Per Hansson Adrian
on behalf of the HPS Collaboration

UCLA Dark Matter 2014
Hidden Sectors and Heavy Photons

Dark matter can be a part of a hidden sector

The heavy photon/dark photon/A’ is the U(1) equivalent of the SM photons
- Couples to analogue of electric charge – *dark charge*

Hidden sectors would interact with ordinary matter through gravity and one or more “portals”
- E.g. vector portal: kinematic mixing with SM photon

⇒ Electrically charge matter have a small coupling to heavy photons

Coupling suppressed w.r.t. EM coupling by $\epsilon$

$$\epsilon \sim 10^{-4} - 10^{-2}$$
$$\epsilon \sim 10^{-5} - 10^{-3}$$

Natural mass term?

$$m_{A'} \sim \sqrt{\epsilon} \ m_Z \approx \text{MeV} - \text{GeV}$$
Limits on Heavy Photons

Parameter space of particular interest
⇒ Hidden sector Dark Matter
annihilation valid over much of this space

Constraints from QED precision tests (e⁻/µ⁻ g-2)

Direct production at colliders

(Rare) decays (K, φ, π⁰, η)

g⁻⁻² explained by heavy photon
Focus here on fixed target experiments
Fixed Target Electro-Production Signatures

Resonance bump
• Heavy photon appears as narrow $e^+e^-$ resonance on a copious QED “trident” background

![Resonance bump diagram]

Long life-time: displaced decay vertex
• Heavy photons with mass $\text{MeV-GeV}$ may have decay lengths from $\text{um’s}$ to $\text{10’s of m’s}$ for appropriate couplings
• Distinct signature – smaller backgrounds

Small signal and large backgrounds
• Intense beams, fast detectors and high rate data acquisition
• Intensity frontier physics!
Fixed Target Heavy Photon Kinematics

Cross-section peaks at incident electron energy (contrast with $1/k$ for bremsstrahlung)

$m_{A'} \sim 300\text{MeV}$

Key experimental features

$\Rightarrow A'$ carries most of the beam energy and appears $\sim$ along beam line

$\Rightarrow$ Recoil electron not measured for signal events (in most experiments)

$\Rightarrow A'$ decay products may appear close to the beam $\sim m_{A'}$

$\Rightarrow$ Possibly a displaced vertex
Beam-dump Experiments

Beam dump produces EM shower
($e^+$ and $e^-$ radiate $A'$)

$A'$ with long life-time can escape dump and decay near detector
⇒ High luminosity, access to low couplings
⇒ Small acceptance, sensitivity to small $m_{A'}$

Previous beam dump experiments reinterpreted

S. Andreas DARK2012
Thin Fixed Target Experiments

A’ radiated of beam electron in thin target

A’ appear as narrow resonance on large background
⇒ No decay in shield: access to higher couplings
⇒ Better acceptance: access to higher mass

Bump-hunt analysis: mass resolution matters
⇒ Typically background/rate limited
⇒ Small acceptance
Fixed Target Experiments: how can we improve?

1. Increase signal acceptance

2. Reconstruct $A'$ decay vertex to beat down background
The Heavy Photon Search Experiment (HPS)

⇒ Determine invariant mass of heavy photon decay products
⇒ Discriminate between prompt and non-prompt decays
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⇒ Determine invariant mass of heavy photon decay products
⇒ Discriminate between prompt and non-prompt decays

- Conceptual design
- Beam e⁻'s
- Thin (0.25% χ₀) target
- Si tracker
- Electromagnetic calorimeter
- Dipole magnet
- Muon detector (future upgrade)

Tracking/vertexing "measurement"

Need acceptance close to target and beam...
The Heavy Photon Search Experiment (HPS)

⇒ Determine invariant mass of heavy photon decay products
⇒ Discriminate between prompt and non-prompt decays

Conceptual design

Beam e⁻'s

 Beam e⁻'s

View from top

Beam’s eye view

target

Scattered beam

B ⊗

“sheet of flame”

photons

15mrad
(1.5mm)

15mm
Beam Backgrounds Dominate Occupancy

Split detector in two halves

Additional handles
- High current, thin target to minimize scattered beam
- Operate in vacuum to eliminate beam-gas interactions
- Spread out background in time -> continuous beam
- Fast detectors able to time stamp hits belonging to signal $e^+e^-$ events

Beam’s eye view

Layer 1 @ 10cm

15mrad “dead zone”

$\sim 4\text{MHz/mm}^2$

#hits/cm$^2$/30days
High-current Electron Beam

CEBAF at Jefferson Lab is ideal for HPS!

Delivering DC beam to multiple halls
- 500MHz, 100% duty factor
- Currents up to 500nA (Hall B) or 100uA (Hall A&C)

Excellent beam quality & stability
- Small beam spot size, <30µm, for HPS (helps vertexing and resonance search)

Configurable beam energy
- HPS: 2.2, 6.6GeV (11GeV max)
- Lower (1.1GeV) with special dedicated runs

12GeV upgrade project finish this year– HPS will be one of the first experiments to run
Fast Calorimeter Trigger

PbWO4 crystals with APD readout good match for HPS
⇒ Fast, readily available (JLab CLAS IC), radiation tolerant

2×221 crystals

160mm

15mrad dead zone

LED monitoring system

Large area APD’s

Crystal assembly

Occupyancy up to 500kHz

2.2GeV @ 200nA

• Split in two halves
• Fast readout: virtually no dead time
• Trigger time resolution: 8ns
• Acceptance matched to tracker
Silicon Vertex Tracker Layout

Measures momentum and vertex position

- Small angle stereo-pairs (Si micro-strip sensors)
- Fit inside existing dipole magnet
- Optimized for low mass; multiple scattering dominates measurement

<table>
<thead>
<tr>
<th>Layers</th>
<th>1-3</th>
<th>4-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>z position [cm]</td>
<td>10,20,30</td>
<td>50,70,90</td>
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<tr>
<td>Stereo angle [mrad]</td>
<td>100</td>
<td>50</td>
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<tr>
<td>Non-bend res. [µm]</td>
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<td>≈6</td>
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<tr>
<td>Stereo res. [µm]</td>
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<td>≈120</td>
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<tr>
<td>Dead Zone [mm]</td>
<td>1.5-4.5</td>
<td>7.5-13.5</td>
</tr>
</tbody>
</table>

Split in two halves
- Motion system
- Cooled support structure (H₂O/glycol ~ -20°C)
- Operates in vacuum!
Silicon Vertex Tracker Modules

- Radiation hard D0 RunIIb sensors
  - High readout granularity (60µm readout pitch)
  - Low mass support: tension CF between cooled uprights

- Readout using APV25 ASIC (CMS@LHC)
  - Fast: 40MHz sampling, short (35ns) shaping time
  - Six sample readout allows time reconstruction

Key performance parameters proven in Test run

- S/N>25
- 40MHz, 6-sample readout
- <2.5ns time resolution

Fit CR-RC pulse shape to determine \( t_0 \)
High Rate Data Acquisition

Tracker DAQ
- SLAC-developed generic RCE platform (ATCA)
- In-vacuum ADC, voltage regulation and power distribution
- Optical conversion
- 50kHz trigger rate and 100MB/s

ECal Trigger and DAQ
- Crystals readout by 250MHz FADC
- 8ns $e^+e^-$ coincidence time resolution
- Tested to above 50kHz at HPS occupancies
Reach 2014-2015 and Beyond

Two searches in one experiment

Prompt decay
A’ signal or QED trident

Invariant mass bump-hunt

20μm

2014-2015 and Beyond

2014-2015

2016+

Combined

3months @ 2.2, 6.6 GeV
Reach 2014-2015 and Beyond

Two searches in one experiment

Prompt decay
A' signal or QED trident

Invariant mass bump-hunt

Displaced vertex
A' signal only!

Vertex search

1-3w 2014-2015

2016+

Combined

3 months @ 2.2, 6.6 GeV
More Opportunities with HPS

Discovery of True Muonium!
- Hydrogen-like long-lived bound state of $\mu^+\mu^-$
- Multiple states: all decays to $e^+e^-$ pairs
- Same experimental signature as $A'$ but: known mass and decay lengths (\~cm’s)
  $\Rightarrow$ Great demonstration of vertexing!

Complex final states
- $A'$ decays to lighter dark sector particles
- Search for e.g. 4 $e^\pm$ final states
- Tiny background, but small acceptance
Summary

Searches for heavy photons are well motivated

- Heavy photons are prevalent in many models beyond SM
- Dark Matter may be part of a hidden sector
  ⇒ Heavy photons candidate explanation for observed discrepancies

The Heavy Photon Search (HPS) experiment explores new territory

- Particle physics view: both access remaining g-2 preferred region and unexplored intermediate coupling region
- Experimental view: precise tracking and vertexing 0.5mm from intense electron beam

HPS is funded and approved

- Construction ongoing now
- Install later this year
- Run during 2014-2015 and beyond
HPS Collaboration
HPS at SLAC’s high current FACET beam?

$10^5$ hits/strip => This will not work!

⇒ Need to spread out beam background in time

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Background hits/pulse in Layer 1

SLAC FACET @ 100 nA
30 Hz pulses, 3.2 nC/pulse
It’s getting crowded

HPS 1.1GeV and 2.2GeV only

A' → Standard Model

Status 2015?

Unclear: more Phenix data?
Reach

- 1w @1.1GeV
- 1w @2.2GeV
- 2w @6.6GeV
- Combined

3months @ 2.2,6.6GeV

Prompt

Displaced
Physics Reach

Large signal, **HUGE** background

- "bump-hunt"
- $30k A' \text{ at } 80\text{MeV} \\ \alpha \approx 3 \times 10^{-7}$
- 40M bkg events (50-100MeV)

Small signal, **NO** background

- "vertexing"
- $500 A' \text{ at } 80\text{MeV} \\ \alpha \approx 5 \times 10^{-8}$
- 10M bkg events

**Graphs**

- $m_{A'}$ (GeV)
- $\epsilon^2$
- 2014
- 2015
- 2014+2015
- 3 mo. each @ 2.2, 6.6
What if $M_\chi < M_{A'}$?

**Constraints from:**

$$(g - 2)_e \quad (g - 2)_{\mu}$$

$K \to \pi\nu\bar{\nu}$ (e.g. E787, E949)

**Make a dark matter beam!!**

\[ \text{P} \quad \rightarrow \quad \pi^0 \rightarrow \gamma A' \rightarrow \text{DM} + \text{DM} \]

\[ \text{e}^- \rightarrow \quad e^-/N \rightarrow \quad \text{DM} \]

\[ \text{Target} \quad \text{Decay pipe} \quad \text{Shield} \quad \text{Detector} \]
A’ Lifetime

\[ \gamma c \tau \approx 0.8c m \left( \frac{E}{10\text{GeV}} \right) \left( \frac{10^{-4}}{\varepsilon} \right)^2 \left( \frac{100\text{MeV}}{m_{A'}} \right)^2 \]

“Prompt decays”

“Long-lived”

Lower \( \varepsilon \)

Lower \( m_{A'} \)

Longer lifetime

[Slac]

[Rouven Essig]
Layer 1 occupancy

1% occupancy
Tracking Performance

d
Vertexing Performance

d

- 1.1 GeV
- 2.2 GeV
- 4.4 GeV
Dedicated Run – Photon beam

Collimators

HARP converter target

SVT

ECal

photons

tagger magnet

220cm

77cm

View from side
Beam background verification

Test run detector only exposed to photon beam

Electron beam

Photon beam

“gold radiator”
$10^4$ rad. len.

Target 0.25% r. l.

SVT

ECal

Events/90nC

Ratio

Converter thickness (% rad. len.)

EGS

Data

0.2 0.4 0.6 0.8 1 1.2 1.4 1.6

0 0.2 0.4 0.6 0.8 1
HPS Test Run

Very busy year!

In 2011: “Full” HPS contingent on test run

- Build a tracker and calorimeter that successfully meets key challenges
- Confirm models of backgrounds
- Demonstrate technical approach
- Bonus: physics reach

Design choices: sacrifice acceptance

- 20 tracking sensors
- Inner calorimeter: PbWO$_4$ modules
- Complete, integrated full DAQ for SVT and calorimeter

Very tight schedule:
Run before the 12GeV upgrade
Tridents

• Radiative (irreducible)

• Bethe-Heitler (BH)

\[ \sigma(\text{BH}) \gg \sigma(\text{radiative}) \]
Reject through kinematic selection
\~5x after basic selections

Beam backgrounds

• Coulomb scattering in target
• Secondary prod. (bremsstrahlung, X-rays)
• Pair conversion (two-step process)
Heavy Photon Fixed Target Production

Much higher luminosity than colliders for masses <1GeV
Radiative production dominate

- **Suppressed** relative to Bremstrahlung by $\sim \varepsilon^2 m_e^2 / m_{A'}^2$

\[ \sigma \sim \frac{\alpha^3 Z^2 \varepsilon^2}{m_{A'}^2} \sim O(10\, pb) \]

Rudimentary wish-list
- High Z target
- High luminosity
- Detect $e^+e^-$ and $\mu^+\mu^-$

$\Rightarrow O(1000)$ events/day
$\Rightarrow$ Large backgrounds