The Heavy Photon Search Experiment at Jefferson Lab

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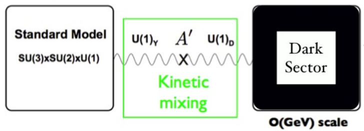
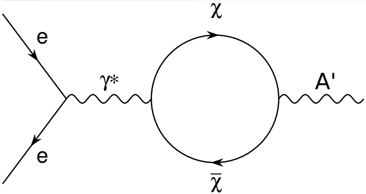
SLAC

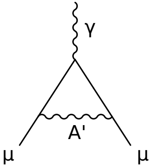
on behalf of the HPS Collaboration

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 → weak coupling to electric charge
- A different motivation: muon g-2 anomaly

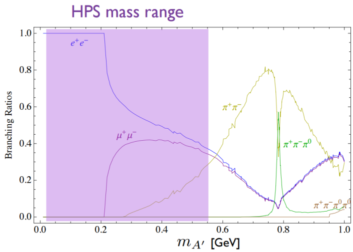






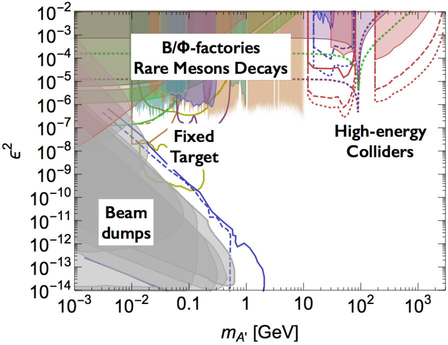
Parameter space

- 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 $m_{A'}$



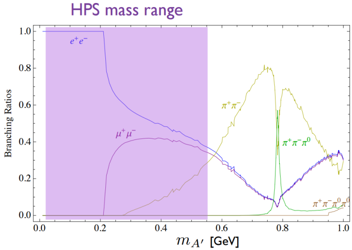
Past and current searches

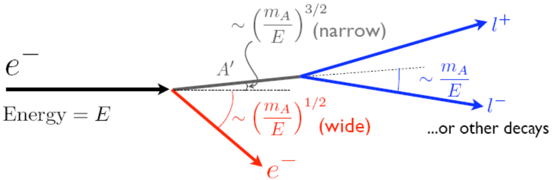
- Production: anything that makes virtual photons (bremsstrahlung, Drell-Yan, e^+e^- annihilation, meson decays)
- Searches: thick fixed targets (beam dumps), thin fixed targets, colliders, meson factories
- Signatures: mass bumps, displaced vertices, missing mass



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

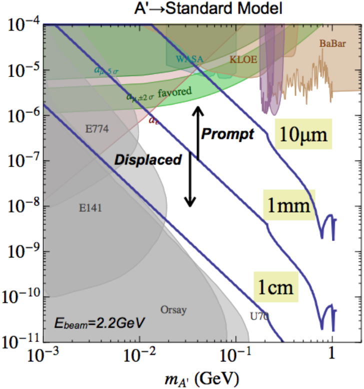


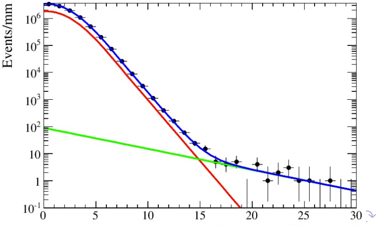


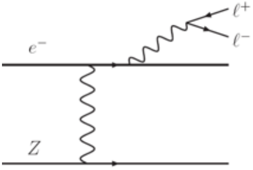
$$E_A \sim E - m_A$$
$$E_e \sim m_A$$

HPS search channels

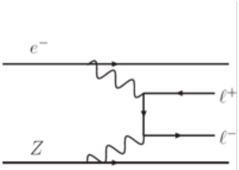
- Bump hunt: look for a peak in pair invariant mass
  - A' decays compete with QED tridents; mass resolution is key
- Vertexing: look for pairs originating downstream of the target (zero-background, cut and count)
  - Requires a tracker close to the target for ∼mm vertex resolution
- Main background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





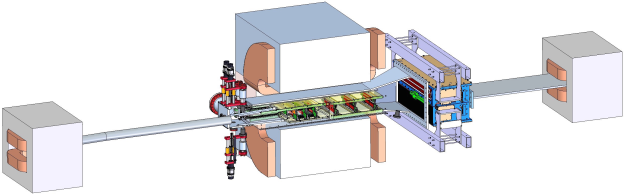


(a)

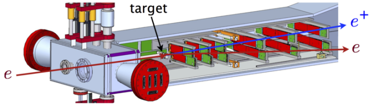


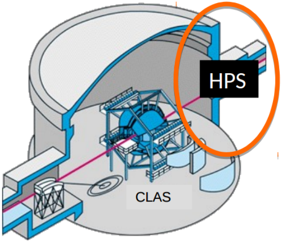
(b)

The HPS detector



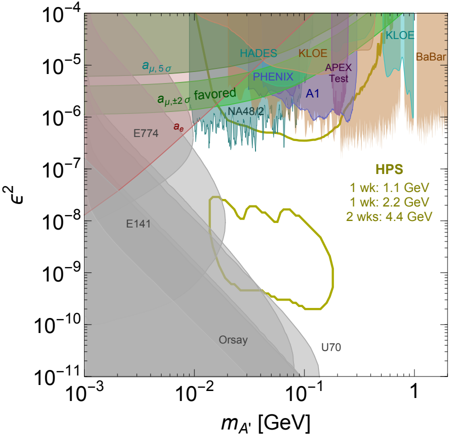
- Chicane downstream of CLAS detector in JLab Hall B
- 50-450 nA electron beam at 1.1-6.6 GeV
- Thin (4 or 8 μm) tungsten target
- Silicon microstrip tracker in dipole magnet for measurement
- $PbWO_4$ calorimeter for trigger





HPS reach

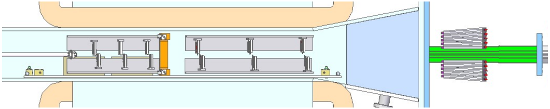
- HPS probes a large unexplored region of the parameter space
- Mass range is limited on the left by detector acceptance, on the right by production cross-section
- Bump hunt reach is limited on the bottom by statistics ($S/\sqrt{B}$ in a mass window)
- Vertexing reach is limited on the upper right by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



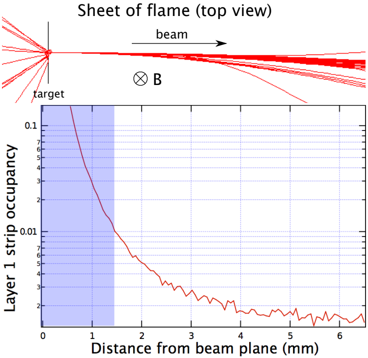
Requirements

- 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

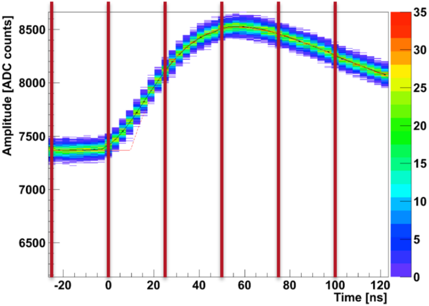


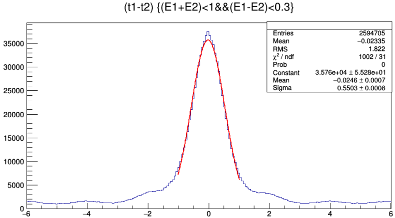
- Main detector background is electrons scattered in the target and bent by the tracking field: “sheet of flame”
- Vacuum transport for primary+scattered beam through entire detector
- All detectors split ±15 mrad above and below beam plane
    - Active region of tracker layer 1 is 1.5 mm from beam (inactive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



Killing backgrounds . . . in time

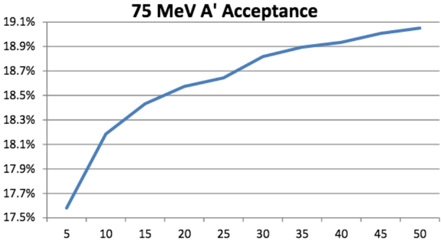
- CEBAF at JLab: continuous beam (499 MHz rep rate and 100% duty cycle)
- Use time resolution to reject out-of-time hits
    - Tracker readout: APV25 (CMS) with 24 ns sampling period ($\sigma_t \approx 2$ ns)
    - ECal readout: FADC250 (JLab) with 4 ns sampling period ($\sigma_t \approx 400$ ps, can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





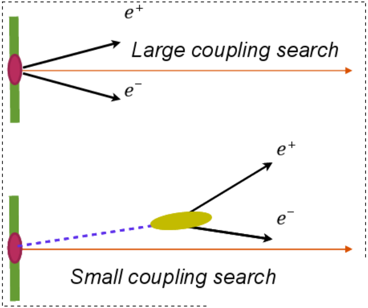
Killing backgrounds . . . with trigger

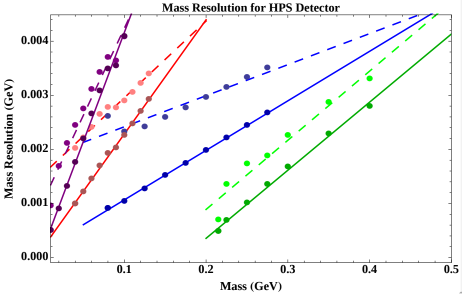
- Trigger requires two clusters in time coincidence, $E_{sum} < E_{beam}$, opposite sides of the beam axis
  - Elastic-scattered electrons: $E \approx E_{beam}$, bent to the electron side
  - Pairs: $E_{sum} < E_{beam}$, split top-bottom and left-right
- Trigger can be highly selective: captures essentially all A' events where the e^+e^- pair hits the ECal, with trigger rate on backgrounds of 5-20 kHz

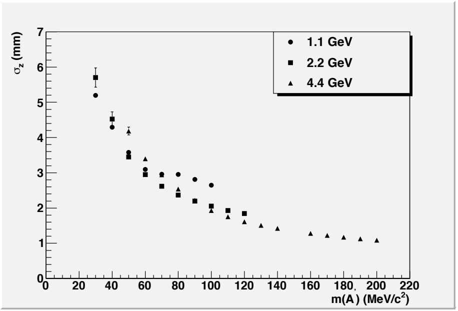


Measurement

- 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



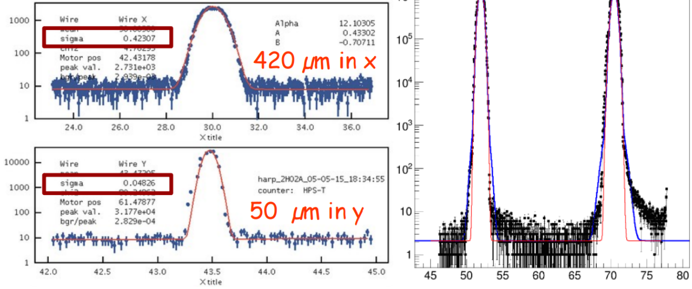




Beamline

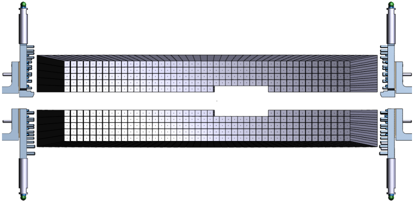
- Asymmetric “pancake” beamspot
  - Narrow σ_y: stronger beamspot constraint for vertexing
  - Wide σ_x: spread out the beam to limit target heating
- Beam tails at 10^{-6} level
- Special precautions to protect the SVT
  - Orbit locks for beam stability
  - Protection collimator in front of SVT
  - Halo counter FSD to trip beam if it scrapes the collimator
  - Scan wires mounted directly on the SVT

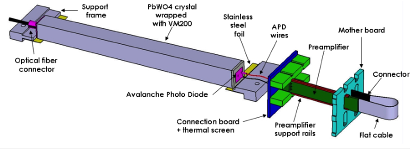
X, Y Beam Profile

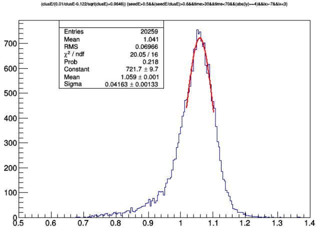


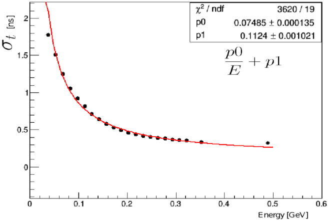
ECal

- $PbWO_4$ 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

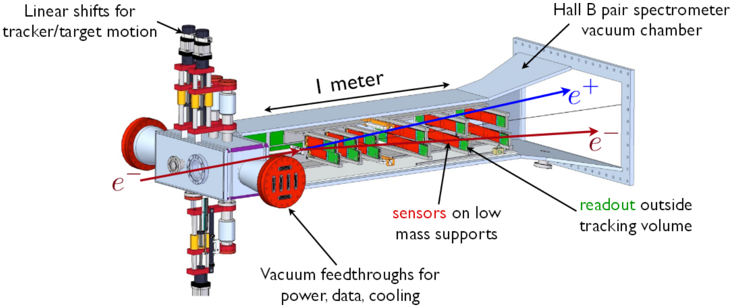








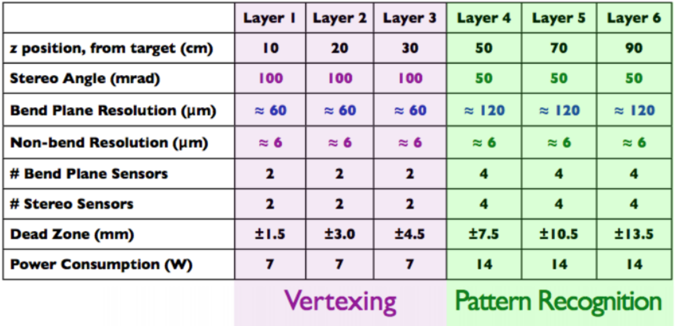
The HPS SVT



- 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



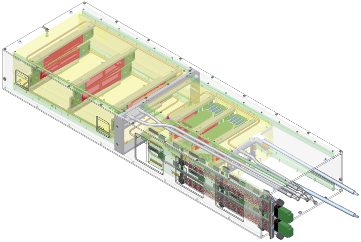
	Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**
z position, from target (cm)	10	20	30	50	70	90
Stereo Angle (mrad)	100	100	100	50	50	50
Bend Plane Resolution (μm)	≈ 60	≈ 60	≈ 60	≈ 120	≈ 120	≈ 120
Non-bend Resolution (μm)	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6
# Bend Plane Sensors	2	2	2	4	4	4
# Stereo 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

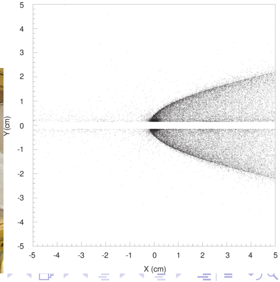
Vertexing

Pattern Recognition

SVT design constraints

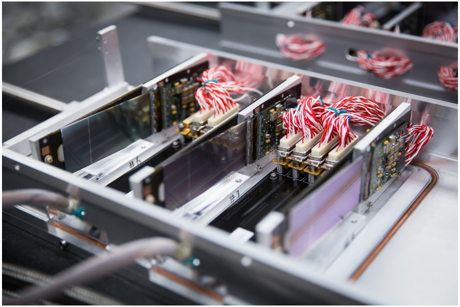
- Thin ($< 1\% X_0$ per layer): minimize multiple scattering
- Fast ($\sigma_t \approx 2$ ns): cut backgrounds (4 MHz/mm^2) with hit time measurement
- Cold: silicon at -10°C to mitigate radiation damage
- Mobile: fine adjustment of distance from beam
- In vacuum: avoid beam-gas backgrounds
- Near target,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

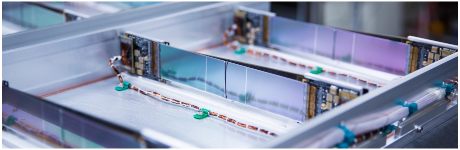


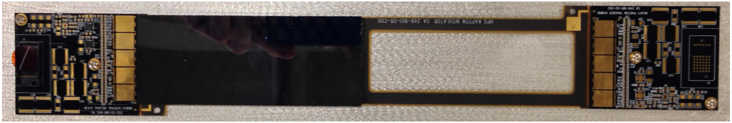


Mechanical design

- 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 μm, surveyed to 50 μm





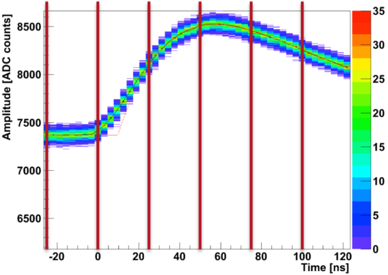


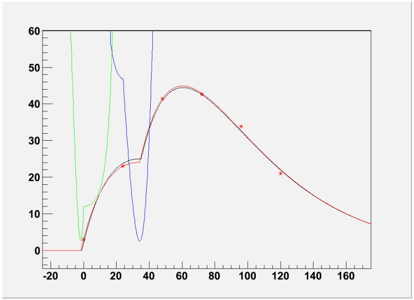
SVT data acquisition

- 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

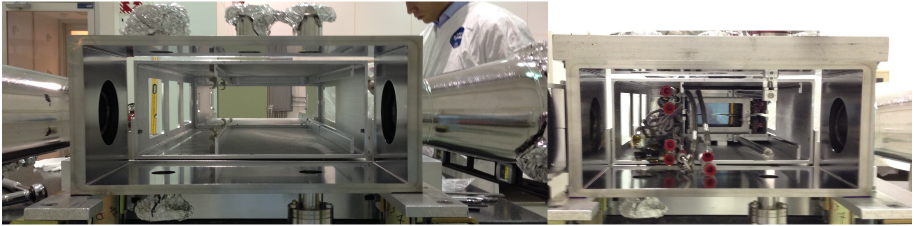
Hit time reconstruction

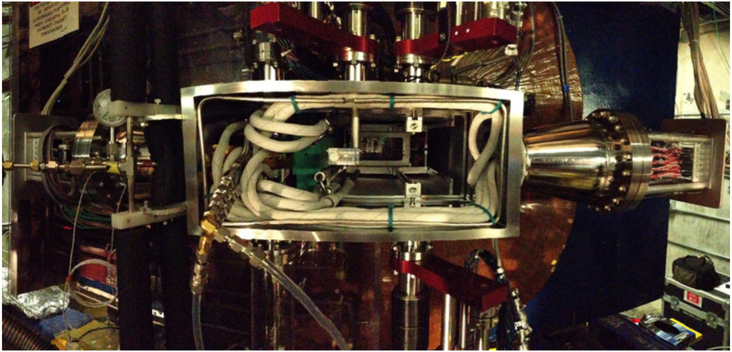
- Beam backgrounds make ∼100 junk hits per event
- Hottest strips see hit rates over 1 MHz; lots of pileup
- Read out six samples at 24 ns intervals, fit preamp pulse shape including pileup for $\sigma_t \approx 2$ ns
- Use hit times in track finder to reject junk hits





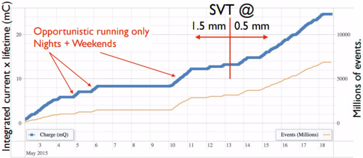
Assembly and installation

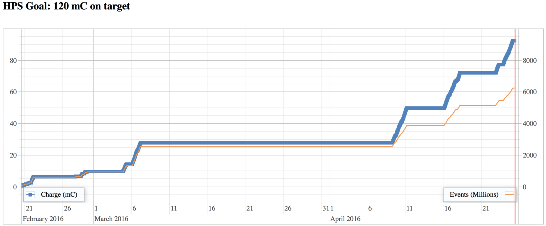




HPS status and run plan

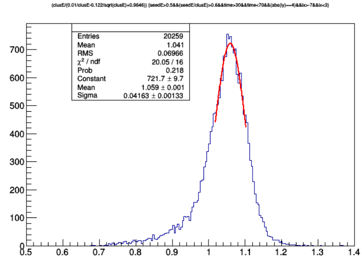
- HPS schedule is constrained by other Hall B experiments (CLAS, PRad)
- Test run (bare-bones SVT, photon beam): May 2012
- ECal-only commissioning run: December 2014
- 1.05 GeV engineering run: March-May 2015
  - 1 week (nights and weekends) of physics data at nominal SVT position: about 2 days of beam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

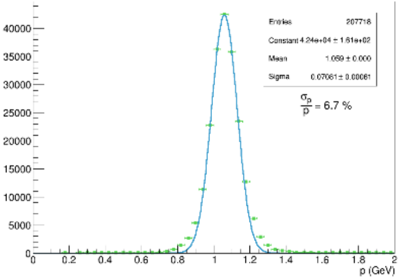




Elastic and Moller scatters

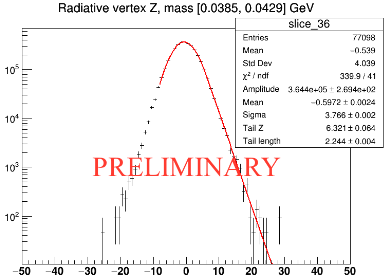
- Elastic scatters ($E \approx E_{beam}$) are a basic normalization and calibration signal
  - Scale and resolution for momentum and energy, time resolution, alignment
  - Rates within 5% of MC
- Moller scatters: $E_{sum} = E_{beam}$, $m = \sqrt{2E_{beam}m_e}$, exact correlation between the two detected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

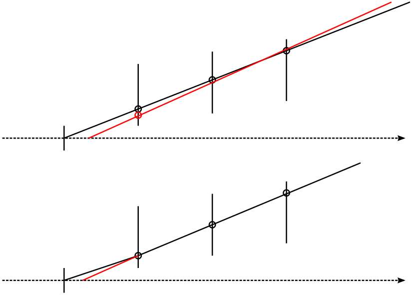




Vertexing tridents

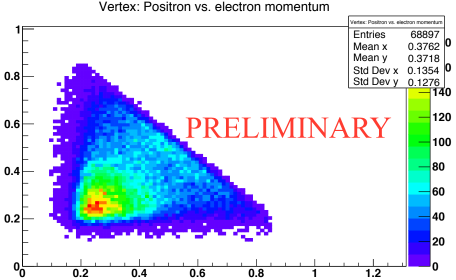
- Multiple scattering distribution leads to Gaussian core and non-Gaussian tail
- Large scatters in L1 can fake a displaced vertex; large scatters in later layers can cause misassociated hits
- Work continues on using both data and MC to characterize tails

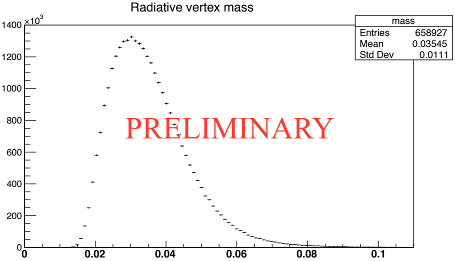




Progress and plans for analysis

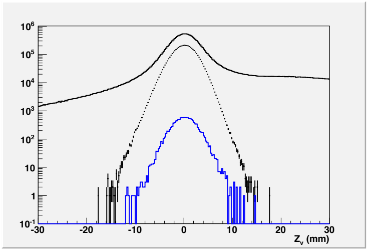
- Finishing detector performance studies, calibrations, alignment
- Preparing bump-hunt and vertexing analyses
- Blinded analysis: only using 10% of the data right now

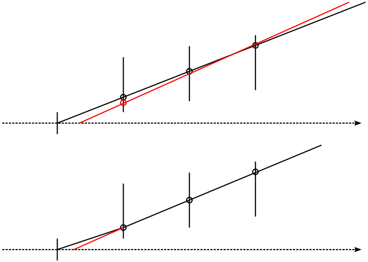




Vertex resolution

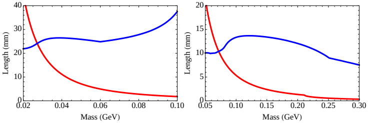
- Vertexing search achieves 10^{-7} rejection of the trident background
- Misassociated layer 1 hits are the main source of vertex tails

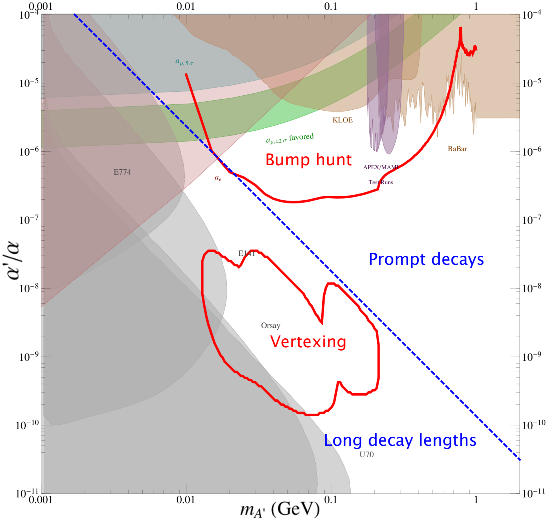




Reach

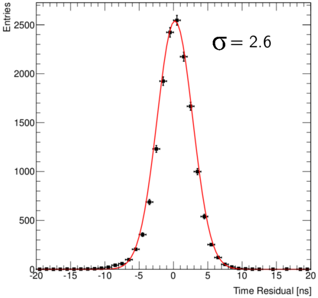
- Vertex cut (10–30 mm) set for < 0.5 events/mass bin

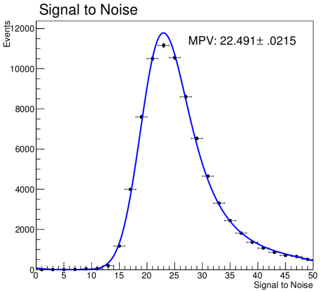




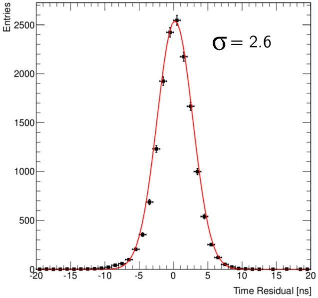
Test run

- 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)

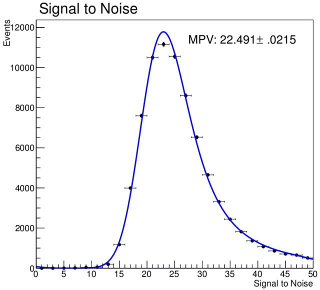




Potential upgrades



- 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 $A' \to e^+e^-$
- light green: 2 weeks of 450nA, 6.6 GeV beam on a 0.25% target, detecting $A' \to \mu^+\mu^-$
- red: the statistical combination of all of the above
- green shaded: 3 months each of 2.2 GeV and 6.6 GeV