The Heavy Photon Search Experiment at Jefferson Lab

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on behalf of the HPS Collaboration
“Dark sector” emerging as a picture of dark matter that allows for self-scattering, collisional excitation, annihilation

- Standard Model forces don’t couple to the dark sector, dark forces don’t couple to Standard Model matter
- “Portals” create weak effective couplings between the sectors

Vector portal: dark mediator is a massive $U(1)$ boson (heavy photon)

- Kinetic mixing with the photon → weak coupling to electric charge

A different motivation: muon $g-2$ anomaly
Parameter space

- Two relevant parameters: mass $m_{A'}$, relative coupling strength $\epsilon^2 = \alpha'/\alpha$
- Let's assume $A' \to \text{dark}$ is kinematically forbidden, and $A' \to e^+e^-$ is allowed
  - If $A' \to \text{dark}$ is allowed, decays compete: generically, coupling to DM $\alpha_D$ is much larger than coupling to SM
- $\epsilon^2$ controls both production from, and decay to, SM (the harder it is to make an $A'$, the longer the lifetime)
- Branching fractions depend on $m_{A'}$

![HPS mass range](image-url)
Past and current searches

- **Production**: anything that makes virtual photons (bremsstrahlung, Drell-Yan, $e^+e^-$ annihilation, meson decays)
- **Searches**: thick fixed targets (beam dumps), thin fixed targets, colliders, meson factories
- **Signatures**: mass bumps, displaced vertices, missing mass
Producing heavy photons

- Similar to bremsstrahlung: $e^-$ on high-Z fixed target
- $A'$ carries most of incident $e^-$ energy
- Pairs from $A'$ decay are produced along beam with small opening angle
- Decay length depends on coupling, can be measurable
- Measure momentum and direction of decay products to get the invariant mass
- The recoil electron can improve the measurement precision, if detected
HPS search channels

- **Bump hunt**: look for a peak in pair invariant mass
  - $A'$ decays compete with QED tridents; mass resolution is key
- **Vertexing**: look for pairs originating downstream of the target (zero-background, cut and count)
  - Requires a tracker close to the target for $\sim\text{mm}$ vertex resolution
- Main background for both searches is QED tridents
The HPS detector

- Chicane downstream of CLAS detector in JLab Hall B
- 50-450 nA electron beam at 1.1-6.6 GeV
- Thin (4 or 8 µm) tungsten target
- Silicon microstrip tracker in dipole magnet for measurement
- PbWO$_4$ calorimeter for trigger
HPS reach

- HPS probes a large unexplored region of the parameter space
- Mass range is limited on the left by detector acceptance, on the right by production cross-section
- Bump hunt reach is limited on the bottom by statistics ($S/\sqrt{B}$ in a mass window)
- Vertexing reach is limited on the upper right by the resolvable decay length (tails of the trident vertex distribution)
Requirements

- big boosts, small opening angles (15 mrad): far forward
- vertexing -> close in (10 cm)
- degraded beam goes through detector: elastic scatters, hard brems
  - avoid backgrounds: space, time, trigger
- multiple scattering dominates: minimize mass
Killing backgrounds ... in space

- Main detector background is electrons scattered in the target and bent by the tracking field: “sheet of flame”
- Vacuum transport for primary+scattered beam through entire detector
- All detectors split ±15 mrad above and below beam plane
  - Active region of tracker layer 1 is 1.5 mm from beam (inactive silicon extends to 0.5 mm from beam)
Killing backgrounds . . . in time

- CEBAF at JLab: continuous beam (499 MHz rep rate and 100% duty cycle)
- Use time resolution to reject out-of-time hits
  - Tracker readout: APV25 (CMS) with 24 ns sampling period ($\sigma_t \approx 2$ ns)
  - ECAL readout: FADC250 (JLab) with 4 ns sampling period ($\sigma_t \approx 400$ ps, can resolve beam bunches)
Killing backgrounds . . . with trigger

- Trigger requires two clusters in time coincidence, \( E_{\text{sum}} < E_{\text{beam}} \), opposite sides of the beam axis
  - Elastic-scattered electrons: \( E \approx E_{\text{beam}} \), bent to the electron side
  - Pairs: \( E_{\text{sum}} < E_{\text{beam}} \), split top-bottom and left-right

- Trigger can be highly selective: captures essentially all \( A' \) events where the \( e^+e^- \) pair hits the ECal, with trigger rate on backgrounds of 5-20 kHz
Measurement

- Track momentum: limited by MS in silicon
- Opening angle: limited by layer 1 $\sigma_y$ and vertex $\sigma_z$
- Bump-hunt: vertex is fixed at $z = 0$
- Vertexing: vertex Z is limited by MS in layer 1

![Graph showing mass resolution for HPS detector with different mass points at 1.1 GeV, 2.2 GeV, and 4.4 GeV.](image)
Beamline

- Asymmetric “pancake” beamspot
  - Narrow $\sigma_y$: stronger beamspot constraint for vertexing
  - Wide $\sigma_x$: spread out the beam to limit target heating

- Beam tails at $10^{-6}$ level

- Special precautions to protect the SVT
  - Orbit locks for beam stability
  - Protection collimator in front of SVT
  - Halo counter FSD to trip beam if it scrapes the collimator
  - Scan wires mounted directly on the SVT
ECal

- PbWO₄ crystals with APD readout, based on CLAS Inner Calorimeter
- 250 MHz digitization and pulse fitting, great time resolution
- Energy resolution can improve on SVT momentum resolution, but limited by edge effects
The silicon vertex tracker (SVT) provides the basic HPS measurements: charge, momentum and vertex.

- Dipole B-field (0.5 T at 2.2 GeV) from target to end of tracker
- Six layers: pairs of silicon microstrip sensors in small-angle stereo
  - Layers 1–3 (single-ended) are mounted on hinges and can move away from the beam
  - Layers 4–6 (double-ended) are fixed at 15 mrad
Design performance and resolutions

- Hit resolutions: $\sigma_x < 125\mu m$, $\sigma_y < 10\mu m$
  - Small-angle stereo trades off $\sigma_x$ for hit confusion
- Single-hit efficiency better than 99%, track efficiency better than 95%
- Momentum resolution $\sigma_p/p \approx 6.5\%$ with 1.05 GeV beam (scales as $1/B$)
- All resolutions (momentum, mass, vertex) dominated by multiple scattering
SVT design constraints

- Thin ($< 1\% X_0$ per layer): minimize multiple scattering
- Fast ($\sigma_t \approx 2$ ns): cut backgrounds (4 MHz/mm$^2$) with hit time measurement
- Cold: silicon at $-10^\circ$C to mitigate radiation damage
- Mobile: fine adjustment of distance from beam
- In vacuum: avoid beam-gas backgrounds
- Near target, near beam (10 cm downstream of target, 0.5 mm from beam): maximize vertex resolution and acceptance
- Compact: fits in existing magnet (16” W × 7” H)
Mechanical design

- Sensors from D0 run IIb
- Support structure is thinner than the silicon; total average thickness $0.7X_0$ per module
- Spring pivot pulls the silicon flat, module structure cools silicon from both ends
- “U-channels” support and cool modules in sets of 3
- Aligned to 100 $\mu$m, surveyed to 50 $\mu$m
SVT data acquisition

- APV25-based hybrid readout board: triggered 40 MHz analog readout
- Frontend boards: control and trigger, low voltage distribution, ADC
- Flange boards: vacuum penetration and copper-to-fiber transceivers
- RCE DAQ: data reduction, event building, integration with JLab DAQ
- Trigger rate up to 50 kHz, data rate to tape up to 100 MB/s
Hit time reconstruction

- Beam backgrounds make \( \sim 100 \) junk hits per event
- Hottest strips see hit rates over 1 MHz; lots of pileup
- Read out six samples at 24 ns intervals, fit preamp pulse shape including pileup for \( \sigma_t \approx 2 \) ns
- Use hit times in track finder to reject junk hits
Assembly and installation
HPS status and run plan

- HPS schedule is constrained by other Hall B experiments (CLAS, PRad)
- Test run (bare-bones SVT, photon beam): May 2012
- ECal-only commissioning run: December 2014
- 1.05 GeV engineering run: March-May 2015
  - 1 week (nights and weekends) of physics data at nominal SVT position: about 2 days of beam
- 2.3 GeV physics run: February-March 2016
  - 6 weekends of physics data: about 5 days of beam
- 4.4 GeV run scheduled for 2018
Elastic and Moller scatters

- Elastic scatters \((E \approx E_{\text{beam}})\) are a basic normalization and calibration signal
  - Scale and resolution for momentum and energy, time resolution, alignment
  - Rates within 5% of MC
- Moller scatters: \(E_{\text{sum}} = E_{\text{beam}},\) \(m = \sqrt{2E_{\text{beam}}m_e}\), exact correlation between the two detected particles
  - Mass resolution as expected
  - Tag-and-probe measurement of tracking efficiency: roughly 95%
Vertexing tridents

- Multiple scattering distribution leads to Gaussian core and non-Gaussian tail
- Large scatters in L1 can fake a displaced vertex; large scatters in later layers can cause misassociated hits
- Work continues on using both data and MC to characterize tails
Progress and plans for analysis

- Finishing detector performance studies, calibrations, alignment
- Preparing bump-hunt and vertexing analyses
- Blinded analysis: only using 10% of the data right now

**Vertex: Positron vs. electron momentum**

- Entries: 68897
- Mean x: 0.3762
- Mean y: 0.3718
- Std Dev x: 0.1354
- Std Dev y: 0.1276

**Radiative vertex mass**

- Entries: 658927
- Mean: 0.03545
- Std Dev: 0.0111
Vertex resolution

- Vertexing search achieves $10^{-7}$ rejection of the trident background
- Misassociated layer 1 hits are the main source of vertex tails
Reach

- Vertex cut (10–30 mm) set for $< 0.5$ events/mass bin
Test run

- 2012 test run with first-attempt design on a very tight schedule
- Developed all the basic elements of our design, and found areas for improvement
- Proved detector performance (timing, S/N, efficiencies)
Potential upgrades

- Layer 0: add thin silicon at 5 cm to improve vertex resolution and recoil electron acceptance
- Possible increases in rate and current
- SuperHPS: two-armed spectrometer with much higher luminosity
Detailed reach

- purple, dashed: 1 week of 50nA, 1.1 GeV beam on a 0.125% target
- blue, dashed: 1 week of 200nA, 2.2 GeV beam on a 0.125% target
- blue, solid: 3 weeks of 200nA, 2.2 GeV beam on a 0.125% target
- dark green: 2 weeks of 450nA, 6.6 GeV beam on a 0.25% target, detecting $A' \rightarrow e^+ e^-$
- light green: 2 weeks of 450nA, 6.6 GeV beam on a 0.25% target, detecting $A' \rightarrow \mu^+ \mu^-$
- red: the statistical combination of all of the above
- green shaded: 3 months each of 2.2 GeV and 6.6 GeV