Heavy Photons?

Old idea: Nature may have an additional $U(1)$ symmetry. If so there will be kinetic mixing between the photon and the new gauge boson.

$$L_{U(1)'} = -\frac{1}{4} V_{\mu\nu}^2 - \frac{\epsilon}{2} V_{\mu\nu} F_{\mu\nu} + |D_\mu \phi|^2 - V(\phi)$$

Holdom, Phys. Lett B166, 1986

Kinetic Mixing term.
Mixing

Photon mixing with $A'$ is equivalent to ordinary charged matter acquiring a milli-charge under the $A'$

$e^- \gamma^* \rightarrow A' \quad e^- \Rightarrow e^- + e^- , \mu^+ + \mu^- , \pi^+ + \pi^- , ...$

$A_\mu \rightarrow A_\mu + \epsilon a_\mu$

$e \times \epsilon \Rightarrow e^+ e^- , \mu^+ \mu^- , \pi^+ \pi^- , ...$
Putting this in perspective

Venn Diagram
“DM Candidate Landscape”

We are here

T. Tait from arXiv:1401.6085v1 [hep-ex]
Putting this in perspective

Jaeckel and Ringwald ('10) *Ann.Rev. of Nuclear and Particle Science, 60(1), 405–437*

Maurik Holtrop
LEPP, April 5, 2016
“Natural*” Coupling and Mass

Mass inherited from “electro-weak” scale

\[ m_{A'}^2 \sim \epsilon M_W^2 \]

or

\[ m_{A'}^2 \sim \frac{egD}{16\pi^2} M_W^2 \]

Stückelberg mechanism:

\[ m_{A'} \sim \text{meV} \]

Leading to: \[ M_{A'} \sim \text{MeV} - \text{GeV} \]

Natural \( \epsilon \) could be \( \sim 1 \) (tree level)

or \( 1 < \epsilon < 10^{-8} \) (loops)

or “anything” ...

Neil Weiner, Intensity Frontier WS ’11

See: R. Essig et al, Intensity Frontier WS ’11 summary paper.
Search area of choice

\[ \frac{\alpha'}{\alpha} \]

\[ M_{A'} \text{ (GeV/c}^2) \]

\[ \log_{10} m_{\gamma'} \text{ (eV)} \]
A lot of interest!

Since 2010, a lot of interest in this field.

Exclusion areas in 2010

At the time of the HPS proposal, exclusion areas were mostly due to beam dump searches.
A lot of interest!

Since 2010, a lot of interest in this field.

Exclusion areas in 2015

Lots of places to look:
- Flavor Factories
- Rare Meson Decays
- Fixed target experiments
- Precision Measurements
- Beam dump experiments
Fixed Target Searches

Bump Hunt:
Look for signal over background.

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

\[ \sigma_{\text{B-H}} \text{ very large } \gg \sigma_{\text{Rad.}} \]
But kinematically distinct \( \rightarrow \)
Use clever trigger to separate.

Very high luminosities:
Intensity Frontier Physics.

\( \sigma_{\text{B-H}} \) very large \( \gg \) \( \sigma_{\text{Rad.}} \).
But kinematically distinct \( \rightarrow \)
Use clever trigger to separate.

Bethe-Heitler \quad \text{Radiative}

\begin{align*}
E(e-) \ [\text{GeV}] & \quad E(e+) \ [\text{GeV}] \\
0 & \quad 0 \\
0 & \quad 1 \\
1 & \quad 2 \\
2 & \quad 3 \\
3 & \quad 4 \\
4 & \quad 5 \\
5 & \quad 6 \\
6 & \quad 7 \\
7 & \quad 7
\end{align*}

Black: BH
Red: Rad.
\[ \gamma c \tau \approx 1 \text{ mm} \left( \frac{\gamma}{10} \right) \left( 10^{-8} \frac{\alpha}{\alpha'} \right) \left( \frac{100 \text{ MeV}}{m_{A'}} \right) \]

**A´ lifetime**

- Lower \( \alpha' \), lower mass \( \rightarrow \) longer lifetime
- Background is all prompt \( \rightarrow \) Lower coupling can be reached using vertexing.

![Graph showing \( \alpha'^2/\alpha \) vs. \( m_{A'} \) (GeV)](image-url)

- \( a_{\mu \pm 5\sigma} \)
- \( a_{\mu \pm 2\text{ favored}} \) KLOE
- BaBar
- E141
- E774
- Orsay
- U70

\( \gamma \) ct = 3.5 mm, 14 mm, 35 mm

Prompt
Detecting $A'$ decays

\[ E = m_A \left( \frac{E}{E} \right)^{3/2} \] (narrow)

\[ \sim \left( \frac{m_A}{E} \right)^{1/2} \] (wide)

$e^-$

Energy = $E$

$A'$

$\sim \frac{m_A}{E}$

$e^-$

$E_{e^-} \approx m_{A'}$

$e^-$

$e^+$

Nucleus

Need:

- Small angle detection of $e^+ e^-$
- Very high luminosity
- Good invariant mass resolution

$E_{A'} \approx E_{\text{beam}}$

$\theta_{A'} \approx 0$

$\theta_{\text{decay}} = \frac{m_{A'}}{E_{A'}}$
The HPS Experiment
Downstream: HPS and tunnel

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.
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
Detecting scattering angles down to 15 mrad means the edge of the layer 1 tracker is only 0.5 mm from the beam.
The Engineering Runs ’15 & ’16

HPS is making use of “opportunistic” running in 2015 & 2016, while the CLAS12 detector is being build in Hall-B.

Spring 2015: Beam time during nights and weekends.
Beam: 1.05 GeV @ 50 nA on 4 µm W target
Data rate: 20 kHz, 150 MB/sec

Spring 2016: Beam time during weekends only
Beam: 2.3 GeV @ 200 nA on 4 µm W target
Data rate: 25 kHz (up to 50 kHz), 200 MB/sec

• These are challenging running conditions, with a lot of time spend on beam tuning each startup.
• Excellent support from accelerator division made physics quality data possible.
• Both runs had interruptions due to issues with accelerator (CHL)
• Both runs received extensions from lab management.
The Engineering Runs ’15 & ’16

Timeline:

• February 2015: HPS fully installed.
• March- April: Commissioned Hall B beam line 1 GeV
• mid-April: CEBAF down (CHL crash)
• late April: Commissioned Trigger and SVT DAQ
• late April: Explore SVT backgrounds
  • Move SVT closer to beam
• May 1-12: Production running, 1 GeV at 1.5 mm
• May 12-18: Production running, 1 GeV at 0.5 mm
• February 2016: Commissioned Hall B beam line 2.3 GeV
• March 2016: CEBAF down (CHL problem)
• April 2016: Production running …

Layer 1 silicon sensors are just 0.5 mm above and below beam. Min opening angle is $\theta_y = 15$ mrad.
Beam Quality

HPS requires a very high quality beam, with very low halo.
\[ \sigma_X \sim 300 \text{ to } 500 \ \mu\text{m} \ - \text{To spread heat load.} \]
\[ \sigma_Y \sim 15 \ - 50 \ \mu\text{m} \ - \text{To help vertexing & tracking.} \]

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.

Maurik Holtrop
LEPP, April 5, 2016
2015: 1.05 GeV Run, Charge on target.

Proposal: 1 full week of 50 nA beam on target, 30mC
Achieved: ~10 mC with SVT at 1.5mm, 10 mC at 0.5 mm
2016: 2.3 GeV Run, Charge on target.

Running 200 nA, 2.3 GeV on target
Still opportunistic running, weekends only.
CHL work stopped run from March 8 until April 1.
Run is still happening! Extended until end of April 2016.

Oppportunistic running only Weekends

SVT @ 0.5 mm
Online data quality

Total: 3.7E+05 Hz
ECAL FADC SCALERS
Total: 372.2 kHz

SVT Number of layers hit

Occupancy rates agree with MC calculations
ECal Calibrations

- Ecal provides fast trigger for experiment
- At 1 GeV beam, Ecal and SVT energy resolution comparable

Raw ADC Spectra

Cluster Energy (GeV)

Ecal timing can reduce accidentals!

Cosmic ray muon passing vertically through 10 crystals in the Ecal

σ = 476 ps

Plots from Holly Szumila-Vance

LEPP, April 5, 2016
ECal Resolution

Further calibration reduces
Timing resolution ~ 340 ps

Full energy electrons
used for calibration:
Energy resolution ~ 4%

σ_E/E = 4.1%

Plots from Holly Szumila-Vance
Tracker Performance

Tracker has good timing and momentum resolution.

Very good vertex resolution for small angle tracks!

Plots from Sho Uemura

σ_{p/p} \sim 6.7\%
Good vertex resolution is critical for the experiment. Excellent agreement between Monte-Carlo & Data. Normalized to 7 PAC days luminosity (5420 nb$^{-1}$) ⇒ results (reach) agree with original HPS proposal.

Plots from Sho Uemura
Tracked Pairs

A’ candidates have \( P_{e^+} + P_{e^-} \approx P_{\text{beam}} \)

A’ selection cut at \(|P_{e^+} + P_{e^-}| = 0.8 P_{\text{beam}}\)

\[ P_{\text{beam}} = 1.05 \text{ GeV} \]

Positron vs. Electron momentum

\[ P_{\text{beam}} = 2.3 \text{ GeV} \]

Positron vs. Electron momentum

Simulation (for 6GeV)
Selected Tracked Pairs

$A'$ candidates have $P_{e^+} + P_{e^-} \approx P_{\text{beam}}$

$A'$ selection cut at $|P_{e^+} + P_{e^-}| = 0.8 P_{\text{beam}}$

$P_{\text{beam}} = 1.05 \text{ GeV}$

$P_{\text{beam}} = 2.3 \text{ GeV}$
Pairs Mass Distribution

Data blinding policy: only 10% of data made available.
This plot is a small fraction of unblinded data, tiny fraction of all data.
Very preliminary look!
To do: better calibrations, study cuts, more data, …

1.05 GeV beam

2.3 GeV beam

Maurik Holtrop
LEPP, April 5, 2016
Reach vs Runtime

For 1 GeV beam

Assumes coverage to 15 mrad

Contours:
1 PAC week
5/7 PAC week
3/7 PAC week

We got about 1/3 PAC week of good data at 0.5 mm

1 GeV beam vertex reach.

Measurement assured, but no new territory
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
The HPS experiment has successfully completed its first physics data with 1.05 GeV beam, during the 2015 “Engineering Run”.

- Roughly 1/3 “PAC week” of data was gathered for 1.05 GeV with the SVT at 0.5 mm from the beam. Enough data for several PhD theses.

Current “Engineering Run 2” (2016) taking data at 2.3 GeV

- Initial look at the data looks very promising.

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

- We hope to take a lot more data in the next few years.
Some Extras
HPS SVT Design

L4-6 (stationary)
L1-3 (movable)
DAQ front-end boards
outer box w/ support ring
signal flange
SVT, target movers
power flange
L1-3 support channel w/ motion lever
SVT, target movers
DAQ front-end boards
outer box w/ support ring

Maurik Holtrop
LEPP, April 5, 2016

Slide from Per Hansson
SVT sensors

D0 RunIIb upgrade sensors
- High readout granularity
- Acceptable radiation tolerance (-10C, 1kV)
- Available and inexpensive (FNAL)

FR4 hybrid housing ASIC and services
- Five APV25 ASIC
- Sensor bias voltage filtering
- Temperature monitoring and high density connector

<table>
<thead>
<tr>
<th>Sensor Technology</th>
<th>&lt;100&gt;, p-in-n, polysilicon bias</th>
</tr>
</thead>
<tbody>
<tr>
<td># channels</td>
<td>639</td>
</tr>
<tr>
<td>Active area (mm²)</td>
<td>98.33x38.34</td>
</tr>
<tr>
<td>Readout (sense) pitch</td>
<td>60(30)µm</td>
</tr>
<tr>
<td>Thickness</td>
<td>320µm</td>
</tr>
<tr>
<td>Breakdown voltage</td>
<td>&gt;350 V</td>
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</table>

I-V (bias) curves
SVT sensors

Excellent fit for HPS requirements (CMS dev.)
- Low noise (S/N>25)
- Fast front-end (35ns shaping time) w/ overlapping trigger and readout
- Analog output with flexible readout modes
- Robust and proven (used in CMS tracker)
- Readily available; 15CHF/chip

Multi-peak mode: sample pulse shape 6 times (41MSPS)

Hit time resolution

2.2ns hit time resolution

Preliminary

<table>
<thead>
<tr>
<th>Technology</th>
<th>0.25μm</th>
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<tbody>
<tr>
<td># channels</td>
<td>128</td>
</tr>
<tr>
<td>Input pitch [μm]</td>
<td>44</td>
</tr>
<tr>
<td>Noise [ENC e⁻]</td>
<td>270+36×C(pF)</td>
</tr>
<tr>
<td>Power consumption</td>
<td>350mW</td>
</tr>
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</table>
Tracker layout

**Acceptance limitations**
- Small $m_A$: limited by dead zone
- High $m_A$: magnet bore size
- L4-6 double sensors wide

**Mass and vertex resolution**
- Layer 1-3: vertexing
- Layer 4-6: pattern recognition w/ adequate pointing to Layer 1-3
- Bend plane hit resolution of same order as multiple scattering

<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 [cm]</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>Stereo angle [mrad]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Bend plane res. [µm]</td>
<td>≈70</td>
<td>≈70</td>
<td>≈70</td>
<td>≈130</td>
<td>≈130</td>
<td>≈130</td>
</tr>
<tr>
<td>Stereo res. [µm]</td>
<td>≈6</td>
<td>≈6</td>
<td>≈6</td>
<td>≈6</td>
<td>≈6</td>
<td>≈6</td>
</tr>
<tr>
<td>Dead Zone [mm]</td>
<td>±1.5</td>
<td>±3.0</td>
<td>±4.5</td>
<td>±7.5</td>
<td>±10.5</td>
<td>±10.5</td>
</tr>
</tbody>
</table>

**Momentum**

36 sensors/hybrids 180 APV25 ASICs 23,040 channels
Electromagnetic Calorimeter

Features:
- 442 PbWO₄ scintillating crystals
- Large Area Avalanche Photo Diodes (APD) for readout
- Light Monitoring System (LED)

Upgraded from 5x5 mm² to 10x10 mm²

Photon beam hole

Electron beam hole

Top view of HPS ECAL crystals

Single PbWO₄ crystal

Crystal face dimensions: 1.3x1.3 cm²

Slide from Holly Szumila-Vance
Mass resolution vs. Mass

Invariant mass for Möller scattering.
Hints from astrophysics?

PAMELA, FERMI, AMS
Energetic e+/e- cosmic rays from DM annihilation through $A'$?

10-100 MeV $A'$ could explain muon g-2 anomaly

Arkani-Hamed, Finkbeiner, Slatyer, Weiner. ’09 PRD 79, 015014
Pospelov and Ritz ’09 PLB, 671, 391–397
Cholis, Finkbeiner, Goodenough, Weiner ’09 JCAP 0912 (2009) 007

More recent hints?

Excess of $\gamma$-rays from the galactic center is compatible with 50 GeV DM annihilating through a dark photon ("light mediator")

Caveat: Astro-physics is complicated! (and theorists are creative)

10.1103/PhysRevLett.114.211303 (May 2015)