Searching for Hidden Sectors via the Vector Portal

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SLAC
SLAC Experimental Seminar
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The goals of this talk are three-fold

• Convince you (again? even more?) that searches for hidden sectors are interesting & worthwhile (and not crazy at all)
• Update you on heavy photon & beam-based neutrino groups’ activities
  • HPS (& APEX), LBNE, microBoone
• Attempt to convince you that there are some interesting physics links between the two programs
• Discuss some (possible) future directions

Much of the material comes from Snowmass & followups

• This topic was mostly discussed in the NLWCP subgroup
  • NLWCP=New Light, Weakly Coupled Particles
New Physics on the Side

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{HS}} + \mathcal{L}_{\text{portal}} \]
Portals to a hidden sector

\[ \mathcal{L}_{\text{portal}} \]

Higgs portal \[ \epsilon_h |h|^2 |S|^2 \] rare higgs decays

neutrino portal \[ \epsilon_\nu (hL)\psi \] “sterile neutrino”

vector portal \[ \epsilon_Y F^Y_{\mu\nu} F'_{\mu\nu} \] massive “photon”

axion portal \[ \frac{1}{f_a} a_h F_{\mu\nu} \tilde{F}^{\mu\nu} \] axion-like particle
Experimental hidden sector probes

\[ \mathcal{L}_{\text{portal}} \]

Higgs portal \[ \epsilon_h |h|^2 |S|^2 \rightarrow \text{higgs factory} \]

neutrino portal \[ \epsilon_\nu (hL) \psi \rightarrow \nu \text{ oscillations/very rare meson decays} \]

vector portal \[ \epsilon_Y F_Y^Y F'_{\mu\nu} \rightarrow \text{everywhere (almost)} \]

axion portal \[ \frac{1}{f_a} a_h F_{\mu\nu} \tilde{F}^{\mu\nu} \rightarrow \text{axion searches} \]
Hidden Sector ⇒ Dark Matter?

link between SM and hidden sector is weak...good place for DM to hide!

WIMP miracle ⇒ wiMP miracle

My favorite Venn diagram from Snowmass

Here we are

Theories of Dark Matter

T. Tait
an old idea: if there is an additional $U(1)$ symmetry in nature, there will be mixing between the photon and the new gauge boson

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

• extremely general conclusion...even arises from broken symmetries
• gives coupling of normal charged matter to the new “heavy photon” $q=\epsilon e$
Why the vector portal is special

...from somebody’s slide at the NLWC closeout session....
“Natural” coupling and mass

Depending on model, mass scales like:
\[ \frac{M(A')}{M(W)} \sim \varepsilon^1 - \varepsilon^{1/2} \]
leading to
\[ M(A') \sim \text{MeV-GeV} \]

N. Weiner, JLAB PAC37 Talk
The coupling-mass sweet spot

Both “naturalness” arguments and hints from experiments block out the same region in mass-coupling space:

\[ \epsilon \sim 10^{-2} - 10^{-5} \]

\[ m(A') \sim \text{MeV} - \text{GeV} \]

Most of this region is unexplored!
Some existing constraints ($A' \rightarrow \text{visible}$)

Lots of places to look for the $A'$

old beam dumps ($EXXX$)
flavor factories ($BaBar/Belle/KLOE$)
rare meson decays ($WASA, Phenix$)
fixed target expts. ($APEX/MAMI$)
precision measurements ($g-2$)

......
A' decay length

lower $\varepsilon$, lower mass $\rightarrow$ longer lifetime

Much of parameter space will have displaced vertex
Collider vs. Fixed Target

Wherever there is a photon there is a dark photon...

Collider

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

\[ O \ ab^{-1} \ per \ decade \]

Fixed Target

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

\[ O \ ab^{-1} \ per \ day \]

...much higher backgrounds
**A' production & decay**

**Production** is analogous to bremsstrahlung:

\[
\frac{d\sigma}{dx} \approx \frac{8Z^2\alpha^3\varepsilon^2x}{m_{A'}^2} \left(1 + \frac{x^2}{2(1-x)}\right)
\]

- prefers \(x \sim 1\) (i.e. \(E_{A'} = E_{\text{beam}}\))
- small angle emission dominates

A' **decays** back to charged SM fermions with BFIs taken from \(R(e^+e^-\rightarrow\text{hadrons}/e^+e^-\rightarrow\mu^+\mu^-)\)

The decay length depends on \(m_{A'}\) and \(\varepsilon\):

\[
\ell_0 \equiv \gamma c \tau \approx \frac{3E_1}{N_{\text{eff}}m_{A'}^2\alpha\varepsilon^2} \\
\approx \frac{0.8\text{cm}}{N_{\text{eff}}} \left(\frac{E_0}{10\text{GeV}}\right) \left(\frac{10^{-4}}{\varepsilon}\right)^2 \left(\frac{100\text{ MeV}}{m_{A'}}\right)^2
\]

HPS is sensitive to A's with decays \(\sim 5-100\text{mm}\)

assumes \(A'\) can't decay to hidden sector particles
Backgrounds @ fixed target

Two physics backgrounds, collectively known as “tridents”

BH and Radiative cross-sections calculated by MadGraph at NNLO

- BH cross section is huge, but dominated by $E(e^+)+E(e^-) \ll E_{\text{beam}}$
  - this background is reducible, but still large (~2x radiative) after $E(e^+)+E(e^-) > 0.8E_{\text{beam}}$
- Radiative tridents have the same kinematics as $A'$ decays...only invariant mass & decay vertex can resolve these two
- All trident events decay promptly!
Broad-brush Responsibilities
SLAC: SVT(daq), Sim&Reco
JLAB: Beam, Trigger, DAQ
Orsay&INFN: ECAL
HPS will sit in an alcove in *JLAB Hall-B* …behind CLASS, in front of beam dump

- energy: *1.1-11.1 GeV*
- current: up to ~700nA
- roughly CW…*2ns* bunch spacing
- can focus beamspot ~ *300µm × 40µm*

To CLASS

**PbW ECAL** for trigger

Fe/Sci muon system…future upgrade?

Analyzing magnet, W Target & SVT (in vacuum)
The CLASS toroid magnets are late…this gives us an opportunity between CEBAF beam turn-on (Fall 2014) and when CLASS is ready to take date.


- proposed a commissioning run @ 1.1, 2.2GeV (2 weeks beam time) followed by a data run @ 2.2, 6.6 GeV (4 weeks)

Our goal is to get installed ~Sept 2014 and “be ready” to take data. CLASS toroid installation will take precedence (to put it lightly)...nights & weekends through 2015 (and nights may be tricky).
SVT is the key ingredient! Needs to measure momenta & vertex pairs with extreme purity in a busy environment. **Require low material & very fast.**

**Si μstrip sensors**
- Rad hard, thin (320μ), 60μ/30μ readout/sense pitch & $$$=Free (from RunIIb)

**APV25 readout chip**
- S/N>25 & ~2ns timing resolution

<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>
<th>Layer 6</th>
</tr>
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<tbody>
<tr>
<td>z position, from target (cm)</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>70</td>
<td>90</td>
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<tr>
<td>Stereo Angle (mrad)</td>
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<td>100</td>
<td>50</td>
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<tr>
<td>Bend Plane Resolution (μm)</td>
<td>≈ 60</td>
<td>≈ 60</td>
<td>≈ 60</td>
<td>≈ 120</td>
<td>≈ 120</td>
<td>≈ 120</td>
</tr>
<tr>
<td>Non-bend Resolution (μm)</td>
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<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
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<tr>
<td># Bend Plane Sensors</td>
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<td>2</td>
<td>2</td>
<td>4</td>
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<td>4</td>
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<tr>
<td># Stereo Sensors</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</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>±13.5</td>
</tr>
</tbody>
</table>

Layer 1 strip occupancy / 8 ns trigger window

occupancy = 1%

1.00% X₀
0.50% X₀
0.25% X₀
0.125% X₀
0.05% X₀

**“non-bend plane”**

36 sensors total; 23004 channels
Heavy photon signatures: bump hunt

Pure bump hunt in $m(e^+e^-)$
$\rightarrow$ large coupling region
$(\alpha > 10^{-7})$

mass resolution is the key...

toy MC for example only... does not reflect reality
**HPS momentum/angular resolution**

\[
M = 2p_e + p_e^- (1 - \cos \theta)
\]

\[
\left( \frac{\Delta M}{M} \right)^2 \sim \left( \frac{\Delta p}{p} \right)^2 + \left( \frac{\Delta \theta}{\theta} \right)^2
\]

- momentum resolution → material throughout whole tracker & $\hat{J} L \times B$
- angular resolution → material in first few layers

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

\[
\sigma(p)/p \sim 4.5\%
\]

$\sigma(\theta_{\text{bend}}) \sim 2\text{-}6\text{mrad}$

$\sigma(\theta_{\text{nonbend}}) \sim 0.5\text{-}3\text{mrad}$
Mass Resolution: Bump-Hunt vs Vertexing

- two types of searches → two kinematic fits → two mass resolutions
- Large coupling A's decay in the target → constrain the e⁺ & e⁻ to originate from beamspot
  - very good constraint on angles
- Small coupling A's decay outside of target → point decay products back to target
  - good at removing poorly reconstructed tracks

40µm (vertical)

Small coupling search

Large coupling search

\[ \sigma_{m,(NC)} \sim 2-3 \text{ MeV} \]
\[ \sigma_{m,(BSC)} \sim 0.7-2.7 \text{ MeV} \]

not included yet…recoil electron!
⇒ adds mass resolution/BH discrimination
Heavy photon signatures: displaced vertex

- 4000 bkg events (50-100MeV)
- 50 A’ at 80MeV $\alpha \approx 5 \times 10^{-8}$

Toy MC for example only... does not reflect reality

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

2D search in mass & vertex position (z) $\rightarrow$ small coupling region ($\alpha \approx 10^{-8} - 10^{-10}$)

good mass and (more importantly) vertex resolution are the keys here
HPS Vertex Resolution

Huge prompt trident background ⇒ cut on the extreme tails of the vertex Δz distribution.

Need the tracks to be extremely pure:
• dark green: “reasonable” cuts ... e.g. track chi$^2$, vertex chi$^2$ etc
• dark red: >0 hits not matched to the true $e^+$ or $e^-$; “mishits”
• light green: all pairs after isolation cut
• light red: mishits after isolation cut

...after isolation cut: >99.9% track purity

L1 hit isolation

prompt tridents $M(e^+e^-)=80$ MeV @ 2.2 GeV

“optimized” vertex cut

SLAC Experimental Seminar
We built a test detector & installed May 2012…
…unfortunately, parasitic to another experiment using photon beam

…still, able to take data, find tracks and even pairs.
Got some useful data (all in the last 8 hours before JLAB shut down).

NIM article in progress
SVT Test Run Performance

SVT worked reasonably well…
• S/N ~ 21-25
• timing resolution ~ 2.5ns
• hit efficiency > 98%
• similarly high tracking efficiency

Δt for hits on a track

σ_t=2.5ns
Beam scattering model

HPS Si is very close to beam...L1 guard ring is 500µm from beam center. How well do we know what the occupancy will be? GEANT and EGS give different answers!

During our 8 hours, ran the photon beam through different converter thicknesses...compare with MC. EGS is correct! Good news...lower occupancy.
**Expected HPS (’15-’16) Reach**

**Commissioning Run (dashed):**
- 1 week with 50nA @ 1.1 GeV
- 1 week with 200nA @ 2.2 GeV

**Production Run (solid):**
- 2 weeks with 200nA @ 2.2 GeV
- 2 weeks with 450nA @ 6.6 GeV

**Shaded green:**
- 3 months with 200nA @ 2.2 GeV
- 3 months with 450nA @ 6.6 GeV

*time given is beam time=floor time/2*
The Competition/Compliments

Lots of dedicated experiments planned, however…

**HPS searches a region no other experiment can!**
• true muonium: $\mu^+\mu^-$ bound state
• same signature as an $A'$ at di-muon mass
• expect 10-20 accepted events (after vertex cut → no background)

• strongly coupled dark sector could give rise to events with many leptons in final state
• high multiplicity events with many mass peaks
• similar signature if dark higgs is ~ nearby

• according to Pospelov et al., MeV-scale force carrier could explain muonic Hydrogen anomaly...could also induce polarization-dependent muon-trident rate
Filling the space…

**Diagram Description:**
- The diagram plots the ratio $\alpha'/\alpha$ versus $m_{A'}$ (GeV) on a logarithmic scale.
- Key data points and experiments:
  - $a_{\mu,5\sigma}$
  - $a_{\mu,\pm2\sigma}$ favored
  - KLOE
  - APEX/MAMI Test Runs
  - BaBar
  - Orsay
  - Mont's Gap
  - Mount Rho
  - Beam-Dump Valley

**Experiments and Collaborations:**
- **BaBar:**
- **Full:**
- **Mont's Gap:**
- **Mount Rho:**
- **Beam-Dump Valley:**
Pushing HPS to the limit

![Graph showing various experimental data and theoretical curves, with labels for different experiments and observations like BaBar, KLOE, and light versus heavy mass resolution. The graph is labeled with $a' / \alpha$ on the y-axis and $m_{A'} (\text{GeV})$ on the x-axis.]
Something simple…

\[ \int \mathcal{L} \times 24 \Rightarrow \]

- 2 weeks \( \times 6 \)
- (beam current \( \times \) thickness) \( \times 4 \)

...or some other combo.

Improve vertex resolution (i.e., tail rejection) by \( \times 2 \Rightarrow \)

Move target from 10 cm to 5 cm

This is an exercise, not a run plan.
Tim’s crazy idea #1: $HPS^2$

Tim’s exercise for Snowmass: come up with crazy ideas.
- dual-armed spectrometer, copy of HPS for each “arm”
- forget about vertexing, open up dead region
- blast a thick-ish target
Tim’s exercise for Snowmass: come up with crazy ideas.

- HPS with a mini-beam dump
  - minimal dead zone.
  - Require vertexing outside of dump ⇒ 0 background
- blast the dump… fair bit of power to take away. Still a lot of radiation on SVT…

These are good ideas for after HPS!
SLAC has an Accelerator-Based Neutrino Group (ABNG)
- M. Convery, D. Muller, JJ Russell, T. Usher, L. Rochester, MG

We are members of LBNE & microBoone
- LBNE: 35t physics (MC) & DAQ (MG & RED)
- µBoone: sim & reco (TU, LR, DM)
- Joined LBNE first; µBoone chosen for near term physics opportunities and to get into the LAr TPC game

Why am I bringing this up?
- µBoone → short-baseline experiment investigating sterile neutrino anomalies
  - sterile neutrino could be sign of a hidden sector (neutrino mixing with a fermionic singlet)
  - these same experiments can be used to detect hidden sector dark matter
Another scenario…

⇒ **BUT**, if there is a state, $\chi$, with dark charge and is lighter than $2m(A')$

$\chi = \text{light, hidden sector dark matter}$

...unless $g_D \ll \varepsilon$, $A'$ decays to dark sector will dominate
Light dark matter from proton beam dumps

...at low energies (8 GeV=FNAL Booster)

\[ \pi, K, \eta, \text{etc} \]

...at high energies (120 GeV=FNAL Main Injector)

\[ \pi^0, \eta \]

There are a few proton beams running in the world now...
primarily for neutrino osc:
FNAL Booster & NuMI
JPARC
...SNS too.
Detection of light dark matter (from beams)

- M~10s MeV
- E~GeV

- ~10s-100s MeV

**nuclear recoils**

- coherent—low mA', low E\text{recoil}, Z^2 enhanced
- quasi-elastic—mid mA', mid E\text{recoil}
- DIS—high energies (both $\chi$ and recoil)

...QE has received most attention

**electron recoils**

- low mA', low E\text{recoil}, low background

These are the sorts of signals neutrino detectors are designed to see. *Very convenient!*
Dark matter @ neutrino beams

⇒ target/horn/decay pipe optimized to produce neutrino beam

BUT! neutrino NC events are ~irreducible background

⇒ lots of mesons produced, but most of them are captured or are stopped

Greatly reduced neutrino background
The off-target miniBoone proposal

miniBoone proposal to run in “off-target mode” … not quite ideal beam dump, but better than neutrino mode!

miniBoone with beam off target

\[
\frac{\text{Rate (events/POT)}_{\nu \text{ mode}}}{\text{Rate (events/POT)}_{\text{beam off target mode}}} = 42 \pm 7.
\]

Additional \( \nu \) suppression by placing absorber upstream (25m) of usual dump (50m)…most of the neutrinos come from interactions with the air!

\[R. \text{ Van de Water et al.}\quad \text{arXiv/hep-ex 1211.2258}\]
**miniBoone off-target reach**

- $m_{A'} = 300$ MeV
- Note: constrain in parameter-space = $(\kappa = \varepsilon, \alpha_D, mA', m\chi)$

---

**Table:**

<table>
<thead>
<tr>
<th>Scattering Channel</th>
<th>Beam Mode (2.0 $\times 10^{20}$ POT)</th>
<th>WIMP mass (MeV)/cross section (cm²)</th>
<th>Signal</th>
<th>Background and Errors</th>
<th>Probability</th>
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<tbody>
<tr>
<td>1</td>
<td>Nucleon 25m</td>
<td>10/4 $\times 10^{-37}$</td>
<td>1859</td>
<td>350±66</td>
<td>$&lt; 10^{-10}$</td>
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<tr>
<td>2</td>
<td>Nucleon 25m</td>
<td>30/3 $\times 10^{-36}$</td>
<td>1453</td>
<td>350±66</td>
<td>$&lt; 10^{-10}$</td>
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<tr>
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<td>Nucleon 25m</td>
<td>50/8 $\times 10^{-36}$</td>
<td>1326</td>
<td>203±40</td>
<td>$&lt; 10^{-10}$</td>
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<tr>
<td>4</td>
<td>Nucleon 25m</td>
<td>100/3 $\times 10^{-35}$</td>
<td>1186</td>
<td>9.2±3.4</td>
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<td>13.2</td>
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<td>1.4</td>
<td>0.004</td>
<td>$&lt; 10^{-8}$</td>
</tr>
</tbody>
</table>
microBoone off-target reach

By the way, μBoone people thinking about this too (some are the same people as mBoone)…even though quite a bit smaller, can get decent reach.

Much more information in the LArTPC…may be able to reduce backgrounds significantly. Not included in these plots.
mBoone & μBoone off-target plans

- miniBoone request of a $0.35 \times 10^{20}$ POT off-target test run was approved by FNAL...this is happening NOW.
- they are proposing to PAC to run until μBoone is ready for beam, mid-late-next year. Hope for ~ $1 \times 10^{20}$ POT total
• better than proton beams ⇒ electron beams
• production mechanism more straightforward...not limited to meson production/decay at low energy
  • (hardly) no neutrinos produced
• high-current electron beams today: JLAB (11GeV), SLAC (FACET, 20GeV)!
• drawback/opportunity: no detectors on these dumps

Izaguirre, Krnjaic, Schuster, Toro
hep-ph/1307.6554
Building a detector

- according to IKST, beam related backgrounds are negligible (needs more study)…backgrounds come from cosmics. Particularly cosmogenic neutrons.
- pulsed beam: use beam gate…for 30Hz beam ~10 neutrons/year
- continuous beam: active/passive vetos, directionality?
- looking for ~low recoils…want large active volume
  - scintillator+PMT, LAr TPC, etc.
  - lower the threshold, the better
  - long & lean

10s mwe

\[ \chi \text{ beam} \]

\[ \sim 10 \text{ m (length}=\text{mass}) \]
Events from 1 year @ JLAB-type beam

- **e^- Beam**: $10^{22}$ electrons @ 12 GeV
- $E_{\text{recoil}} > 10\text{MeV}$ for QE-NR
- Detector = 1m x 1m miniBoone

The red contours are events, not reach...expect ~ 10k cosmogenic neutrons without any mitigation

**Izaguirre, Krnjaic, Schuster, Toro**
hep-ph/1307.6554
What’s SLACs role in this?

• …not much right now. It’s still early and we are focused on getting HPS built and running.
• mini-workshop/offshoot of the MENU conference this year dedicated to this topic (dark matter from electron beams) organized by HPS Italian collaborators.
• proposal to put CORMORINO detector behind HALL-B beam dump to test beam & cosmic backgrounds
  • HALL-B doesn’t work for this type of experiment long term…not enough current. Other halls have different problems.
• Stay Tuned!

M. Battaglieri
Summary & Sermon

- There are good theoretical arguments for the existence of a hidden sector...particularly one that talks to us via the vector portal.
- Dark matter...what is it? Don’t believe anyone who tells you they know the answer.
  - The answer is that it is a hidden sector particle.
- HPS is well on its way...next few years will be busy and exciting.
- To really explore vector portal, need to look for “invisible” decays as well...for low masses, this means beam dumps.
- This is good stuff! High impact, low cost...we need more of this in our field!