy photon signal:
- Cluster energy sum
- Cluster energy difference
- Time coincidence
- Cluster size
- Cluster energy
- Coplanarity
- Energy-distance
HPS Running

Spring 2015 running, Engineering Run

- Beam energy: 1.05 GeV
- SVT at 1.5 mm
- SVT at 0.5 mm
- Nights + Weekends
- Commissioning
- Achieved: 2 of 7 proposed run days

Spring 2016 running, Physics Run

- Beam energy: 2.3 GeV
- Achieved: approx 5 of 7 proposed run days
- Commissioning
High quality beam:
• Asymmetric beam profile
• Prevent potential overheating of target
• Small in vertical size for precise vertex reconstruction

First layer of SVT at ± 0.5 mm from the beam!

Fast Shut-Down if halo counter rates too high, cuts off beam in 5 ms
SVT Performance

• Consistent with proposal
Ecal Performance

Cosmics for initial gain calibration

Time difference between 2 clusters

\[ \sigma = 330 \text{ ps} \]

Beam bunch structure

Timing offsets were calibrated using RF time from accelerator
Mass resolution

- A' MC
- Moller - MC
- Moller - Data

Scaled resolution

Moller data

MC resolution

Moller MC

$m(e^+ e^-)$ (GeV)
Agreement with Simulation

Need good agreement in order to calculate amount of radiative tridents in final sample

- Additional significant background: Wide Angle Bremsstrahlung (WAB), $e\gamma$
- Agrees at high energy sum
- Differences at lower energy sum are being studied
Cuts:
• Track Quality
• Target-Constrained Vertex Quality
• Timing (2 beam buckets)
• Track-Ecal cluster matching

Because the conversion electron is missing there will be a $p_t$ imbalance.

$p(e^-) \text{ (GeV)}$

$p(e^+) \text{ (GeV)}$

Bethe-Heitler $A'$ Signal

Positron D0 at target

Trident MC

WAB MC

Trident MC

WAB MC

$P_{\text{ositron}} \text{D0 at target}$

(truncated formula)

$\frac{(p_t(e^-) - p_t(e^+))}{(p_t(e^-) + p_t(e^+))}$
Bump hunt procedure

- Fix Gaussian peak width $\sigma_m$
- Optimal search window size from pseudo-experiments:
  - 11 $\sigma_m$ at the edges
  - 17 $\sigma_m$ in the center
- Scan window in 1 MeV steps from 18 to 95 MeV
- Fit a Gaussian plus a 7th order Chebyshev polynomial
- Likelihood ratio from S+B vs B fits
- Translate the signal upper limit into the coupling-mass phase space

Account for Look Elsewhere Effect!
Bump hunt results

Most significant bump
\( m = 51 \text{ MeV} \)

p-value = 0.0071

Search window width

Invisible mass \([\text{GeV}]\)

0.035  0.05  0.065

Residual

0.035  0.05  0.065

Events / (GeV)

0  5000  10000  15000  20000  25000  30000  35000  40000

\( \Delta' \) mass (GeV)

10^{-8}  10^{-7}  10^{-6}  10^{-5}  10^{-4}  10^{-3}  10^{-2}  10^{-1}  10^{0}

2015 Engineering Run - 1.7 PAC Days
Search for heavy photons with displaced vertices

Procedure:
• Scan in bins of 2.8 \( \sigma_m \) from 20 to 70 MeV
• Fit vertex distribution with \textbf{Gaussian} plus \textbf{Exponential} to determine \( z_{\text{Cut}} \), fewer than 0.5 background events beyond
• Either
  • Look for events beyond \( z_{\text{Cut}} \) [discovery!]
  • Calculate expected events beyond \( z_{\text{Cut}} \) (90% CL exclusion region for \( n > 2.3 \))

\[
S_{bin,z_{\text{Cut}}} = \left( \frac{N_{rad}}{N_{tot}} \right) N_{bin} \left( \frac{3\pi e^2}{2N_{\text{eff}}\alpha} \right) \left( \frac{m_{A'}}{\delta m_{A'}} \right) \epsilon_{bin} \int_{z_{\text{Cut}}}^{z_{\text{Max}}} e^{-ztg_t-z/\gamma c T} \epsilon_{\text{vtx}}(z, m_{A'}) dz
\]

84\% \( A' \) signal in mass bin

\( A' \) yield in mass bin

Fraction of events beyond \( z_{\text{Cut}} \) we can reconstruct (includes inefficiencies and acceptance effects)
Displaced vertex event selection

Cuts:
- Track Quality
- Unconstrained Vertex Quality
- Timing (2 beam buckets)
- Track-Ecal cluster matching
- Isolation cut
- Difference between Beamspot constrained and Unconstrained vertex quality
Searching for $A'$ with detached vertex

**Mass:**
31 MeV

**Gaussian Exponential**

**Slice 60-61**
- Entries: 108885
- Mean: $-4.404$
- RMS: 5.249
- $\chi^2 / \text{ndf}$: 645.1 / 63
- Constant: $8445 \pm 33.1$
- Mean: $-4.366 \pm 0.016$
- Sigma: $5.113 \pm 0.013$

**10% data sample**

**Validated vertex procedure**

**Extra background at high z**

\[
\begin{align*}
F(z < b) &= Ae \frac{(z - z_{\text{mean}})^2}{2\sigma^2} \\
F(z > b) &= Ae \frac{b^2}{2\sigma^2} \left( \frac{z - z_{\text{mean}} - b}{l} \right)
\end{align*}
\]
Backgrounds from wide angle bremsstrahlung

\[ e^-\gamma \rightarrow e^-e^+e^- \]
Backgrounds from scattering

Reduce backgrounds:
• Layer 1 requirement for both tracks
• Hit isolations in first two layers
Expected signal count:
SVT at 0.5 mm, both tracks through Layer 1

Highest signal contour <2.3 events

No exclusion.
Need more data!
Why didn’t we exclude anything?

Separate datasets from 1 GeV Engineering Run:
• Both tracks pass through 1st layer (significant)
• One track misses 1st layer
• Both tracks miss 1st layer

- Only two days of beam time
- Proposal assumed 0.5 constant efficiency to 10 cm
- Initial projections omitted beam hole in calorimeter
- Need more data!!

Fraction of vertices reconstructed

0.5mm, A' mass = 30 MeV
Future upgrades

Hodoscope on positron side of Ecal:
• Keeps events where e- lost in hole
• Reduce WAB triggers from e^-\gamma

Add SVT layer at 5cm

![Hodoscope diagram]

- Positron side
- Electron side

![Vertex Resolution graph]

- Preliminary
- 6 Layers
- 7 Layers

Mass [GeV] vs. Vertex Resolution [mm]
Summary

Great “table top” nuclear physics experiment!

Successful running
• Engineering Run at 1GeV in 2015: commissioned detectors, first analyses
• Physics Run at 2.3 GeV in 2016: analyses underway

Recently released bump hunt results
Paper in progress

NIM articles accepted
• Beamline: arXiv:1612.07821
• Electromagnetic calorimeter: arXiv:1610.04319

Upgrade planning in progress
Future running in 2018!
Thanks!

HPS Collaboration
May 3 - 5, 2017
Jefferson Lab • Newport News, VA