

The Heavy Photon Search Experiment at Jefferson Lab

Sho Uemura

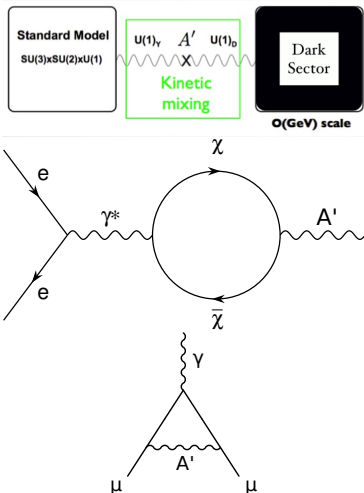
SLAC

on behalf of the HPS Collaboration



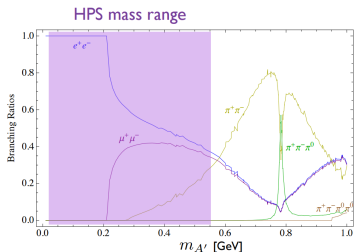
Dark forces and the heavy photon

- “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 \rightarrow weak coupling to electric charge
- A different motivation: muon $g-2$ anomaly



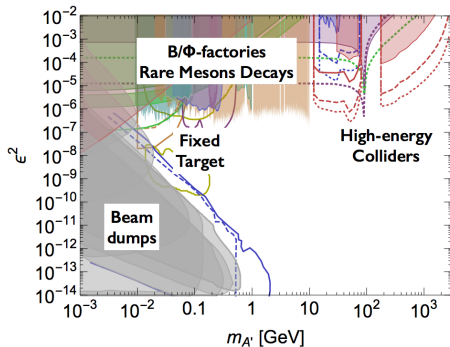
Parameter space

- Two relevant parameters: mass $m_{A'}$, relative coupling strength $\epsilon^2 = \alpha'/\alpha$
- Let's assume $A' \rightarrow$ dark is kinematically forbidden, and $A' \rightarrow e^+e^-$ is allowed
 - ▶ If $A' \rightarrow$ dark is allowed, decays compete: generically, coupling to DM α_D is much larger than coupling to SM
- ϵ^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 $m_{A'}$



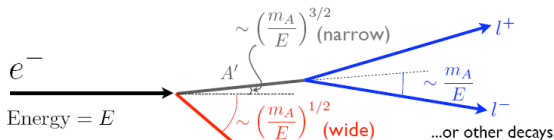
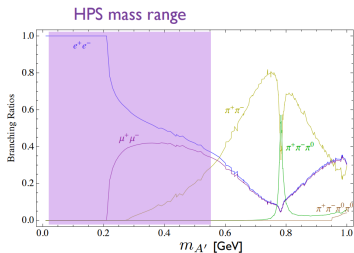
Past and current searches

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



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

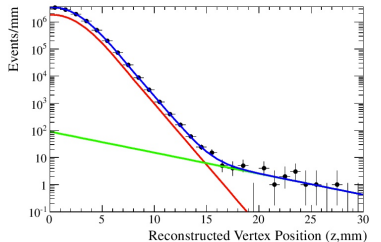
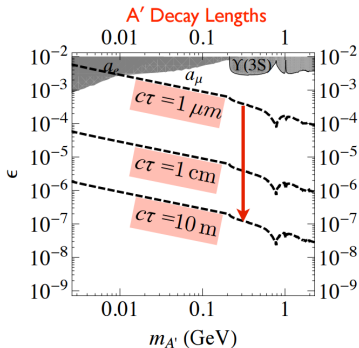
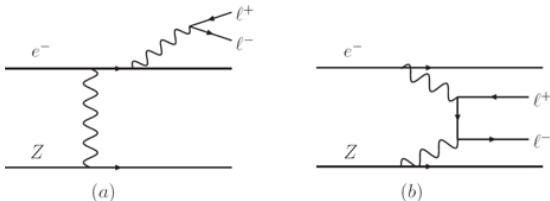


$$E_{A'} \sim E - m_{A'}$$

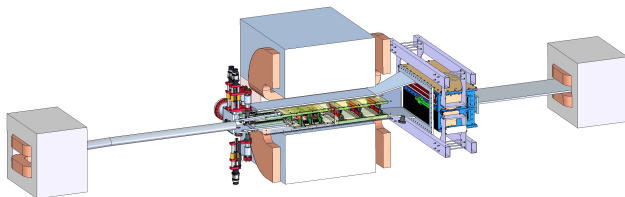
$$E_e \sim m_{A'}$$

HPS search channels

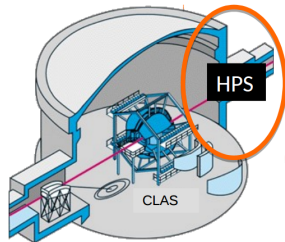
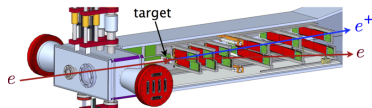
- Bump hunt: look for a peak in pair invariant mass
 - ▶ A' decays compete with QED tridents; mass resolution is key
- Vertexing: look for pairs originating downstream of the target (zero-background, cut and count)
 - ▶ Requires a tracker close to the target for \sim mm vertex resolution
- Main background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



The HPS detector

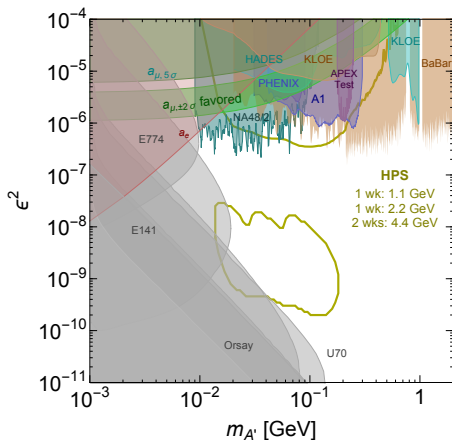


- Chicane downstream of CLAS detector in JLab Hall B
- 50-450 nA electron beam at 1.1-6.6 GeV
- Thin (4 or 8 μm) tungsten target
- Silicon microstrip tracker in dipole magnet for measurement
- PbWO_4 calorimeter for trigger



HPS reach

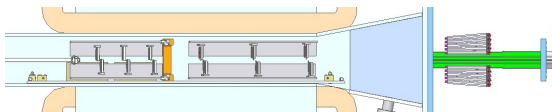
- HPS probes a large unexplored region of the parameter space
- Mass range is limited on the left by detector acceptance, on the right by production cross-section
- Bump hunt reach is limited on the bottom by statistics (S/\sqrt{B} in a mass window)
- Vertexing reach is limited on the upper right by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



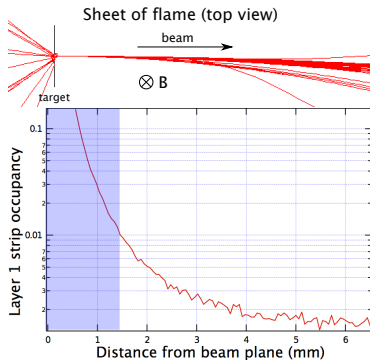
Requirements

- 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

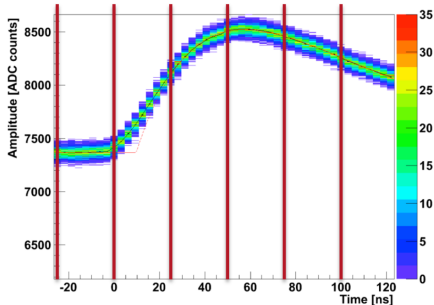


- Main detector background is electrons scattered in the target and bent by the tracking field: “sheet of flame”
- Vacuum transport for primary+scattered beam through entire detector
- All detectors split ± 15 mrad above and below beam plane
 - ▶ Active region of tracker layer 1 is 1.5 mm from beam (inactive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

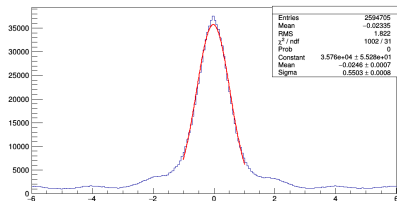


Killing backgrounds ... in time

- 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)

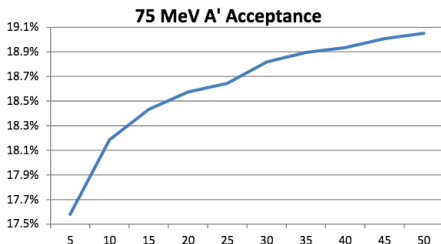


$((t1-t2) \{ (E1+E2) < 1 \&\& (E1-E2) < 0.3 \})$



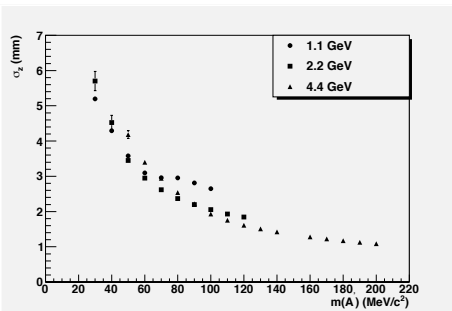
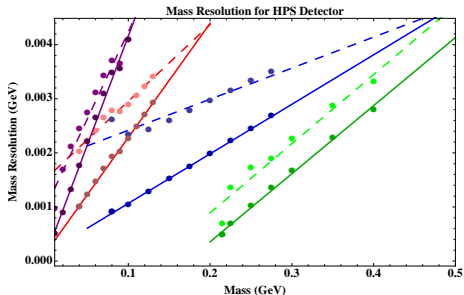
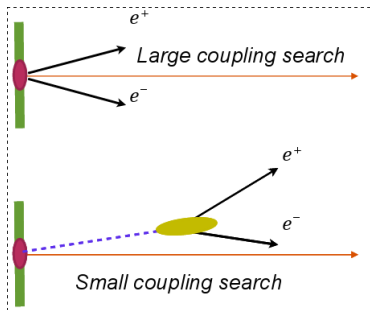
Killing backgrounds ... with trigger

- Trigger requires two clusters in time coincidence, $E_{sum} < E_{beam}$, opposite sides of the beam axis
 - ▶ Elastic-scattered electrons: $E \approx E_{beam}$, bent to the electron side
 - ▶ Pairs: $E_{sum} < E_{beam}$, 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



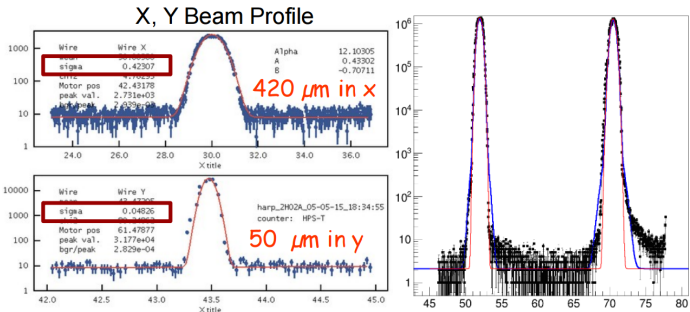
Measurement

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



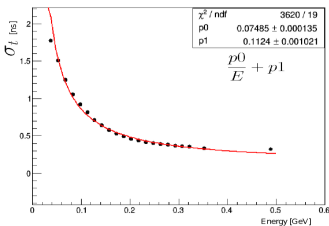
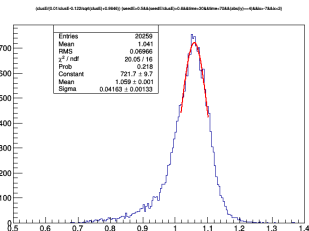
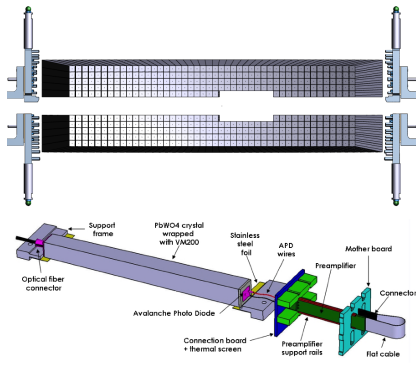
Beamline

- Asymmetric “pancake” beamspot
 - ▶ Narrow σ_y : stronger beamspot constraint for vertexing
 - ▶ Wide σ_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

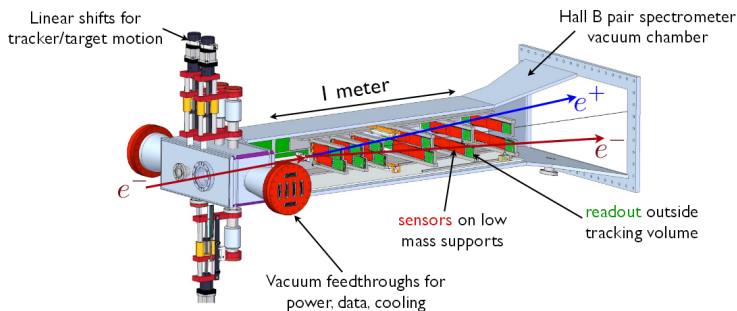


ECal

- 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 HPS SVT



- 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: $\sigma_x < 125\mu\text{m}$, $\sigma_y < 10\mu\text{m}$
 - ▶ Small-angle stereo trades off σ_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

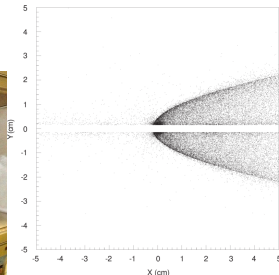
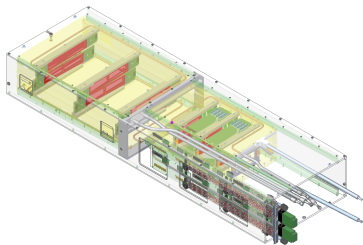
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
z position, from target (cm)	10	20	30	50	70	90
Stereo Angle (mrad)	100	100	100	50	50	50
Bend Plane Resolution (μm)	≈ 60	≈ 60	≈ 60	≈ 120	≈ 120	≈ 120
Non-bend Resolution (μm)	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6
# Bend Plane Sensors	2	2	2	4	4	4
# Stereo Sensors	2	2	2	4	4	4
Dead Zone (mm)	± 1.5	± 3.0	± 4.5	± 7.5	± 10.5	± 13.5
Power Consumption (W)	7	7	7	14	14	14

Vertexing

Pattern Recognition

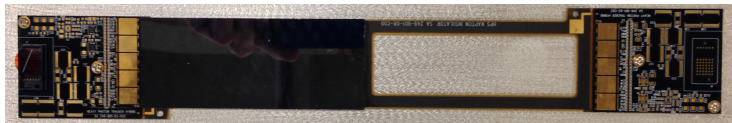
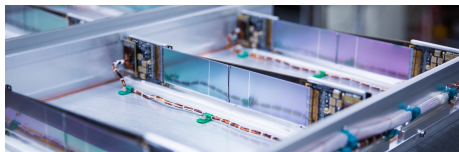
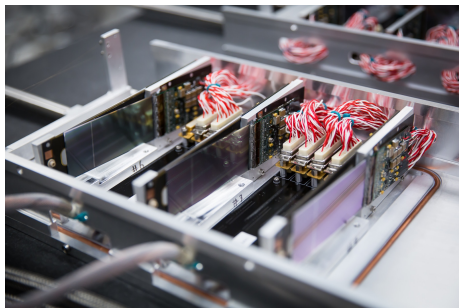
SVT design constraints

- Thin ($< 1\%X_0$ per layer): minimize multiple scattering
- Fast ($\sigma_t \approx 2$ ns): cut backgrounds (4 MHz/mm²) with hit time measurement
- Cold: silicon at -10°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 \times 7" H)



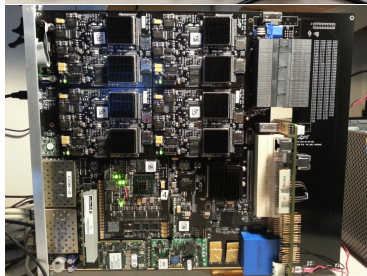
Mechanical design

- 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 $100\ \mu\text{m}$, surveyed to $50\ \mu\text{m}$



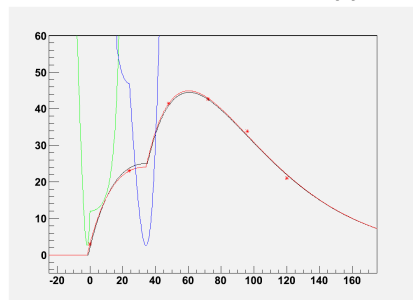
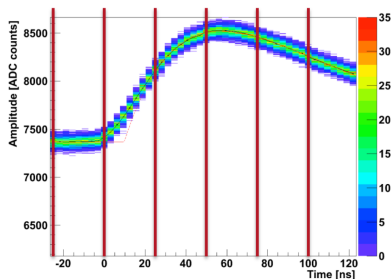
SVT data acquisition

- 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

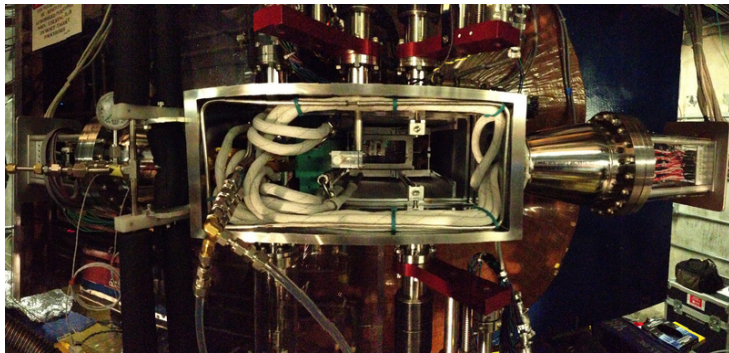
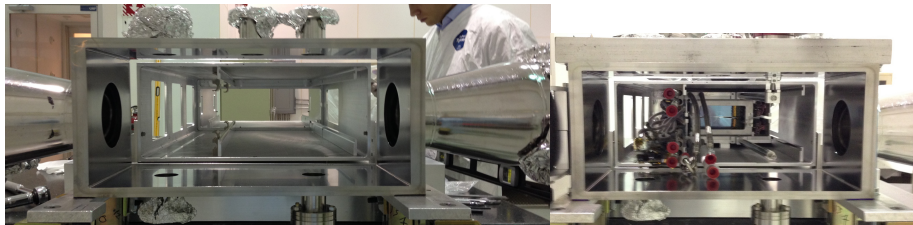


Hit time reconstruction

- Beam backgrounds make ~ 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

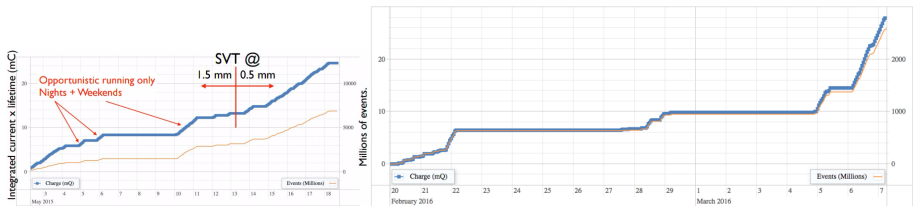


Assembly and installation



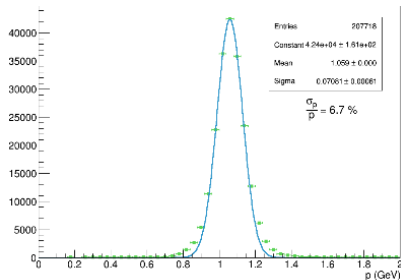
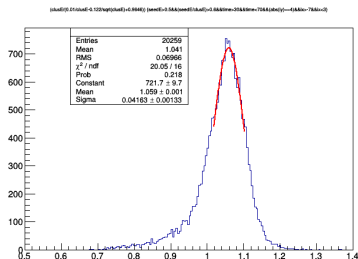
HPS status and run plan

- 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
- Engineering run: March-May 2015
 - ▶ 1 week (nights and weekends) of physics data at 1.05 GeV and nominal SVT position: about 2 days of beam
- 2.3 GeV physics run February-March 2016
 - ▶ 4 weekends of physics data: about 1.5 days of beam so far



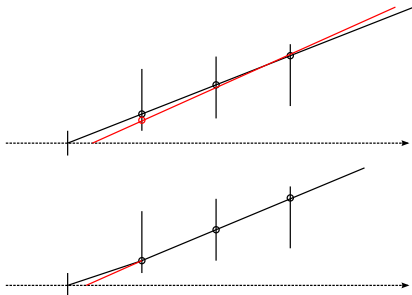
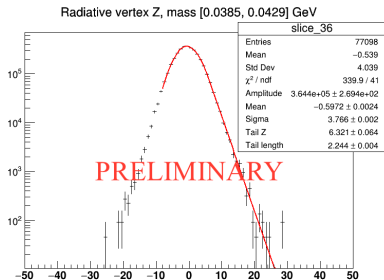
Elastic and Moller scatters

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



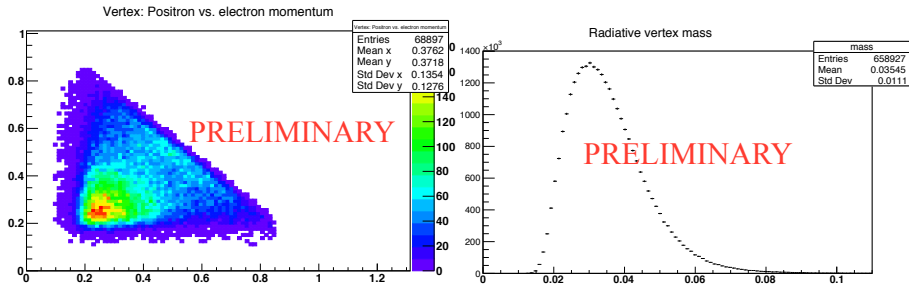
Vertexing tridents

- 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



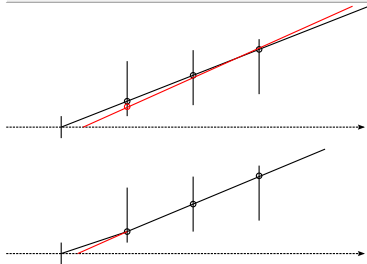
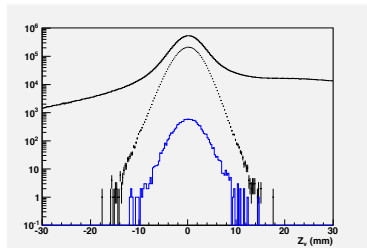
Progress and plans for analysis

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



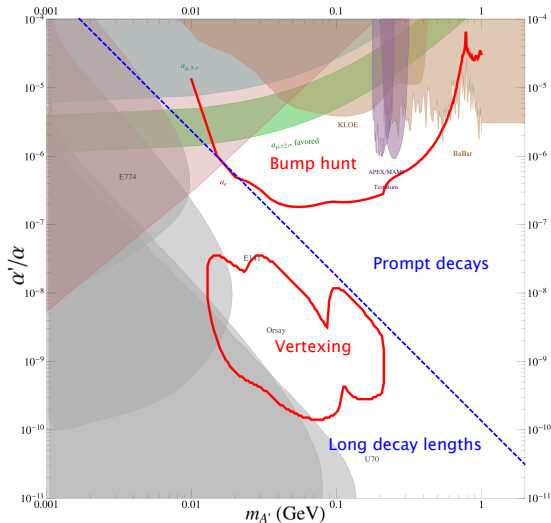
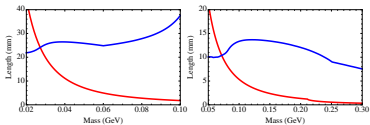
Vertex resolution

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



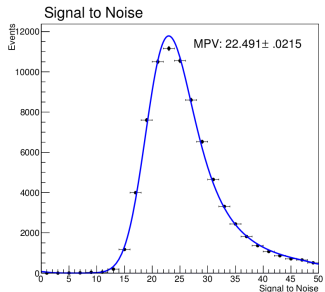
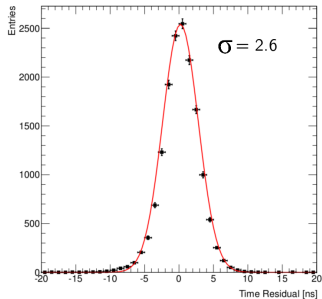
Reach

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



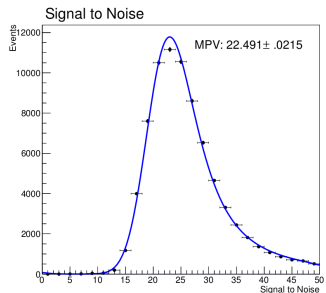
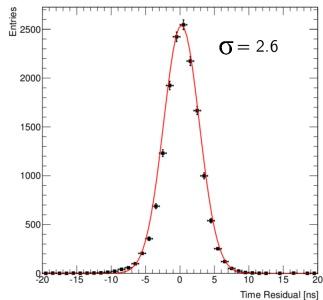
Test run

- 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

