HPS and the Search for Dark Forces

Tim Nelson - SLAC
HE Seminar - UC Davis
December 3, 2013
Outline

• **The case for dark forces and dark photons**
  • Fundamental physics motivation
  • *Dark matter motivation*
  • Astrophysical anomalies
  • *Precision anomalies*

• The HPS experiment

• 2012 Test Run

• 2014-2015 Run and beyond
Beyond the Standard Model

We know there is dark matter

... but what is it?
Why Should Dark Matter be Simple?

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

Gauge and Lorentz invariance restrict possible interactions
Portals

Standard Model \rightarrow \text{"portal"} \rightarrow \text{Dark Sector}

Scalar (Higgs): $h^+ h$ \times \boldsymbol{a} \phi \text{ non-standard Higgs decays}

Vector (photon): $F_{\mu\nu}$ \times \boldsymbol{F}^\mu_\nu \text{ dark sector gains EM interactions}

Neutrino: $\bar{L}H$ \times \boldsymbol{N} \text{ not-so-sterile neutrinos}
Two U(1)'s and $\epsilon$ Charge Shifts

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Received 24 October 1985

If new particles are gauged by a new U(1) then their electromagnetic charges may shift.

$M_{A'} = 0$ results in $q_\chi = \epsilon e$

Quarks & charged leptons have $\epsilon \cdot e$ coupling to $A'$

$M_{A'} > 0$
The Grand Parameter Space!

The Low-Energy Frontier of Particle Physics

Figure 4: Summary of cosmological and astrophysical constraints for hidden photinos (kinetic mixing $\chi$ vs. mass $m_{\gamma'}$) (compilation from Ref. [35]). See text for details. In addition we also show laboratory limits (see Sect. 4 for details on the constraints in the sub-eV regions; at higher mass we have electroweak precision measurements (EW), bounds from upsilon decays ($\Upsilon_3S$) and fixed target experiments (EXXX)). Areas that are especially interesting are marked in light orange.

The effective number of extra thermal neutrino species, $N_{\text{eff}}\nu, x = \frac{4}{7} \left( \frac{\rho_x}{T^4} \right)$, during BBN, usually expressed as the effective number of extra thermal neutrino species, $N_{\text{eff}}\nu, x = \frac{4}{7} \left( \frac{\rho_x}{T^4} \right)$. (22)

Recent determinations of this number [42] result in $N_{\text{eff}}\nu, x = -0.6^{+0.9}_{-0.8}$, (23) for three standard neutrinos. Therefore, while an extra neutral spin-zero particle thermalized during BBN is allowed, this is not the case for other WISPs like a mini-charged particle, for which $N_{\text{eff}}\nu, \text{MCP} \geq 1$, (24) or a massive hidden photon, with $N_{\text{eff}}\nu, \gamma' = \frac{21}{16}$. (25)

$\log_{10} \epsilon$

$\log_{10} m_{A'} (\text{eV})$

[Diagram showing parameter space with various constraints and regions labeled such as Jupiter, Earth, CMB, Coulomb, Rydberg, Solar Lifetime, LSW, Firas-MCB, CAST, $\alpha_{e,\mu}$, $\Upsilon(3S)$, EW, E774, E141, E137, 1987a, Unified DM, Hidden Photino DM, luke DM].
Natural Coupling Strength?

Simplest model:

\[ \psi \gamma^* A' \]

generates \( \epsilon \sim 10^{-2} - 10^{-4} \)

Model with GUT-breaking:

\[ \psi \gamma^* A' \]

generates \( \epsilon \sim 10^{-3} - 10^{-5} \)

\( \rightarrow 10^{-7} \) if both U(1) are in unified groups.
Mass Term?

Possible origin: related to $m_Z$ by small parameter.

\[ m_{A'} \sim \sqrt{\epsilon} \ m_Z \approx \text{MeV} - \text{GeV} \]
Motivated Territory (SM decays)

**FIG. 1:** Existing constraints on heavy photons ($A'$). Shown are existing 90% confidence level limits from the beam dump experiments E141, E774, Orsay, and U70 [29–32, 35, 37, 38], the muon anomalous magnetic moment $a_\mu$ [39], KLOE [40], the test run results reported by APEX [12] and MAMI [13], an updated estimate using a BaBar result [35, 41, 42], and an updated constraint from the electron anomalous magnetic moment [33, 34]. In the green band, the $A'$ can explain the observed discrepancy between the calculated and measured muon anomalous magnetic moment [39] at 90% confidence level.

**2.1.1 Heavy Photons and Dark Matter**

The possible role of heavy photons in the physics of dark matter [1, 2] has provided an urgent impetus to search directly for heavy photons. Results from two classes of dark matter searches — “indirect” searches for galactic dark matter annihilation and “direct” searches for dark matter scattering on nuclei — have both been interpreted as potential signals of dark matter interacting through a heavy photon. Both areas have developed considerably in recent years, but not decisively. Here we briefly summarize the status of dark matter, the case for its interactions with heavy photons, and pertinent recent developments in both.

Unexplored
Dark Matter Motivation

These dark photons are important in models with light DM!

\[ \sigma_{SI} = 8 \times 10^{-45} \text{ cm}^2 \left( \frac{c_{h\chi X}}{0.1} \right)^2 \]

Cheung, Hall, Pinner, Ruderman 2013

cm²

non-SM force carriers welcome down here too!
A’ Explains Astrophysical Anomalies

No proton excess: expected if $M_{A'} < 2M_p$
A’ Explains Precision Anomalies

A’ modifies anomalous magnetic moment of electron and muon!

FIG. 5. Feynman graphs for (a) the electron anomalous magnetic moment, (b) the interaction of the electron with quarks.
Outline

• The case for dark forces
• The HPS experiment
  • Direct searches for dark photons
  • Heavy Photon Search experimental concept
  • Technical challenges and solutions
• 2012 Test Run
• 2014-2015 Run and beyond
Direct Searches for Dark Photons

**colliders**

\[ \sigma \sim \frac{\alpha^2 e^2}{E^2} \sim O(10 \text{ fb}) \]

- \( e^- \)
- \( e^+ \)
- \( \gamma \)
- \( A' \)
- \( \mu^+ \)
- \( \mu^- \)

**fixed target**

\[ \sigma \sim \frac{\alpha^3 Z^2 e^2}{m^2} \sim O(10 \text{ pb}) \]

- \( e^+ \)
- \( e^- \)
- \( A' \)
- \( \text{Nucleus} \)

**BaBar**

These experiments have significant backgrounds!
Direct Searches for Dark Photons

beam dumps

\[ \gamma \epsilon T \propto \left( \frac{10^{-4}}{\epsilon} \right)^2 \left( \frac{100 \text{ MeV}}{m_{A'}} \right)^2 \]

These experiments have very low backgrounds.
FIG. 5: Expected mass vs coupling parameter space reach full 2014-2015 running (solid red). Red line contour corresponds to 1 week of beam time at 1.1 GeV, and 3 weeks of beam time at 2.2 GeV and 6.6 GeV.

Spatial resolution. The expected parameter reach in the first phase of the HPS is shown in Figure 5. The reach in mass-coupling parameter space is calculated using the simulated detector response as shown in Section 6. The plot shows two distinct regions, one at larger coupling corresponding to a purely bump-hunt region and another at lower coupling where the vertex of the $A_0$ decay is displaced.

increase acceptance

measure
decay length

Better Fixed Target Experiments?
Heavy Photon Search (HPS)

- determine invariant mass of $A'$ decay products (estimate momentum vectors)
- distinguish $A'$ decay vertexes as non-prompt (extrapolate tracks to their origins)

Tracking and vertexing system immediately downstream from target and inside an analyzing magnet provides both measurements with high acceptance from a single, relatively compact detector.
Physics Backgrounds

- Virtual photon tridents: irreducible
- Bethe-Heitler tridents: dominant

![Diagrams of Feynman diagrams for virtual photon and Bethe-Heitler tridents]

![Graph showing background vs. signal kinematics with cuts and acceptances marked]

- Positron, $P = E_0/2$
- $A'\gamma^*$
- Nucleus $A$
- Electron $e^-$
- Positron $e^+$

The following procedure is performed:

1. Calculation of the background kinematics
2. Choice of kinematic cuts
3. Final events at high momenta

Additional cross checks at specific energies provide confidence in the reliability of an interpolation.
Beam Backgrounds Dominate Occupancy

Mitigating this background requires

- high currents, thin targets to minimize scattering
- operation in vacuum to eliminate secondaries
- DC beam to spread out background in time
- fast ECal to trigger on coincident $e^\pm$ pairs at high rate in short window
- fast tracker with sufficient time resolution to tag hits in trigger window

\[ E_A \sim E - m_A \]
\[ E_e \sim m_A \]
High-current DC Electron Beam

CEBAF at JLab

- Simultaneous beam to multiple halls with 2 ns bunch separation

- $I_{beam} < 100 \, \mu\text{A} \, (A\&C)$, $<500 \, n\text{A} \, (B)$ ($1 \, \text{bunch} \sim 10000 \, e^-$)

- $E_{beam} = n \times 1.1 \, \text{GeV}, n \leq 5 \, (5.5 \, \text{GeV Max})$ until Spring 2012

- energy upgrade complete 2014: $E_{beam} = n \times 2.2 \, \text{GeV}, n \leq 5 \, (11 \, \text{GeV Max})$
Fast ECal and Trigger

PbW04 crystals with APD readout are fast, radiation tolerant (in hand at JLab)

250 MHz Flash ADC readout allows precise, high-rate trigger (under development at JLab)

250 MHz Flash ADC readout allows precise, high-rate trigger (under development at JLab)
SVT Sensor Selection

*Low-mass acceptance requires sensors very close to beam...*

At 15 mrad, 10 cm from target (L1):

- Active detector 1.5 mm from beam
- Peak occupancy \(\sim 4 \text{ MHz/mm}^2\) (>LHC pixels)
- Fluence \(4.8 \times 10^{15} \text{ e}^- \approx 1.6 \times 10^{14} \text{ 1 MeV neq. in 6 months of running} \)

Also need...

- < 1% \(X_0\) per layer (MCS limited)
- \(\approx 50 \mu m\) single-hit resolution in both measurement coordinates
- < $1M for a complete system, soon!

MAPS? (rate) Hybrid-pixels? (mass)

\(\rightarrow\) Strip sensors (edges 500 \(\mu m\) from beam!)
Silicon Microstrip Sensors

**Production Tevatron Run IIb sensors (HPK):**

- Fine readout granularity
- Most capable of 1000V bias: fully depleted for 6 month run.
- Available in sufficient quantities
- Cheapest technology (contribution from FNAL)

<table>
<thead>
<tr>
<th>Technology</th>
<th>&lt;100&gt;, p+ in n, AC-coupled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Area (L×W)</td>
<td>98.33 mm × 38.34mm</td>
</tr>
<tr>
<td>Readout (Sense) Pitch</td>
<td>60μm (30μm)</td>
</tr>
<tr>
<td>Breakdown Voltage</td>
<td>&gt;350V</td>
</tr>
<tr>
<td>Interstrip Capacitance</td>
<td>&lt;1.2 pF/cm</td>
</tr>
<tr>
<td>Defective Channels</td>
<td>&lt;0.1%</td>
</tr>
</tbody>
</table>

![Graph showing leakage current vs bias voltage]
Front-end Electronics: APV25

Developed for CMS
- available (28 CHF/ea.)
- radiation tolerant
- fast front end (35 ns shaping time)
- low noise (S/N ≈ 25)
- “multi-peak” readout
- ~2 ns $t_0$ resolution!

<table>
<thead>
<tr>
<th># Readout Channels</th>
<th>128</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Pitch</td>
<td>44 μm</td>
</tr>
<tr>
<td>Shaping Time</td>
<td>50ns nom. (35ns min.)</td>
</tr>
<tr>
<td>Noise Performance</td>
<td>$270+36\times C(pF)\ e^{-ENC}$</td>
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<tr>
<td>Power Consumption</td>
<td>345 mW</td>
</tr>
</tbody>
</table>
Outline

• The case for dark forces
• The HPS experiment
  • 2012 Test Run
    • The HPS test apparatus
    • Commissioning and operations
    • Results and lessons learned
  • 2014-2015 Run and beyond
HPS Test

Proposed 3/11, Installed 4/12

- Develop technical solutions
- Prove operational principles
- Capable of A′ physics (stretch goal)
**HPS Test ECal**

- Pair of modules (upper and lower) with 221 crystals each around vacuum chamber
- Crystals/APDs from CLAS Inner Calorimeter
- New motherboards route APD power/signals
- New JLab VXS FADC250 for CLAS12
- No time for light monitoring system.

**JLab VXS FADC250**

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### Input range vs Nominal charge resolution

<table>
<thead>
<tr>
<th>Input Range (V)</th>
<th>Nominal charge resolution (fC per ADC count)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5</td>
<td>9.76</td>
</tr>
<tr>
<td>-1.0</td>
<td>19.53</td>
</tr>
<tr>
<td>-2.0</td>
<td>39.06</td>
</tr>
</tbody>
</table>

**TABLE III: Nominal FADC charge resolution for different front-end input ranges.**
HPS Test SVT

<table>
<thead>
<tr>
<th></th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 4</th>
<th>Layer 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>z position, from target (cm)</strong></td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td><strong>Stereo Angle (mrad)</strong></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td><strong>Bend Plane Resolution (μm)</strong></td>
<td>≈ 60</td>
<td>≈ 60</td>
<td>≈ 60</td>
<td>≈ 120</td>
<td>≈ 120</td>
</tr>
<tr>
<td><strong>Non-Bend Resolution (μm)</strong></td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
</tr>
<tr>
<td><strong># Bend Plane Sensors</strong></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong># Stereo Sensors</strong></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>Dead Zone (mm)</strong></td>
<td>±1.5</td>
<td>±3.0</td>
<td>±4.5</td>
<td>±7.5</td>
<td>±10.5</td>
</tr>
<tr>
<td><strong>Power Consumption (W)</strong></td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

Linear shifts for tracker/target motion

Wire scanner

Target

Motion levers

Support plates

Hinged “C” support

Vertexing

Pattern Recognition

Momentum

60 cm
Test SVT

Half Modules (20):

Thin CF frame + FR4 hybrid + sensor

Full module:

Half-modules held back-to-back on Al cooling block w/ Cu tubes

⇒ 0.7% $X_0$ average per 3d measurement

- 28/30 half-modules pass QA with good noise, linearity, uniformity, time resolution
- Assembly precision at cooling block: $x$-$y$ ~10 μm, $z$ ~ 25 μm
- Silicon cooling and flatness compromised by design

Gain Curve

Calibration Delay Scan
Test SVT DAQ

**SLAC RCE DAQ**

- High performance ATCA-based platform based on set of “Reconfigurable Cluster Elements”
- Adopted for LCLS, LSST, ATLAS upgrades, LBNE(?) ...
- Custom Rear Transition Module (RTM) for HPS

**CAEN power supplies**

- Inherited from CDF SVXII
- Infamously fussy when new. Now very crufty.

![Diagram of SVT DAQ system](image-url)
Installation, Commissioning, Operation

- Final assembly to first tracks in <1 month
- No vacuum or cooling problems for SVT
- All chips working in SVT
- Ran parasitically with photon beam on conversion target
- Scheduled experiments in Hall B precluded running with electrons.

5/19/12 - End of CEBAF 6 GeV running
Test Run ECal Results

- Old APDs have poorly matched gains
- Motherboard issues cause a high rate of noisy channels (87% good)
- FADC250 and TDAQ performed as expected up to 100 kHz

Trigger Turn-on

![Trigger Turn-on Graph]

E/p (not corrected for sampling fraction)

![E/p Graph]

Test ECal APD Gains

![Test ECal APD Gains Graph]
ECal Requirements Status

- Acceptance
  - >15 mr from beam axis

- Hit efficiency and resolution
  - >99% good channels
  - $\sigma(E)/E \approx 4.5%/\sqrt{E}$ (GeV) energy resolution
  - 4 ns trigger window

- Occupancy / speed
  - trigger rate up to 50 kHz
  - peak occupancy $\approx 1$ MHz / channel

- Radiation
  - Scattered beam electrons
  - Neutrons from backscattered beam

<table>
<thead>
<tr>
<th>Met and verified</th>
<th>Met, not verified</th>
<th>Not met by design</th>
<th>Not met</th>
</tr>
</thead>
</table>

34
Test SVT Hit Occupancy and Efficiency

- Reflections on 4m analog readout cables: added FIR filter to DAQ firmware.
- DAQ timing issues effect a small number of chips intermittently.

With noisy channels masked, occupancy is as expected... and efficiency for finding hits on tracks is >99%.
Test SVT Amplitude and Time Reconstruction

Cluster Charge Reconstruction

\[ S/N = 24 \]

Hit Time Reconstruction

\[ \sigma_{t_0} \approx 2.5 \text{ ns} \]
SVT Requirements Status

- Material budget
  - 0 material along beamline (detector in vacuum)
  - 0.7% $X_0$ / 3d measurement in tracking volume
- Acceptance
  - >15 mr from beam axis
- Hit efficiency and resolution
  - >99% single-hit efficiency
  - position: $\sigma_x < 125 \mu m$, $\sigma_y < 10 \mu m$ (performance limited by multiple scattering / beam size)
  - time: $\sigma_{t0} \approx 2$ ns
- Occupancy / speed
  - trigger rate up to 50 kHz (Need to add support for APV25 burst trigger mode to get >20 kHz)
  - peak occupancy $\approx 4$ MHz/mm$^2$
- Radiation
  - Bulk damage from electrons equivalent to $> 1 \times 10^{14}$ 1 MeV neq. (Need improved cooling design)
  - Neutrons from backscattered beam
  - X-rays from target

Met and verified
Met, not verified
Not met by design
Not met
Outline

• The case for dark forces
• The HPS experiment
• 2012 Test Run
• 2014-2015 Run and beyond
  • HPS design overview
  • Run plan and physics reach
  • Future upgrades
  • Beyond HPS
HPS for 2014-2015

CEBAF comes back late 2014. HPS will be first experiment ready in Hall B.

• Same beamline, magnet chicane, vacuum chamber
• upgrade SVT, ECal, DAQ, some beamline elements
• reserve space for muon detector
ECal Upgrades

Completely new motherboard design

- based on extensive experience at IPN-Orsay and INFN-Genova
- simplified design with fewer layers, shorter traces, lower trace density

Replace S8644 0.5x0.5 cm$^2$ APD (CMS) with new HPK LAAPD S8664-1010 1.0x1.0 cm$^2$

- 10% gain-matched
- 4x more light
- Better S/N w/ new IPN-Orsay preamps

Light monitoring system

- RAPID 56-0352 blue/red LED
- Monitoring for both radiation damage and APD response

Goal: $\frac{\sigma_E}{E} \approx 2%/\sqrt{E}$ (GeV)
HPS SVT Layout

**Evolution of HPS Test SVT**

- Layers 1-3: same as HPS Test SVT
- Layers 4-6: double width to match ECal acceptance and add extra hit.
- 36 sensors & hybrids
- 180 APV25 chips
- 23004 channels
New SVT Modules

Reuse half-modules from HPS Test for L1-3 with improved module supports: tension CF between cooled uprights.

- 80% smaller $\Delta T$ to hot spot in silicon
- Flattens sensor

Extend concept to new double-ended L4-L6 modules: same material budget.

- similar CF frame, kapton passivation
- more compact hybrid design
SVT Support, Cooling and Services

Cooled support channels for L1-L3
- reuse motion system
- lighter, stiffer, shorter = negligible sag
- cuts radiative heat load on sensors

Cooled support channels for L4-L6 are stationary

DAQ/power inside chamber on cooling plate
- Low-neutron region (upstream, e^+ side)
- Reduces readout plant

Reuse vacuum box and linear shifts with new vacuum flanges
New chiller operable to -20°C with 1°C stability.
SVT DAQ

- In-vacuum ADC, voltage generation and power distribution/control on Front End Boards
- Penetration for digital signals via high-density PCB through flange. Optical conversion on outside of flange.
- Firmware support for APV25 burst trigger mode (50 kHz trigger rate for 6 samples)
- Much more flexible timing adjustability
- Wiener MPOD power supplies
Schedule and Run Plan

“keep alive” funding until about 1 month ago...

**SVT**
- Currently ramping production, within ~2 weeks of schedule.
- Tight schedule for shipping in 8/14

**ECal**
- With addition of APD replacement, also tight.
- Critical new effort from IPNO&INFN.

Not clear that CEBAF/Hall B will be ready for us.

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### HPS Construction
- Mar.13
- FY13
- FY14

### Data Runs
- Oct.’14
- FY15
- 1 week commissioning
- 1 week @ 2.2 GeV
- 2 weeks @ 6.6 GeV

### Analysis
- May.’15
- FY16
- 2016-?
- Detector capable of ~6 months running

### Early Physics Opportunity
- Sep.’16
- 2014 Running
  - 1 week commissioning
  - 1 week @ 2.2 GeV
  - 1 week @ 1.1 GeV
- 2015 Running
  - 1 week commissioning
  - 2 weeks @ 2.2 GeV
  - 2 weeks @ 6.6 GeV
Physics Reach

Large signal, **HUGE** background

![Graph showing large signal with huge background](image)

Small signal, **NO** background

![Graph showing small signal with no background](image)

**vertexing**

40M bkg events (50-100MeV)

30k A' at 80MeV $\alpha \sim 3 \times 10^{-7}$

4M bkg events (50-100MeV)

500 A' at 80MeV $\alpha \sim 5 \times 10^{-8}$

**vertexing**

2014

2015

2014+2015

3 mo. each @ 2.2, 6.6

m$_{A'}$ (GeV)
Beyond HPS

**Extending high-coupling reach:**
- 2-3 orders of magnitude more data: more time won’t work
  - More luminosity × acceptance

**Double-arm HPS downstream of existing dipole?**
- A high-rate, high acceptance version of APEX
- Capable of ~200× luminosity.
- Dead zone reduced to 5 mr: better low mass acceptance than HPS (but no vertexing) with modest loss at high mass

![Diagram showing mass vs coupling parameter space with expected reach for full 2014-2015 running (solid red). Red line contour corresponds to 1 week of beam time at 1.1 GeV, and 3 weeks of beam time at 2.2 GeV and 6.6 GeV.](image)
Double-arm HPS Reach

Can eliminate annoying gap with technologies already in hand.

Pion detection and low-Z targets will be important at higher masses!
Extending Low-coupling Reach

**HPS downstream of 30 cm tungsten dump**

*Radiation Limitation:*
- Large flux of forward-going fast neutrons
- At 10 $\mu$A, SVT survives $\sim$1 month

*Power Limitation:*
- Dump absorbs entire beam power: 66 kW @ 10 $\mu$A, 6.6 GeV.
- Cooling for dump will be difficult

*Hit/track occupancies are manageable:*
- Average $\sim$4 $\pi^+/\pi^-/\mu^+$ in each half of SVT per 8 ns window. Rate of $e^\pm$ negligible
- ECal dominated by low-energy $\gamma$ from $\pi^0$
- After coincidence trigger and vertexing, zero background is possible

**$E_{\text{beam}} = 6.6$ GeV**
HPS Dump Reach

**Significant improvement over previous dump experiments:**

- Extends low-coupling reach to new mass regime
- Intersects region most interesting for low-mass WIMP candidates.
What if $M_{\chi} < M_{A'}$?

Constraints from:

$(g - 2)_e$  $(g - 2)_\mu$

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

BaBar

$A' \to DM + DM$

Make a dark matter beam!!

$P \to \pi^0 \to \gamma A' \to DM + DM$

$e^- \to \gamma A' \to DM + DM$

$A' \to invisible (m_\chi = 10 \text{ MeV})$

$\alpha = 0.1$ for LSND, JLab, ILC, MiniBooNE
Summary and Conclusions

• It is reasonable to expect force carriers in the dark sector. A dark photon with MeV-GeV mass and effective coupling to the SM photon $10^{-2} \lesssim \epsilon \lesssim 10^{-5}$ sits at the intersection of a number of theoretical and experimental motivations.

• A large fraction of the interesting parameter space is unconstrained and the race is on to explore the terrain with a number of experimental techniques.

• The HPS experiment can explore a significant fraction of this parameter space, including a challenging region at small couplings where HPS has unique reach.

• The HPS Test run established the feasibility of this experiment, which is in construction now for running in late 2014 and 2015.

• These searches are in their infancy, and new ideas and techniques will be required to cover the entire region of interest. In particular, the possibility of invisible decays to dark matter particles requires new and largely orthogonal experiments.
Heavy Photon Search Experiment at Jefferson Laboratory: proposal for 2014-2015 run


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(Dated: May 10, 2013)
Backup Slides
Astrophysical Explanation?

Fitting Fermi data with nearby pulsars

Upper limits on dipole anisotropy

![Graphs showing Fermi data fitting and dipole anisotropy limits]

arXiv:1008.5119

Requires ~30% of total emitted energy in these e+e- pairs: \(O(10-100) \times\) expectation!!
Indirect Searches

- Expect gammas (Fermi, Cherenkov Telescopes...)
- Possibly neutrinos (IceCube, Super-K...)

Searches underway, nothing conclusive yet.
CMB Effects

Recent direct detection experiments such as CDMS, CoGeNT, CRESST, and DAMA, have also reported results that are not consistent with the current dark matter models. The third column is an updated version of Table I in [3], and the fourth column includes systematic uncertainties.

<table>
<thead>
<tr>
<th>Channel</th>
<th>DM Mass (GeV)</th>
<th>Current Efficiency</th>
<th>Signal Efficiency</th>
<th>Systematic</th>
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</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>1</td>
<td>0.85</td>
<td>0.45</td>
<td></td>
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<tr>
<td>Muons</td>
<td>1</td>
<td>0.30</td>
<td>0.21</td>
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<tr>
<td>Z bosons</td>
<td>2</td>
<td>0.24</td>
<td>0.18</td>
<td></td>
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<tr>
<td>W bosons</td>
<td>2</td>
<td>0.24</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>Higgs bosons</td>
<td>200 0.24 0.18</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>b quarks</td>
<td>200</td>
<td>0.31</td>
<td>0.23</td>
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<tr>
<td>XDM muons</td>
<td>10</td>
<td>0.29</td>
<td>0.23</td>
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</tr>
<tr>
<td>XDM pions</td>
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<td>0.24</td>
<td>0.19</td>
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</tr>
<tr>
<td>XDM taus</td>
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<td>0.19</td>
<td>0.15</td>
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</tr>
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<tr>
<td>XDM electrons</td>
<td>1000 0.23 0.18</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Madhavacheril, NS, Slatyer 2013, (1310.3815)
Direct Searches: Tevatron/LHC

Lightest SUSY particle ("LSP") not stable, and can decay to $A'$ + hidden sector

some searches at Tevatron completed (no signal)

others planned

"lepton jet"

Arkani-Hamed, Weiner
Bumgart, Cheung, Ruderman, Wang, Yavin

D-zero, arXiv: 1008.3356
Excellent beam quality, stability

Beam Tail $\sim 10^{-6}$

10 $\mu$m spot possible with additional quads: constrains $A'$ trajectory, reducing background
Why Vacuum?

δ-ray background in 25 ns

<table>
<thead>
<tr>
<th></th>
<th>Air</th>
<th>4.7 δ-rays/ cm</th>
<th>He</th>
<th>0.7 δ-rays/ cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td></td>
<td></td>
<td></td>
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<td>2)</td>
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<td>3)</td>
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</table>

15 cm
Trigger: Pions?

Pion rates lower than initially thought: a pion trigger may be manageable.

Add more shallow planes to improve pion trigger/ID?
Trigger Selection

<table>
<thead>
<tr>
<th>Trigger Cut.</th>
<th>75 MeV/c² A' Acceptance</th>
<th>Background Acceptance</th>
<th>Background rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events with least two opposite clusters</td>
<td>49.4%</td>
<td>3.55%</td>
<td>4.4 MHz</td>
</tr>
<tr>
<td>Cluster energy &gt; 100MeV and &lt; 1.85 GeV</td>
<td>70.8%</td>
<td>2.43%</td>
<td>3.0 MHz</td>
</tr>
<tr>
<td>Energy sum &lt;= E_{beam} * sampling fraction</td>
<td>66.4%</td>
<td>1.15%</td>
<td>1.4 MHz</td>
</tr>
<tr>
<td>Energy difference &lt; 1.5 GeV</td>
<td>66.3%</td>
<td>0.95%</td>
<td>1.2 MHz</td>
</tr>
<tr>
<td>Lower energy - distance slope cut</td>
<td>57.8%</td>
<td>0.11%</td>
<td>138 kHz</td>
</tr>
<tr>
<td>Clusters coplanar to 35°</td>
<td>57.2%</td>
<td>0.051%</td>
<td>63 kHz</td>
</tr>
<tr>
<td>Eliminate crystals -5,-4,-3,-2,1,2</td>
<td>52.0%</td>
<td>0.020%</td>
<td>25 kHz</td>
</tr>
<tr>
<td>Not counting double triggers</td>
<td>38.3%</td>
<td>0.018%</td>
<td>22.5 kHz</td>
</tr>
</tbody>
</table>

- Simple 3×3 clustering with 50 MeV seed threshold
- Total trigger budget estimated at 50 kHz
Tracking Efficiency/Purity

~99% tracks have 12/12 hits assigned correctly
Mis-assigned hits mostly in high-occupancy view of 90-degree stereo layers.

after selections $E_{\text{beam}} = 2.2$ GeV

full simulation
Mass Resolution

Angular resolution at vertex dominates error: limited by multiple scattering

significant improvement from constraining track to vertex
For purposes of this proposal, we make the following cuts:

Fortunately there are a number of quantities we can use to minimize the tails. Namely, the tail is primarily comprised of events where one or both of the tracks use one or more bad pairs (solid black histogram, Fig. 69) shows a long tail, still significant beyond 5 cm. This target.

Even for prompt decays, the z vertex position (Vz) distribution of all reconstructed hits and triangles with one or more.

For each electron/positron pair reconstructed in the tracker, we compute the invariant mass of the pair and is shown in Fig. 67. The closed circles in Fig. 67 shows the mass based on the fitted momenta of the tracks. The mass resolution depends on the impact parameter.

Decay Length

Impact Parameter

FIG. 66: The resolution of the position of closest approach to the beam axis versus track momentum

FIG. 68: The Gaussian resolution dependence versus decay length.
Prompt Vertex Rejection and Experimental Reach

need $\sim 10^{-7}$ rejection for sensitivity to small signals!

$E_{\text{beam}} = 2.2$ GeV

30M events!
Reach Estimates

“bump hunt”

\[
\frac{d\sigma(e^-Z\rightarrow e^-Z (A'\rightarrow e^+e^-))}{d\sigma(e^-Z\rightarrow e^-Z (\gamma^*\rightarrow e^+e^-))} = \left( \frac{3\pi\varepsilon^2}{2N_{\text{eff}}\alpha} \right) \left( \frac{m_{A'}}{\delta m_{A'}} \right)
\]

\[
\left( \frac{S}{\sqrt{B}} \right)_{\text{bin}} = \left( \frac{N_{\text{radiative}}}{N_{\text{total}}} \right) \sqrt{N_{\text{bin}}} \left( \frac{3\pi\varepsilon^2}{2N_{\text{eff}}\alpha} \right) \left( \frac{m_{A'}}{\delta m_{A'}} \right) \varepsilon_{\text{bin}}
\]

“bump hunt” + vertexing

\[
\left( \frac{S}{\sqrt{B}} \right)_{\text{bin, zcut}} = \left( \frac{S}{\sqrt{B}} \right)_{\text{bin}} \frac{\varepsilon_{\text{sigeff(zcut)}}}{\sqrt{\varepsilon_{\text{rejection(zcut)}}}}
\]

\[
\varepsilon_{\text{sigeff(zcut)}} \approx \varepsilon_{\text{vtx}} \times \left( e^{-\left( z_{\text{cut}} \frac{1}{\gamma c \tau} \right)} - e^{-\left( \frac{z_{\text{max}}}{\gamma c \tau} \right)} \right)
\]

\[E_{\text{beam}} = 2.2 & 6.6 \text{ GeV Statistics}\]

solid = BH

dashed = radiative

**E_{\text{beam}} = 2.2 \text{ GeV}**

\[Z_{\text{cut}} \quad \gamma c \tau \text{ for } \varepsilon = 10^{-4}\]

\[z_{\text{max}} = 20 \text{ cm}\]

**E_{\text{beam}} = 6.6 \text{ GeV}**

\[Z_{\text{cut}} \quad \gamma c \tau \text{ for } \varepsilon = 10^{-4}\]
Test SVT Mechanics

Cooling blocks mount on Al support plates with hinged “C-support” and motion lever

- Provide solid mounting for modules, routing for services, and simple motion for tracker
- PEEK pedestals create 15 mr dead zone, provide some thermal isolation
- Support plates + motion levers ~1.5 m long: sag dominates x-y imprecision (300 μm)
- Load on C-support introduces small roll in top plate.

Works, but can be improved upon
Test SVT Services

• Borrowed CDF SVXII power supplies (very crufty) and JLab chiller (limited to > 0°C)
• Intricate welded cooling manifolds with 2 compression fittings/module
• 600 wires into vacuum chamber for power and data (3600 total pairs of connector contacts): recovered three sensors with internal connectivity problems after assembly/installation at JLab

We got away with this, but it doesn’t scale well to a larger detector.
Layer 4-6 Half-Module Concept

Similar to L1-L3 design, but...

- ends of CF/Si supported by hybrid
- bias supply on Kapton passivation layer
- Silver epoxy between Cu pad on CF and thermal vias provides ground

- simplifies assembly process
- separates heat path for silicon from APV heat loads
- easier wirebonding geometry and better support under bonds