The A' Experiment (APEX)
Searching for New Gauge Bosons in the A' Experiment at Jefferson Laboratory

Natalia Toro (Perimeter Institute)
for the APEX Collaboration

Outline

**In brief:** APEX is a spectrometer-based search, at JLab Hall A, for 50-500 MeV hidden-sector photons decaying **promptly** to $e^+e^-$. 

1) **The APEX experiment:**
   - general setup and rationale
   - a few important details
     JHEP 1102:009,2011, arxiv:1001.2557

2) **Test run (July 2010)**
   - results

3) **Full APEX**
   - extended target
   - SciFi optics calibration for better mass resolution
   - new septum

In brief: APEX is a spectrometer-based search, at JLab Hall A, for 50-500 MeV hidden-sector photons decaying **promptly** to $e^+e^-$. 

![Graph showing various data points and curves related to APEX, E774, KLOE, DarkLight, BaBar, APEX/MAMI Test Runs, HPS, Orsay, and U70.](image)
APEX Concept and Dark Photon Production

\[ E_{A'} \approx E_{\text{beam}} - m_{A'} \]

Energy = \( E \)

Electron, \( P = \frac{E_0}{2} \)

Positron, \( P = \frac{E_0}{2} \)
The High Resolution Spectrometers

Range  | Acceptance  | Resolution
-------|-------------|-------------
0.3<\(p<4.0\) GeV/c | -4.5%<\(\Delta p/p<4.5\)% | \(\delta p/p \leq 2 \times 10^{-4}\)
12.5°<\(\theta_0<150\)° | 6msr | \(\delta \phi=0.5\) mrad (H)

\(4.5\) msr at \(\theta_0=5\)° with septum

\(\delta \theta=1\) mrad (V)
**A’ Production and Background Kinematics (m_A’ ≪ E_{beam})**

### A’ Production

- **Diagram:**
  - A’ Production reaction: \( e^- + A' \rightarrow e^- + e^+ \)
  - Nucleus

- **Equation:**
  \[
  \sigma \sim \alpha'/m^2 = \varepsilon^2 \alpha/m^2
  \]

- **Graph:**
  - (rates before angular cuts)
  - A’ (\( \alpha'/\alpha = 3 \times 10^{-6} \))
  - QED Background/10^3

### QED Backgrounds

- **Graph:**
  - \( d\sigma \sim \alpha^2/m^3 \ dm \)

- **Distinctive kinematics:**
  - **A’ products carry (almost) full beam energy!**
  - Symmetric energy, angles in two arms optimize A’ acceptance
  \[
  E^+ \approx E^- \approx E_{beam}/2
  \]
- also suppresses \( e^- \) singles & other pair backgrounds

### After rejecting accidental \( e^-\pi^+ \) (demonstrated in test run), event rate dominated by QED backgrounds above
APEX test run

- Test run performed in Hall A, July 2010
  Many thanks to JLab & Hall A staff for tremendous support!

- Verified all key aspects of apparatus performance
  - VDC tracking performance at 4–6 MHz singles rates
  - Gas Cerenkov detector in coincidence trigger to reject $\pi^+$’s
  - Spectrometer optics & mass resolution
  - Measurement of physics backgrounds

- Resonance search on 700K good trident events

Data

Accidental

QED (no efficiency correction)
Full APEX run plan and sensitivity

1 Month Beam Time
- 6 days at 1, 2, 3 GeV
- 12 days at 4.5 GeV)

>100x test-run statistics

Approved by JLab PAC 37 with recommendation to run as soon as possible

Explores parameter space with unparalleled efficiency (particularly above ~300 MeV)
Mainz MAMI/A1 experiment
- superficially similar
  (spectrometer $e^+e^-$ coincidence)
- similar test-run sensitivity

but...
- hitting detector rate limits
  at least 6mo run needed to match APEX below 200 MeV
- Search above ~200 MeV also hitting beam current and radiation limits

Bottom line:
APEX has unique advantage due to high-rate capability and septum magnet (small angle $\Rightarrow$ higher signal acceptance)
APEX in Context

Mainz MAMI/A1 experiment
- superficially similar (spectrometer $e^+e^-$ coincidence)
- similar test-run sensitivity

but...
- hitting detector rate limits
  at least 6mo run needed to match APEX below 200 MeV
- Search above ~200 MeV also hitting beam current and radiation limits

Bottom line:
APEX has unique advantage due to high-rate capability and septum magnet (small angle $\Rightarrow$ higher signal acceptance)
APEX vs. Mainz

Detector, beam, and radiation limitations ⇒ Mainz probably can only access high-coupling & low-mass portion of APEX sensitivity (without major upgrades)

Dashed green is updated sensitivity estimate for ~14 total beam-days (9 settings) [1303.2540 Beranek, Merkel, Vanderhaeghen]

- no publishable result expected from 2012 run
- present dark-force plans focus on lower A' mass, including MESA
Readiness for Full Run

- **APEX extended target**
  - target built for test run is at JLab
- **SciFi detector for optics calibration**
  - design and production complete; first arm assembled and tested
- **Septum**
  - design nearly finalized & vendor quotes obtained
- **HRS detector maintenance** is proceeding
Target Design: Minimizing Multiple Scattering

Target designed and built by SLAC APEX group for the test run (but not installed), currently at JLab.

Goals:
• $\sigma(\theta)_{\text{mult scat}} \leq 0.5$ mrad
  $\Rightarrow$ typical $e^+e^-$ pair must only go through 0.3% $X_0$ (2-pass)
• Target thickness 0.7–8% $X_0$ (depending on $E_{\text{beam}}$)
• High-Z target (reduce $\pi$ yield for given QED rates)
• Stable under currents up to $\sim 100 \ \mu$A

long target $\Rightarrow$ wider single-run mass coverage
Target Design: Minimizing Multiple Scattering

Target designed and built by SLAC APEX group for the test run (but not installed), currently at JLab.
Magnetic Spectrometer Optics

Measuring Contributions to the Mass Resolution
(dominant: **angular resolution** + mult. scatter)
Removable sieve plate is inserted upstream of septum.

Use surveyed locations of sieve holes to calibrate magnetic optics.

Use reconstructed hole sizes to measure resolution.

...this method only works for negative polarity, and requires running at different beam energy.

Mass resolution $\approx 1$ MeV $\sim 0.5\%$
Removable sieve plate is inserted upstream of septum.

Use surveyed locations of sieve holes to calibrate magnetic optics.

Use reconstructed hole sizes to measure resolution.

...this method only works for negative polarity, and requires running at different beam energy.

Mass resolution $\approx 1 \text{ MeV} \sim 0.5\%$
HRS optics

“Active sieve slit”: tagging by a Sci Fiber detector

- 1 mm fibers with 1/16” pitch
- Projected rate: 1-3 MHz per fiber
- Off-line time window < 5 ns
- Nearing completion

Allows optics calibration at production beam energy & for both polarities
New HRS Septum Magnet

- Designed for parallel field capability (minimize fringe field near beamline)
- Optimized for full angular acceptance
- High density coils used to enable high-energy use
New HRS Septum Magnet

- Design to be completed in next few weeks
  - quotes obtained from vendors
  - partially funded by NSERC DAS
- New extension box (as for PREX) and vacuum connection to spectrometers needed
- Requires 2kA for high-energy settings (same as SBS magnet)
APEX has demonstrated feasibility and power of spectrometer searches for hidden-sector photons

Strong physics impact already from test run (most cited Hall A result in last 5 years)

APEX can explore important range of mass and coupling most efficiently and before other experiments

Opportunity for immediate science impact – even with commissioning-quality beam.
Thanks!
BACKUP SLIDES
Sieve Slit Method

Left HRS calibration used 35 holes, Right HRS calibration used 38 holes
HRS optics for APEX

Angle Deviation (milliradians)
# Angular Resolutions

## Averages weighted according to statistics

<table>
<thead>
<tr>
<th></th>
<th>LHRS (mrad)</th>
<th>RHRS (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optics calibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>precision</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta_\phi$</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>$\Delta_\theta$</td>
<td>0.24</td>
<td>0.20</td>
</tr>
<tr>
<td>Tracking precision</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\phi_width}$</td>
<td>0.26</td>
<td>0.43</td>
</tr>
<tr>
<td>$\sigma_{\theta_width}$</td>
<td>1.81</td>
<td>1.75</td>
</tr>
<tr>
<td>Final resolutions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_\phi$</td>
<td>0.29</td>
<td>0.44</td>
</tr>
<tr>
<td>$\sigma_\theta$</td>
<td>1.86</td>
<td>1.77</td>
</tr>
</tbody>
</table>

$\varphi/\theta$ – hor / vert angles

$\varphi$ - horizontal angles

$\theta$ - vertical angles
## Mass Resolution

Angular resolution averages (mrad) determined for different masses

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>180</th>
<th>195</th>
<th>210</th>
<th>225</th>
<th>240</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left theta (mrad)</td>
<td>1.95</td>
<td>1.87</td>
<td>1.89</td>
<td>1.93</td>
<td>1.88</td>
<td>1.86</td>
</tr>
<tr>
<td>Left phi (mrad)</td>
<td>0.26</td>
<td>0.3</td>
<td>0.32</td>
<td>0.33</td>
<td>0.33</td>
<td>0.29</td>
</tr>
<tr>
<td>Right theta (mrad)</td>
<td>1.69</td>
<td>1.74</td>
<td>1.81</td>
<td>1.85</td>
<td>1.85</td>
<td>1.77</td>
</tr>
<tr>
<td>Right phi (mrad)</td>
<td>0.38</td>
<td>0.43</td>
<td>0.46</td>
<td>0.5</td>
<td>0.53</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Mass resolutions (MeV) determined for different masses using 3 different methods

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>180</th>
<th>195</th>
<th>210</th>
<th>225</th>
<th>240</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using different angular resolutions for each event</td>
<td>0.833</td>
<td>0.965</td>
<td>1.026</td>
<td>1.061</td>
<td>1.037</td>
<td>1.005</td>
</tr>
<tr>
<td>Using angular resolutions listed in above table for all events</td>
<td>0.822</td>
<td>0.962</td>
<td>1.023</td>
<td>1.054</td>
<td>1.043</td>
<td></td>
</tr>
<tr>
<td>Using angular resolutions from &quot;Total&quot; column in above table for all events</td>
<td>0.869</td>
<td>0.965</td>
<td>0.995</td>
<td>0.994</td>
<td>0.966</td>
<td>0.977</td>
</tr>
</tbody>
</table>
Coincidence trigger and particle ID performance

**Trigger level timing of e⁺ e⁻ with 56 μA on Tantalum target**

10 ns timing gate containing coincident events

**Gas Cherenkov**

- Positron detection eff. 0.964
- Pion rejection eff. 0.979

**π sample from LG**

**e⁺ sample from LG**

**Calorimeter**

- f_{scin} = 765 kHz
- Electron detection eff. 0.967
- Pion rejection eff. 0.969
- Pion leakage 0.044
- Electron detection eff. 0.956
- Pion rejection eff. 0.981
- Pion leakage 0.027

**Sample from GC**

**e sample from GC**

Coincidence peak for two-arm X⁻e⁺ trigger (requires coincident GC signal in positive-polarity arm)