The Heavy Photon Search experiment at Jefferson Lab

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on behalf of PS collaboration
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Outline

• Motivation
  • What is heavy/dark photon
  • How to detect dark photon

• Setup
  • Silicon Vertex Tracker
  • Electromagnetic Calorimeter

• Performance
  • 2015 Run
  • 2016 Run
What is a Dark Photon?

• Nature may have an additional $U(1)$ symmetry. (*Holdom, Phys. Lett B166, 1986*)

• This gives rise to a **kinetic mixing** term where the photon mixes with a new gauge boson (“dark/heavy photon” or $A'$) through the interactions of massive fields → induces a weak coupling to electric charge

• Since dark photons couple to electric charge, they will be produced through a process analogous to bremsstrahlung off heavy targets subsequently decaying to $l^+l^-$
Where to look for a Dark Photon?

- Heavy photons could explain experimental anomalies in particle physics and astrophysics

- $A'$ is characterized by its mass $m_{A'}$, coupling to charge $\varepsilon e$.

- Mass range is limited on the left by detector acceptance, on the right by production cross-section.

- Bump hunt reach is limited on the bottom by statistics.

- Vertexing reach is limited on the upper right by the resolvable decay length (tails of the trident vertex distribution).
HPS in a search for Heavy Photons

- HPS is a new, special purpose experiment, dedicated to searching for an $A'$ in the unique territory with $\varepsilon << 10^{-3}$ which is accessible with a vertex detector.

- Small couplings means very few events what requires lots of luminosity.

- Lots of luminosity means lots of background, low Signal/Background.

- But small couplings also make the $A'$ long-lived. (A powerful secondary vertex signature)

- It’s all in the tails! The $A'$ decay length signal is in the tails of the prompt trident signal. Understanding and controlling the tails of the trident vertex distribution are crucial!
HPS – Fixed Target Experiment

- Even though $A'$ particles are produced by a process analogous to ordinary photon bremsstrahlung, the rate and kinematics differ in several key ways:

  - The $A'$ productions cross section is suppressed relative to photon bremsstrahlung by a factor of $m_e^2 \varepsilon^2 / m_{A'}^2$

  - The $A'$ is produced very forward → opening angle of its decay products is $\sim m_{A'}/E_{\text{beam}}$

  - The $A'$ will take most of the incident beam energy.

  - Long lived $A'$ will have a displaced vertex → Will help cut down prompt backgrounds.

\[
E_{A'} \approx E_{\text{beam}} \quad \theta_{A'} \approx 0 \quad \theta_{\text{decay}} = m_{A'}/E_{A'}
\]
HPS Backgrounds

• Two physics backgrounds collectively known as “tridents”:
  • **Radiative** - Irreducible. Kinematically identical to $A'$.  
  • **Bethe-Heitler** - Dominant but is also kinematically distinct to the $A'$. Even after kinematic cuts, Bethe-Heitler dominates.

• **Beam Backgrounds**
  • Coulomb scattering in the target
  • Secondary particle production: bremsstrahlung and delta-rays
  • Pair conversion of bremsstrahlung photon
HPS Design Choices

- **Vertexing** A’ decays requires detectors close to the target.

- **Invariant mass is an essential signature** Good momentum/mass resolution is required (resonance search).

- **Vertexing** and resonance search need tracking and a magnet. (Displaced Vertex)

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

- Large forward acceptance/moderate currents requires placing **sensors as close as possible to the beam.**

- High occupancy will require **fast readout and trigger system.**
HPS Setup

- $10^{-3} \times_0$ Tungsten Target
  Thin target to reduce multiple scattering

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

- Silicon Vertex Tracker (SVT)
  Used for precise momentum and vertex determination

- Electromagnetic Calorimeter
  Used for triggering and particle ID

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

- Pair Spectrometer

SVT + ECal DAQ capable of 50 kHz
Silicon Vertex Tracker (SVT)

Design:

- Six layers of pairs of Si microstrip sensors → One axial and the other at small angle stereo (50 or 100 mrad)
- Layers 4-6 are double width in order to match calorimeter acceptance
- Thin layers in order to reduce multiple scattering (0.7%\(X_0\)/layer)
- Total of 36 sensors and 23004 channels

Readout

- Makes use of APV25 readout chip
- 40 MHz six sample readout helps achieve a 2 ns \(t_0\) resolution and fight pileup
- Low noise → S/N > 25
- High radiation tolerance
Silicon Vertex Tracker (SVT)

Beam’s Eye View of SVT
Electromagnetic Calorimeter

• Build of 442 PbW$_4$ crystals readout with APDs and preamplifiers

• FADC readout at 250 MHz → allows for a narrow trigger window (8ns).

• FPGA based trigger selection (Two clusters along with some constraints on their energy and geometry) reduces background trigger rate from 3 MHz to 27 kHz.

• Trigger and DAQ capable of a rate > 50 kHz

• Resolution: 4%/√E
HPS Proposed Program

Runs status to date:
- Spring 2015: Engineering Run
  1.05 GeV, 50 nA
  Achieved ~ 1.6 of 7 proposed days (SVT at 0.5 mm)
  ~ 1 of 7 proposed days (SVT at 1.5 mm)
- Spring 2016: Physics Run
  2.3 GeV, 200 nA
  Achieved ~5 of 7 proposed days (SVT at 0.5 mm)

$A' \rightarrow \text{Standard Model}$

$\epsilon^2$ vs $m_{A'}$ [GeV]

- $1 \text{ wk}$: 1.1 GeV
- $1 \text{ wk}$: 2.2 GeV
- $2 \text{ wks}$: 4.4 GeV

$\Large \text{Large coupling search}$
(lots of events)

$\Large \text{Small coupling search}$
(fewer events)
HPS 2015 Run

Goal: 30 mC
Achieved: 10 mC with SVT at +/-1.5 mm, 10 mC with SVT at +/-0.5 mm
HPS 2016 Run

Goal: 120 mC
Achieved: 92.5 mC on target, $6.3 \times 10^9$ events (77% of proposed running)
Beam quality

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

- $\sigma_X \sim 300$ to $500 \mu$m - To spread heat load.

- $\sigma_Y \sim 15$ - $50 \mu$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.
ECAL Performance

- Time resolution ~330 ps
- Energy resolution ~4%@1 GeV

Cosmics for initial gain calibration

Timing calibration and improvement in resolution (with higher energy)

Elastically-scattered beam energy electron calibration
SVT Performance

- Momentum resolution \(\sim 5.9\% @ 2.3\) GeV
- Hit efficiency >95%
  (except of layer 6th)

First look at track efficiency by SVT layer

\[
\mu = 2.3099 \pm 0.0017 \\
\sigma_p = 0.1356 \pm 0.0017 \\
\sigma_p^p = 5.9\%
\]

\[
\mu = 2.3272 \pm 0.0015 \\
\sigma_p = 0.1371 \pm 0.0015 \\
\sigma_p^p = 5.9\%
\]
Invariant mass

$e^+ \text{ vs } e^- \text{ Energy (Simulation)}$

$e^+ \text{ vs } e^- \text{ Energy (Data)}$

Cluster energy (Data)

$e^+ \text{ vs } e^- \text{ momentum (Data)}$

$e^+ \text{ vs } e^- \text{ momentum (Data)}$
Invariant mass

\[ e^+ e^- \text{ invariant mass} \]

1.05 GeV beam

2.3 GeV beam

PRELIMINARY
Summary

• The HPS experiment has successfully completed its first physics data taking with:
  • 1.05 GeV beam, during the 2015 “Engineering Run”
  • 2.3 GeV during 2016 “Engineering Run 2”

• Opportunistic running, with CLAS12 installation during the day, is a challenge, but possible.

• NIM papers underway

• Blind data analysis using 10% of the data
  • Bump hunt analysis nearly complete
  • Vertex cut analysis well advanced
  • In progress:
    • Fix cuts
    • Unblind data (100%)
Backup
Where to look for a Dark Photon?

- Current limits:
  - Fixed target with e⁻ beam
    APEX test run (JLab), Mainz (A1)
  - Fixed target with p beam
    Fermilab
  - Beam dump experiments
    E774, E141, u70, Orsay
  - Annihilation
    BABAR, BELLE, KLOE
  - Meson decay
    KLOE, BES-3, WASA-COSY, NA48/2
    (CERN SPS), PHENIX)
2015 Run Bump Hunt

- 10% of 2015 data, SVT at 0.5 mm
- Conservative cuts
- Fits 7th order polynomial background + A’ peak

- Fix A’ “peak” width, moving “peak” across spectrum to determine upper limits

Plots from dissertation of Omar Moreno
2015 Run Vertex Search

- Search for long-lived $A'$ with separated vertex

Plot from Sho Uemura