Tracking and Vertexing for the Heavy Photon Search Experiment

Tim Nelson - SLAC

on behalf of the HPS Collaboration

Vertex 2012 - Jeju, Korea - Sept. 20, 2012
Hidden Sector Vector Boson: $A'$

“Kinetic Mixing” generated by heavy particles interacting with $\gamma$ and $A'$ [Holdom - 1986]

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

\[ \Delta \mathcal{L} = \frac{\epsilon}{2} F_{Y,\mu \nu} F'_{\mu \nu} \]
What Makes It Interesting?

**A′ can be light!**

*What if dark matter annihilates/decays to A′?*

- Hidden Sector
- **DM** 
  - \( m_{DM} \sim \text{TeV} \)
- **A′** 
  - \( m_{A'} \sim \text{GeV} \)

...would explain observed \( e^+e^- \) excesses

- expected spectrum

see \( e^+e^- \) excess, but no similar excess in protons \( \Rightarrow m_{A'} < 2m_p \)

hypothesis is consistent with other DM anomalies and astrophysical data

---

[Essig Schuster, Toro]
Direct Searches

Collider vs. Fixed Target

Look for peak in $M(f^+f^-) = M_{A'}$

$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10 \text{ fb})$

$O \text{ ab}^{-1} \text{ per decade}$

e.g. BaBar

$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10 \text{ pb})$

$O \text{ ab}^{-1} \text{ per day}$

[Bjorken, Essig, Schuster, Toro]
[Batell, Pospelov, Ritz]
[Reece & Wang]
Existing Limits

Previous experiments:
- Beam dumps
- E141
- E137
- Dark/Light E774
- MESA
- VEPP3
- KLOE
- HPS
- HPS test
- APEX
- MAMI
- MAMI test

arXiv:1209.2558

New Proposals:
- A' decays in shield! (lifetime too small)

A' Decay Lengths

\[ \gamma \tau \propto \left( \frac{10^{-4}}{\epsilon} \right)^2 \left( \frac{100 \text{ MeV}}{m_{A'}} \right)^2 \]

At small couplings, A' is long-lived!

not enough luminosity! (cross-section too small)
Requires New Experiments

In simple models, expect:

- $\epsilon \sim 10^{-5} - 10^{-2}$
- $m_{A'} \sim \sqrt{\epsilon} M_W \sim \text{MeV} - \text{GeV}$
  for Higgs-like U(1)’ breaking.

Interesting region not easily explored!
Sensitivity in this region relies upon abilities to *precisely*...

- determine invariant mass of $A'$ decay products (estimate momentum vectors)
- distinguish $A'$ decay vertexes as non-prompt (extrapolate tracks to their origins)
Simultaneous delivery of electron beams at different energies and intensities in three experimental halls.

- $E_{\text{beam}} = n \times 1.1 \text{ GeV}, n \leq 5$ (5.5 GeV Max)
- $I_{\text{beam}} < 100 \mu\text{A (A&C),} < 800 \text{ nA (B)}$
- 2 ns bunch separation: short integration time reduces $\sim$DC backgrounds
- shutdown for upgrade 2012-2014: $E_{\text{beam}} = n \times 2.2 \text{ GeV}, n \leq 5$ (11 GeV max)

Ideal for this experiment.
HPS SVT Challenges

- At relevant beam energies and interesting $A'$ masses, decay products tend to be electrons with momenta of order 1 GeV. Multiple scattering...
  - dominates both mass and vertexing measurement errors
  - dense environment leads to pattern recognition mistakes in tracker
- Proximity to target means primary beam must pass through apparatus.
  - scattered beam sweeps out a “dead zone” of extreme occupancy and radiation, multiplied by curlers from beam-gas interactions
  - $A'$ acquires most of incoming $e^-$ energy: puts low-mass acceptance in opposition to longevity and tracking purity
- Long-lived $A'$ signal very small: vertexing must be exceedingly pure to eliminate fakes.
Challenges ⇒ Design Principles

- Mass and vertex resolution
  - low-mass construction

- Occupancies and radiation
  - fast, robust sensors, readout and trigger
  - operation in vacuum
  - movability / replaceability

- Acceptance/Purity
  - optimized sensor layout
Sensor Selection

- <1% $X_0$ per layer
- <20 $\mu m$ single-hit resolution in both measurement coordinates
- Occupancies up to 10 MHz / mm$^2$
- $1.6 \times 10^{14}$ neq in 6 months running
- $1M$ total for 0.5 m$^2$ system, today!
  - MAPS?
  - Hybrid pixels?
Sensor Selection

- < 1% $X_0$ per layer
- < 20 μm single-hit resolution in both measurement coordinates
- Occupancies up to 10 MHz / mm²
- $1.6 \times 10^{14}$ neq in 6 months running
- $1M$ total for 0.5 m² system, today!
  - MAPS?
  - Hybrid pixels?
  - **Strip sensors** (edges 500 μm from beam!)

Layer 1 “dead zone” <±1.5 mm (15 mrad) allows for 6 months running at acceptable occupancies

Silicon sees a lot of hits: $>10^{10}$/sec $\Rightarrow$ $>100$ GBytes / second = we need a trigger! (ECal, MuonDet)
Silicon Microstrips

*Production Tevatron RunIIb sensors (HPK):*

- Fine readout granularity
- Most capable of 1000V bias: fully depleted to $>4 \times 10^{15} \text{ e}^-/\text{cm}^2$
- Available in sufficient quantities
- *Cheapest technology (free!)*

<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>$&gt;350$V</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>
Readout Electronics: APV25

Developed for CMS

- available (28 CHF)
- radiation tolerant
- fast front end
- low noise: S/N > 25
- “multi-peak” readout
- ~2 ns $t_0$ resolution!

# Readout Channels | 128
---|---
Input Pitch | 44 µm
Shaping Time | 50ns nom. (35ns min.)
Noise Performance | $270+36\times C(pF)\; e^{-ENL}$
Power Consumption | 345 mW

Belle upgrade studies

Source: PSI 2005 beam test, run201, n-side, 51 µm
Low Mass Support/Cooling

- CF-composite/TPG/rohacell-foam
  - relatively conventional
  - $<1.0\% \text{X}_0/\text{layer}$
- $\text{H}_2\text{O}/\text{glycol}$ at $-10^\circ\text{C}$
  - outside tracking volume
  - vacuum minimizes heat load on sensors

![Diagram of sensor module]

- rail system for tracker removal
- piezo motors for retraction of tracker
- stereo pair
Sensor layout optimized with full, detailed simulation of SVT.

- **Layers 1-3**: vertexing
- **Layers 4-6**: pattern recognition with adequate pointing into Layer 3.
- **Bend plane measurement in all layers**: momentum
- **106** sensors & hybrids
- **530** APV25 chips
- **67840** channels

### Detector Layout Table

<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>
</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>
<td>90</td>
</tr>
<tr>
<td><strong>Stereo Angle</strong></td>
<td>90 deg.</td>
<td>90 deg.</td>
<td>90 deg.</td>
<td>50 mrad</td>
<td>50 mrad</td>
<td>50 mrad</td>
</tr>
<tr>
<td><strong>Bend Plane Resolution (μm)</strong></td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
</tr>
<tr>
<td><strong>Stereo Resolution (μm)</strong></td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 120</td>
<td>≈ 120</td>
<td>≈ 120</td>
</tr>
<tr>
<td><strong># Bend Plane Sensors</strong></td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>10</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td><strong># Stereo Sensors</strong></td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>10</td>
<td>14</td>
<td>18</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>
<td>±13.5</td>
</tr>
<tr>
<td><strong>Power Consumption (W)</strong></td>
<td>10.5</td>
<td>10.5</td>
<td>17.5</td>
<td>35</td>
<td>49</td>
<td>63</td>
</tr>
</tbody>
</table>
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 $E_{\text{beam}} = 6.6$ GeV
full simulation
Angular resolution at vertex dominates error: limited by multiple scattering.

Significant improvement from constraining track to vertex:

\[ \frac{\sigma_m}{m} \approx 1\% \]
Vertexing

Impact Parameter

\[ E_{\text{beam}} = 6.6 \text{ GeV} \]

\[ \sigma(\text{POCA}) \text{ (um)} \]

\[ \sigma(V^2) \text{ (m)} \]

Decay Length

\[ \sigma(V^2) \text{ (m)} \]

\[ m(A) \text{ (MeV/c^2)} \]
Prompt Vertex Rejection and Experimental Reach

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

full simulation
30M events!

E_{beam} = 6.6 \text{ GeV}

Reach for 6 Month Run

$\epsilon^2$

$0.01 \quad 0.1 \quad 1$

$10^{-4}$

$m_{A'} \text{ (GeV)}$

$10^{-10}$

$10^{-5}$

$10^{-8}$

$10^{-11}$

$10^{-14}$

$10^{-17}$

$10^{-20}$

E774

KLOE

E141

KTeV

BaBar

BELLE

HPS

APEX

HPS

$\alpha_e$

HPS

$\alpha_{\mu}$

HPS

$\sigma_e$

HPS

$\sigma_{\mu}$

HPS

$\sigma_e$

HPS

$\sigma_{\mu}$

HPS

$\sigma_e$

HPS

$\sigma_{\mu}$
“Can we build it? Will it work?”

- Jan. 2011 - HPS proposal, including proposal for “test run” approved by JLab PAC, “contingent upon successful test run.”
- June 2011 - DOE funds HPS Test
- May 2012 - CEBAF shuts down for work on 12 GeV upgrade.

- **<1 year:** build the smallest, simplest, and least expensive apparatus possible that...
  - establishes the feasibility of HPS
  - can deliver $A'$ physics with a short electron run (*N.B. $a_\mu$ compatible region!*)
HPS Test Detector

*HPS in miniature:*

- Existing 3-magnet chicane in Hall B with vacuum chamber!
- Just enough room for small SVT
- Add vacuum box for SVT services (SVT/target motion, cooling, cabling)
- PbWO$_4$ calorimeter for trigger
- Reconfiguration of existing CLAS inner calorimeter
- New 250 MHz FADC-based DAQ/trigger
Test SVT Layout

5 layers both above/below beam supported on Al plates

- **Layers 1-3:** vertexing
- **Layers 4-5:** improve pattern recognition with good pointing into L3.
- **Bend plane measurement in all layers:** momentum
- **20 sensors/hybrids**
- **100 APV25 chips**
- **12780 channels**

<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>z position, from target (cm)</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Stereo Angle</td>
<td>100 mrad</td>
<td>100 mrad</td>
<td>100 mrad</td>
<td>50 mrad</td>
<td>50 mrad</td>
</tr>
<tr>
<td>Bend Plane Resolution (μm)</td>
<td>≈ 60</td>
<td>≈ 60</td>
<td>≈ 60</td>
<td>≈ 120</td>
<td>≈ 120</td>
</tr>
<tr>
<td>Non-Bend Resolution (μm)</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
<td>≈ 6</td>
</tr>
<tr>
<td># Bend Plane Sensors</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td># Stereo Sensors</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</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>
</tr>
<tr>
<td>Power Consumption (W)</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>
Test SVT Modules

- **Half Module**
  - 0.17 mm thick CF frame (grounded, passivated)
  - FR4 APV25 hybrid
  - single sensor

  ► *Starting with chips for 30 hybrids, 28 half modules pass QA*

- **Full module**
  - ground Al cooling block
  - glue-less assembly with PEEK hardware

  ► *0.7% $X_0$ average per layer*
Test SVT DAQ and Power

- **SLAC-standard ATCA-based DAQ**
  - A single crate with two Cluster On Board cards (COB) and 10G switch
  - Rear Transition Modules (RTM) with 14-bit ADCs at 41.667 MHz accept data and ECal trigger signal.
  - COBs host FPGA-based data processing modules (DPM) and Trigger Interface (TI) module.
  - Capable of ~20 KHz (goal for full HPS is 50 kHz)
- **Power from CDF SVX/Layer00 CAEN supplies**
Test SVT Support, Cooling, Vacuum

**Al support plates:**
- Modules mounted on PEEK pedestals (thermal break)
- Hinged c-support at back mounted to Al baseplate
- Motion lever at front end connects to linear shifts on vacuum box
- Cable trays and cooling manifolds along edges of support plates

*Building a liquid cooled detector that moves in beam vacuum is a challenge!*
Installation and Commissioning

- From final assembly to first tracks in less than one month
- Scheduled experiments in Hall B precluded running with electrons :-(
  - Ran parasitically with photon beam: establishes performance and technical feasibility of SVT design :-) 
- 5/19/12 - End of CEBAF 6GeV running
What does our signal look like?

Signal amplitude is approx. 2400 ADC Counts or 16,000 electrons → This is lower than expected but may be due to wrong gain

Signal to Noise Ratio is approx. 20

Cluster Charge

intermittent DAQ synch issues with some chips.
Test SVT Alignment and Timing

- surveyed alignments good to ~50 μm
- beginning alignment with millipede
- single chip hit time resolution < 2.5 ns
- still determining $t_0$ offsets across full detector
Beginning comparisons with predictions of full simulation
Summary and Future

- HPS has unique capabilities in the search for dark forces.
- Test detector designed, built, commissioned in < 1 year.
- Many critical lessons learned in developing HPS Test will improve the experiment.
- Design appears technically feasible but not yet tested in e⁻ beam.
- When CEBAF beam returns in 2014, no competition for time in Hall B.
  - Too little time to propose, fund, design, develop, build Full HPS, so...
  - Plan to make minor modifications to HPS Test to run it again in 2014. 1 month run can deliver significant reach at modest cost.
- Meanwhile, continue to move forward with new elements and improvements for full HPS.
HPS Collaboration (20/60 on SVT)

HPS SVT Group (SVT, DAQ, Target, software)

M. Khandaker, C. Salgado
Norfolk State University, Norfolk, Virginia 23504

M. Battaglieri, R. De Vita
Istituto Nazionale di Fisica Nucleare, Sezione di Genova e Dipartimento di Fisica dell’Università, 16146 Genova, Italy

S. Bueltmann, L. Weinstein
Old Dominion University, Norfolk, Virginia 23529

G. Ron
Hebrew University of Jerusalem, Jerusalem, Israel

P. Stoler, A. Kubarovsky
Rensselaer Polytechnic Institute, Department of Physics, Troy, NY 12181

K. Griffioen
The College of William and Mary, Department of Physics, Williamsburg, VA 23185

(Dated: May 7, 2012)