The Heavy Photon Search Experiment Simulation & Reconstruction

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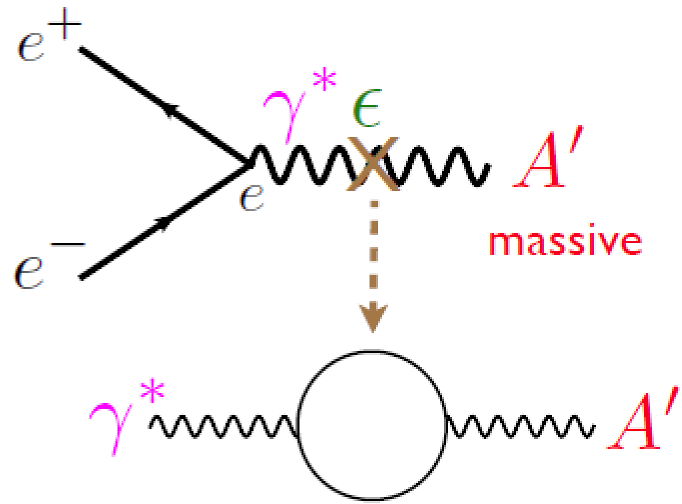
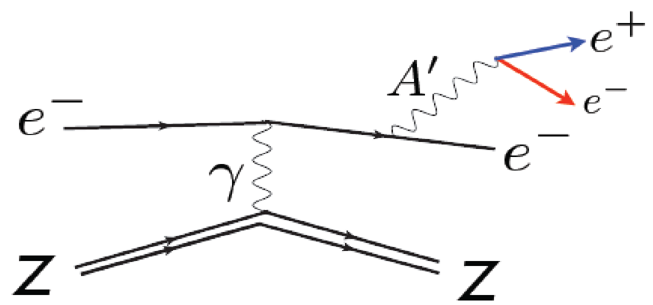
SLAC NATIONAL ACCELERATOR LABORATORY

What is a Dark Photon?

- **If there's an additional U(1) symmetry in nature there can be mixing between the photon and the new gauge boson (Holdom, 1986)**
- **New U(1)'s are expected in many BSM theories**
- **A new U(1) gauge boson A' may mediate dark matter interactions**
- **A' is characterized by its mass $m_{A'}$ and coupling to charge εe**
- **"Kinetic mixing" produces coupling to SM.**



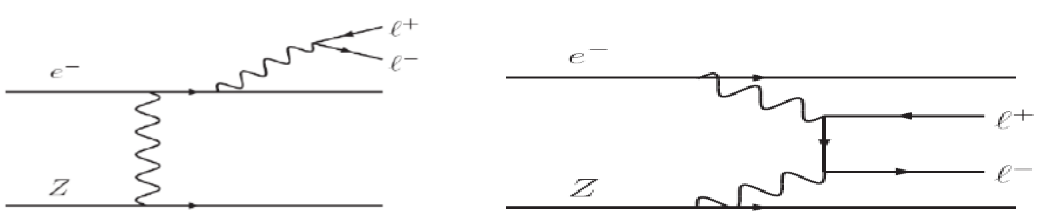
Produced by bremsstrahlung off heavy targets and subsequent decay to e+e-



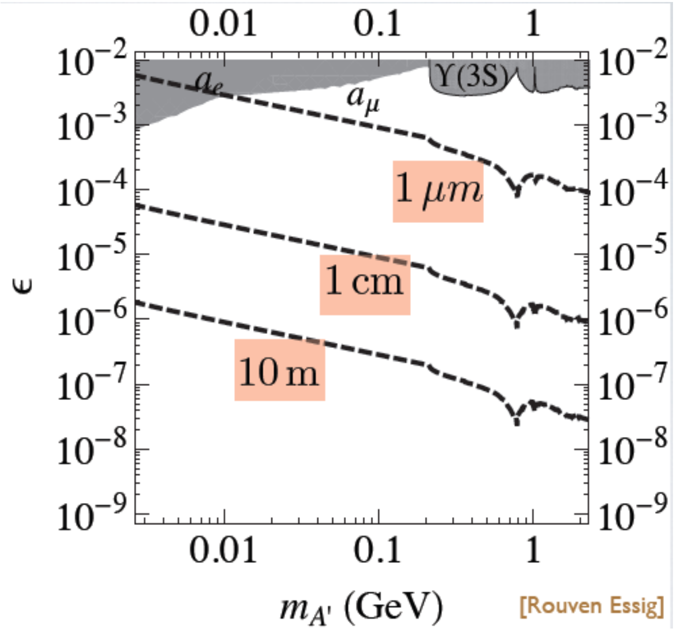
- **Heavy photons have recently become popular since they could explain experimental anomalies in particle physics (g-2) and astrophysics (e+ excess)**
- **The Heavy Photon Search (HPS) Experiment is a fixed-target experiment that uses the JLab electron beam to search for such phenomena.**

Searching for an A' with Small Couplings

- **Small couplings ⇒ very few events.**
  Need lots of luminosity.
- **Lots of lum ⇒ high background, low S/B**
  QED tridents, an irreducible physics background, overwhelm A' production.



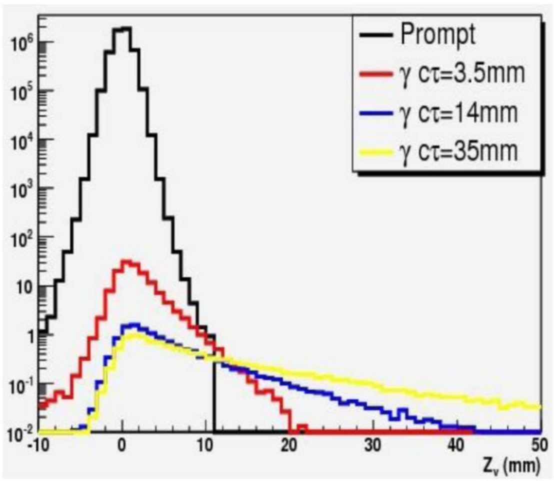
Decay Length cτ



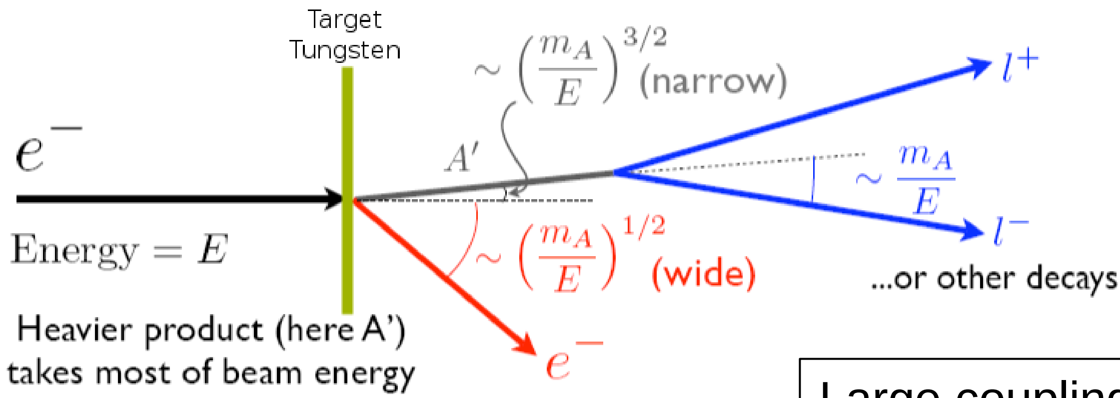
- **Small couplings ⇒ long-lived A'**
  Secondary vertex signature powerfully discriminates against the prompt trident background.

- **Precise simulation essential**
  The A' decay length signal is in the tails of the prompt trident signal. HPS must understand and control the tails of the trident vertex distribution. Full simulation confirms this is possible.

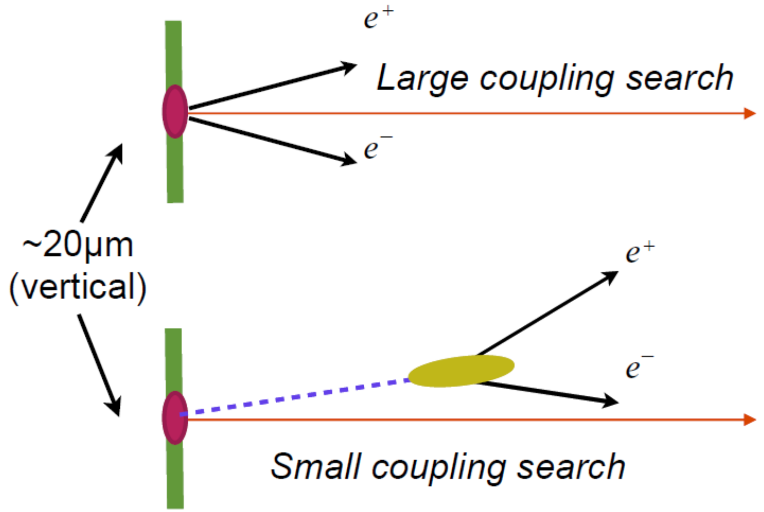
Vertex Distribution



HPS Searches: Bump-Hunt and Vertexing



A' takes most of the incident energy, produced very forward



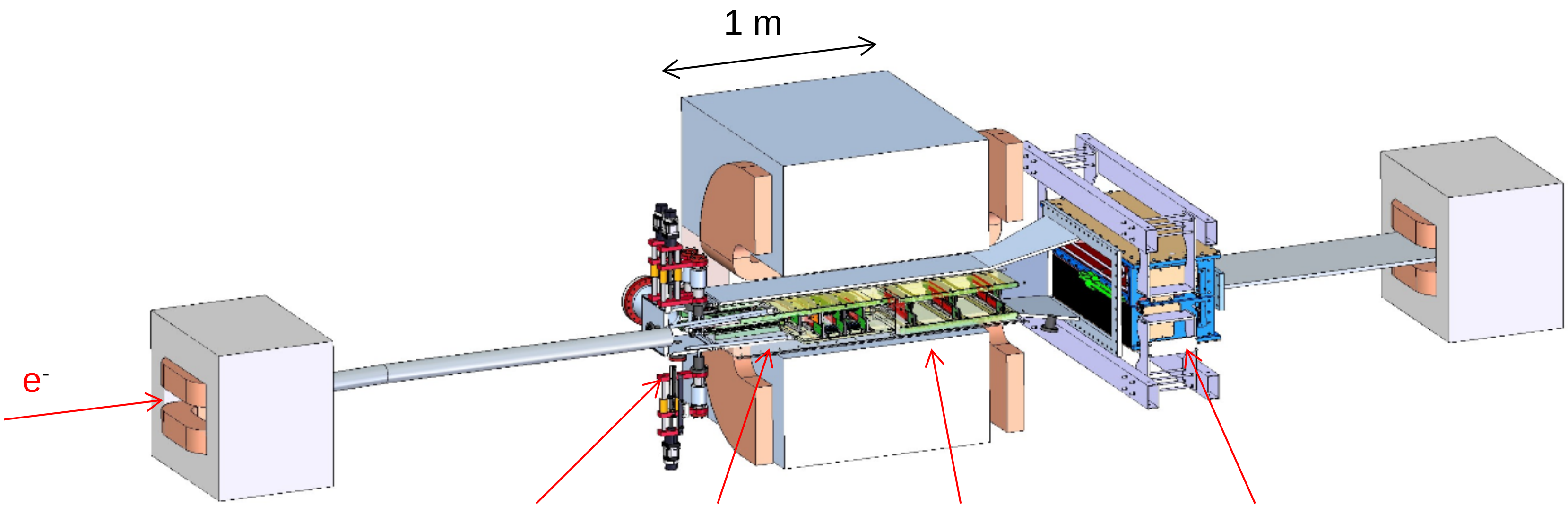
Large coupling regime:
A' decays in target ∴ constrain e+e- to originate from beamspot
Search for peak in invariant mass plot

Small coupling regime:
A' decays outside of target ∴ constrain A' to originate from beamspot
Search for displaced vertices, mass peak, or both

Including recoil e- improves mass resolution

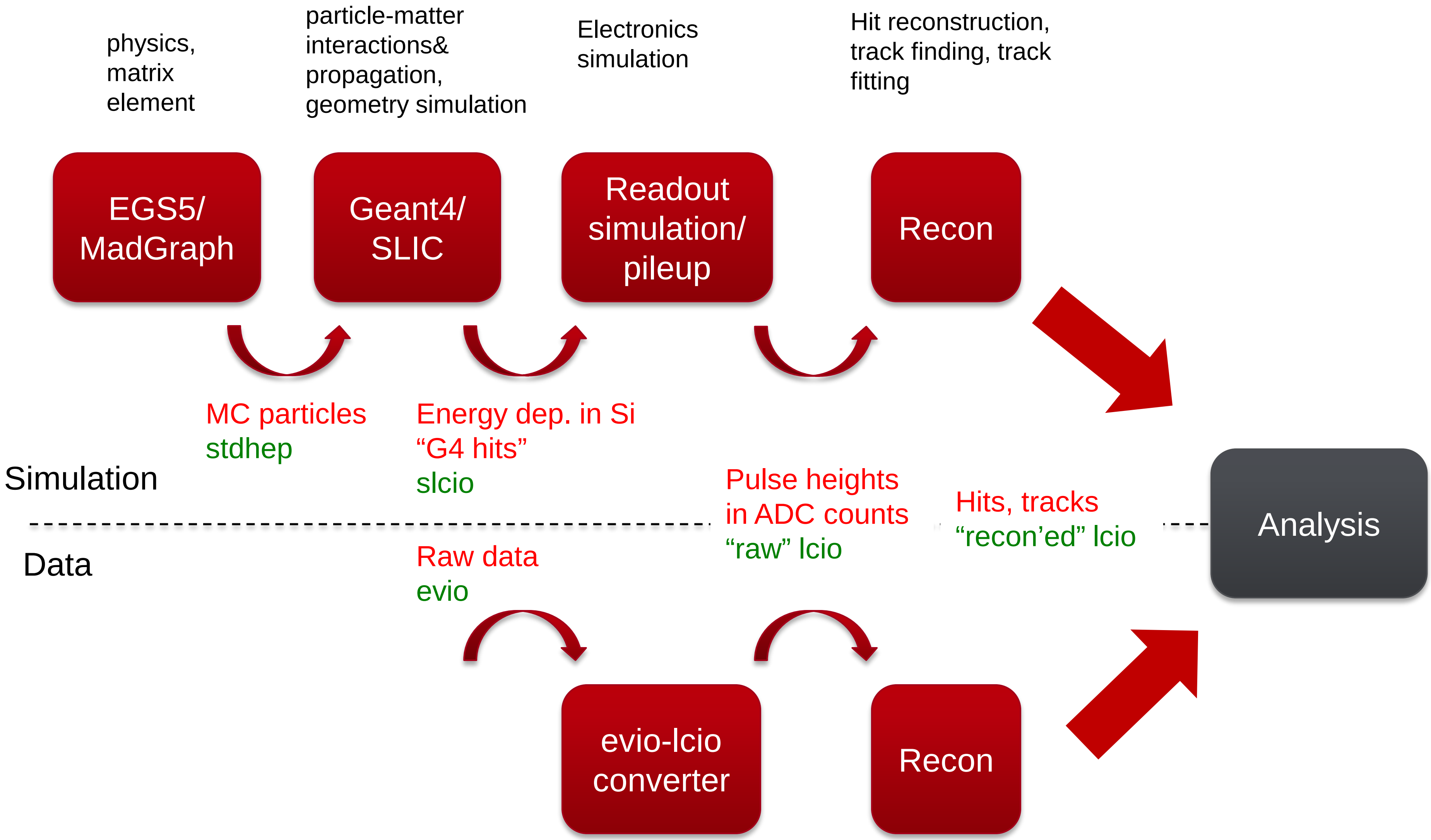
- **HPS opts for large forward acceptance/moderate currents. This requires placing sensors as close as possible to the beam.**

HPS Detector



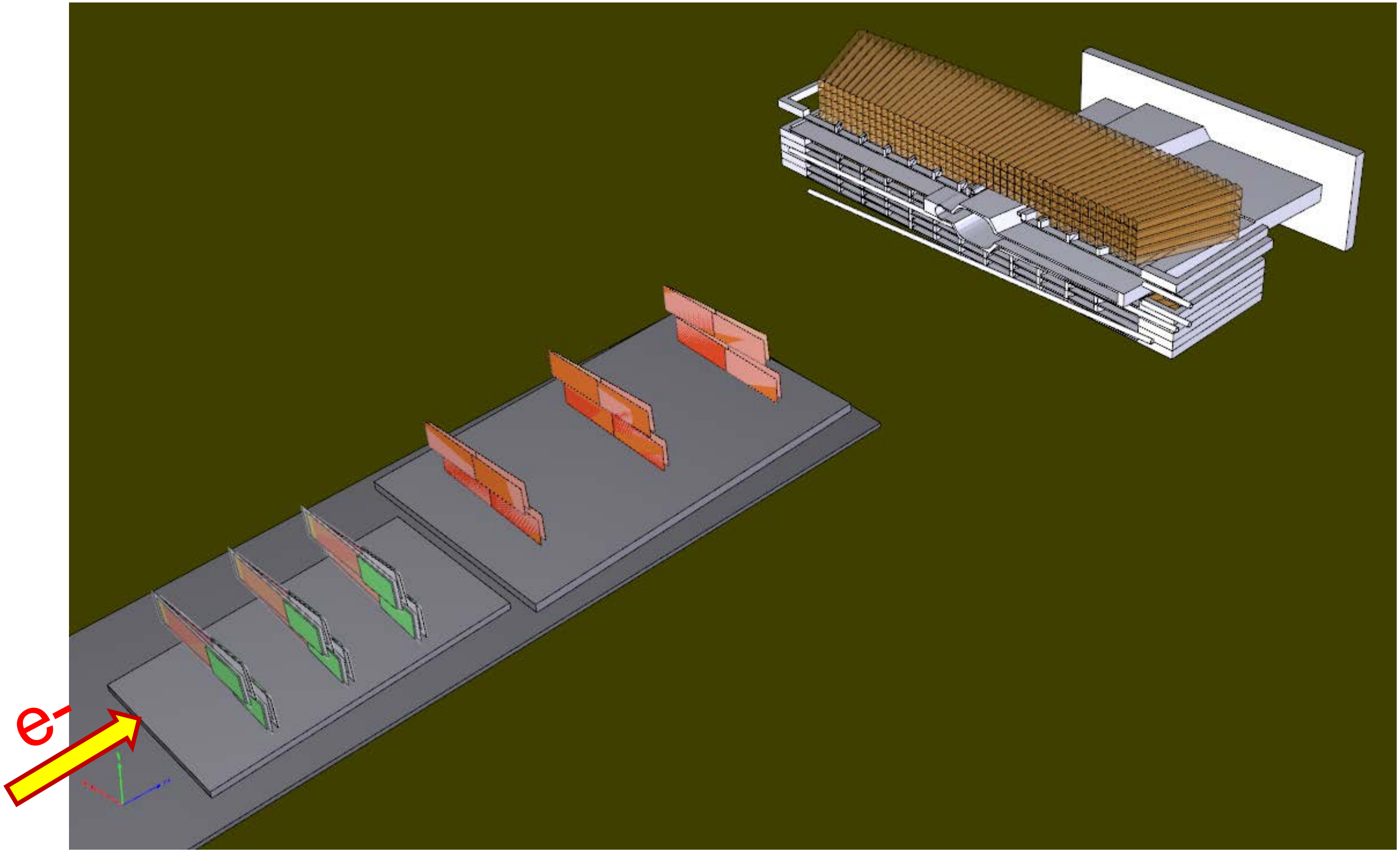
- **Tungsten Target Thin** (10^{-3} X_0) to reduce backgrounds
- **Dipole Analyzing Magnet** small bore (16”x7”), 0.5T for 2.2GeV running
- **6-layer Silicon Vertex Tracker**, composed of stereo pairs of microstrip detectors, split top-bottom and residing in vacuum, measures momentum and decay vertices.
- **442 crystal $PbWO_4$ electromagnetic calorimeter**, also split top-bottom, sits behind the tracker, triggers on e+e- pairs, and identifies electrons.
  - 250MHz FADC readout allows 8ns trigger window
- **FPGA-based Trigger and DAQ** provide 50kHz readout

Simulation & Reconstruction



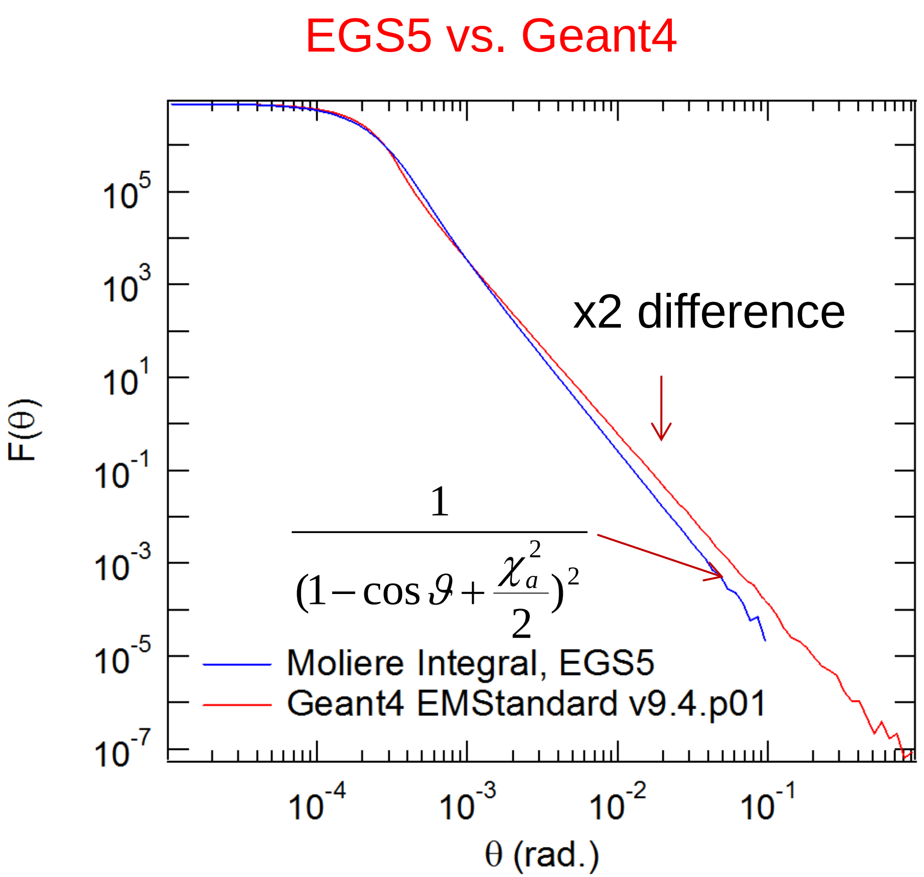
Detector Response Simulation

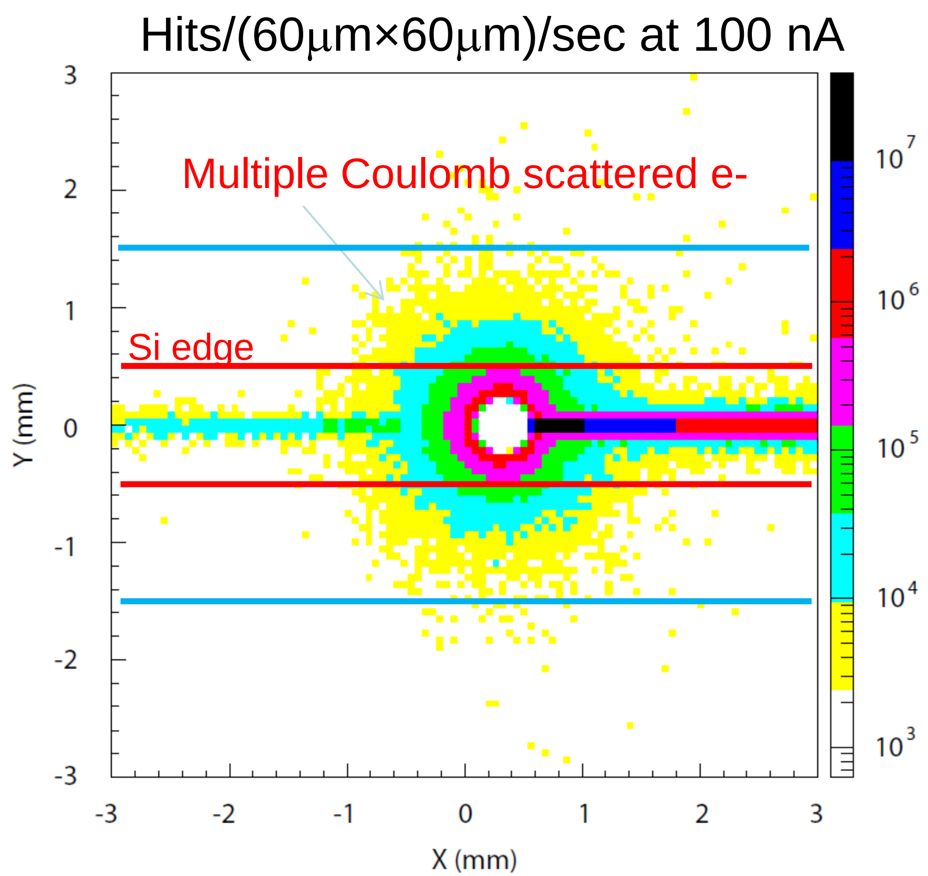
- **Detector response simulation uses the slic and org.lcsim software framework developed for physics and detector studies at the ILC and CLIC.**
- **Geometry defined in xml file, fed into slic, produces output collections of SimTrackerHits, SimCalorimeterHits and MCParticles.**



Multiple Scattering

- **Silicon Trackers will be placed within a millimeter of the beam. Important to understand backgrounds very well in order not to destroy the sensors**



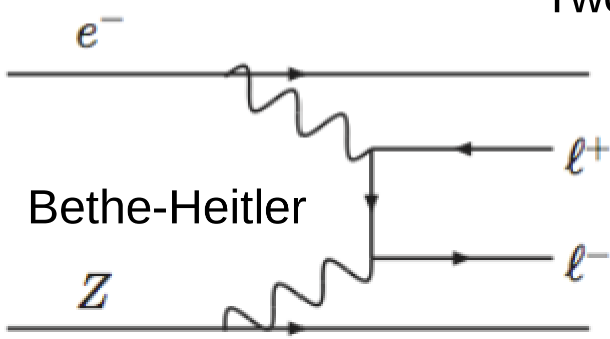


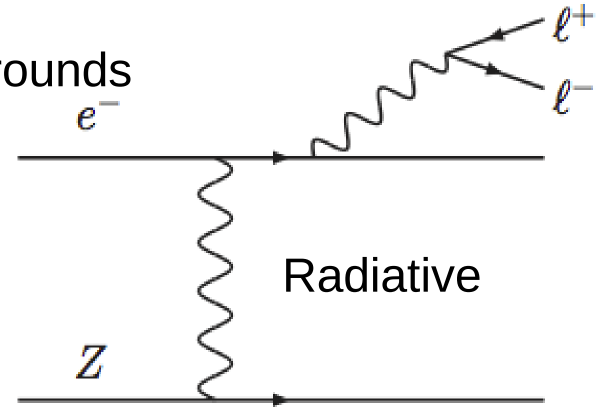
- **Took time to understand differences between Geant4's Urban model and EGS5 / analytic calculation (Geant4 single scattering model agrees)**
- **Pair production and Bremsstrahlung must also be understood**

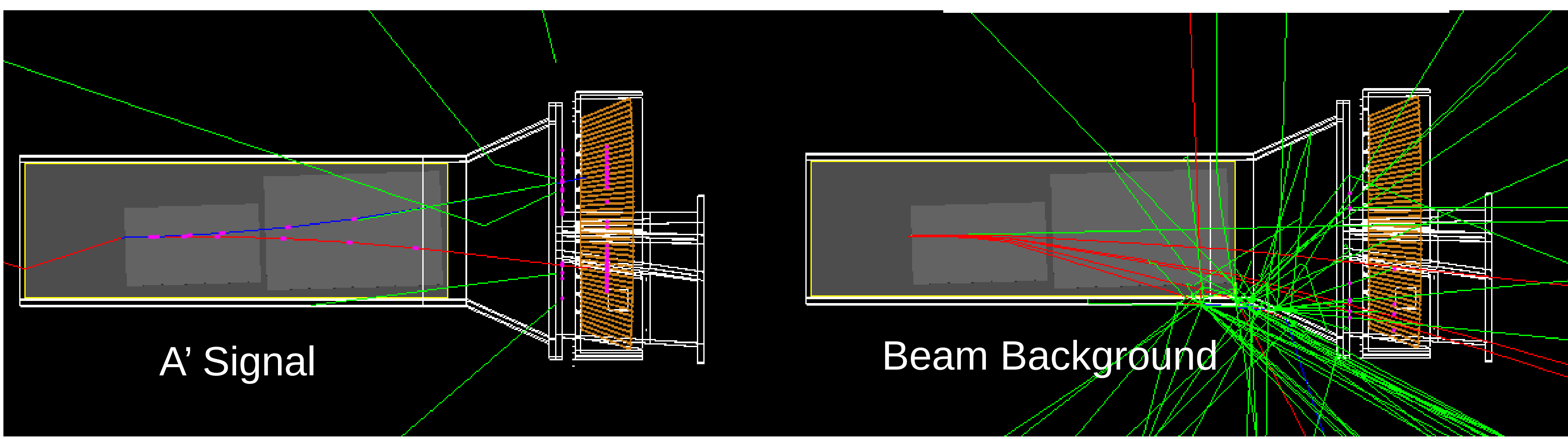
Detector Response Simulation

- **Generate the full gamut of beam backgrounds, tridents and A' signals**
- **Merge generated particles into simulated beam bunches accounting for beam current, size and position.**
- **Run beam bunches through the detector geometry in slic**
- **Process hits through readout simulation to get simulated raw data**

Two Main Backgrounds

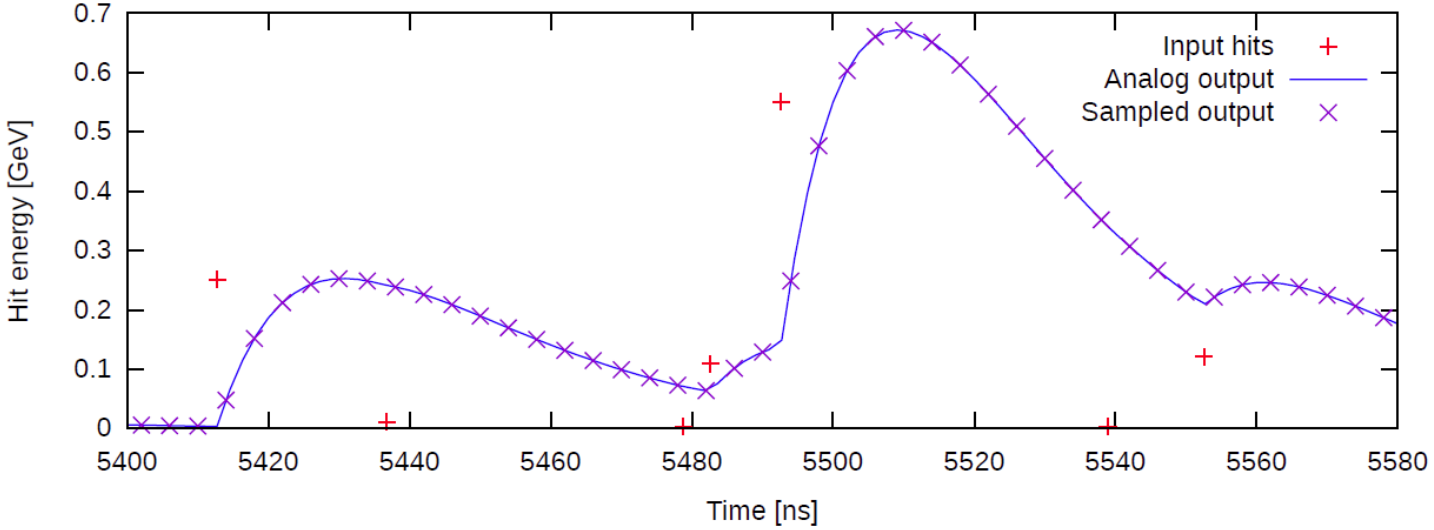






EM Calorimeter and Trigger

- **Repurposed existing $PbWO_4$ modules from CLAS inner calorimeter**
- **New 10x10 mm^2 APD readout**
- **Large occupancy due to proximity to primary beam**
  - **~10% occupancy**
- **Layout optimized using flexible slic/lcsim simulation package**
- **Crystal response, FADC readout and online trigger processor algorithm simulated (with time-shifted overlay of backgrounds)**



- **Clustering provides shower time, position and energy.**
- **Combined with track, produces ReconstructedParticle object used for subsequent analysis.**

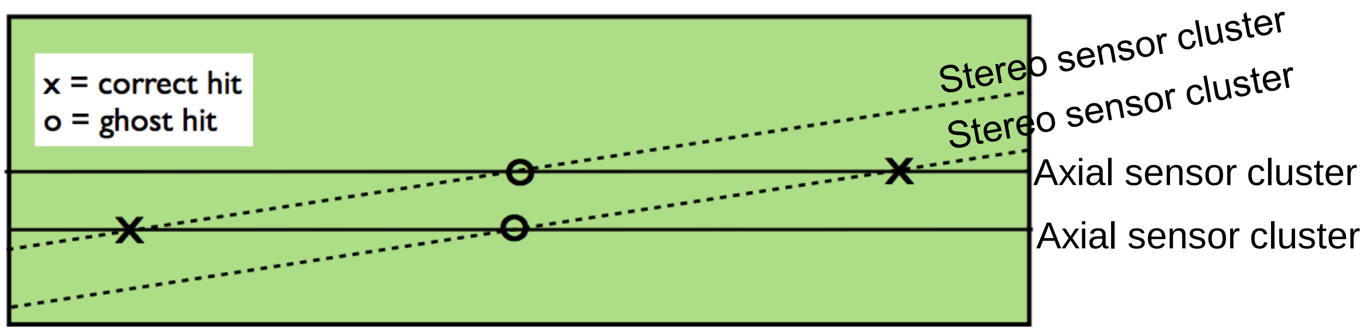
Tracker Hit Digitization

Forming hits from Geant4 energy depositions:

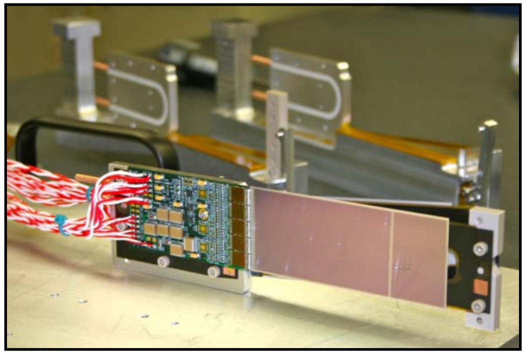
- Charge deposition
  - Take energy deposit from Geant4 step and drift and diffuse it through the sensitive silicon
  - Turn energy deposits into charge on nearby strips
  - Include Lorentz angle, diffusion, capacitive coupling, noise
- Readout Segmentation and Clustering
  - Map strip charges onto the readout segmentation
  - Sum charges when multiple particles produces charge on the same strip
  - APV25 (developed for CMS) preamplifier and shaper produce CR-RC shaping curve. HPS reads out 6 samples at 24ns intervals: 2 before expected t0 and 4 after. Simulation overlaps hits in trigger time window, fits for signal time and amplitude ~2ns hit resolution
  - Use hit times to reject beam backgrounds
  - Find clusters of strips and form “TrackerHit” with hit position and error

Hit and Track Finding

- Build clusters from sensor strips
- Build 3D hits from (2D) strip clusters

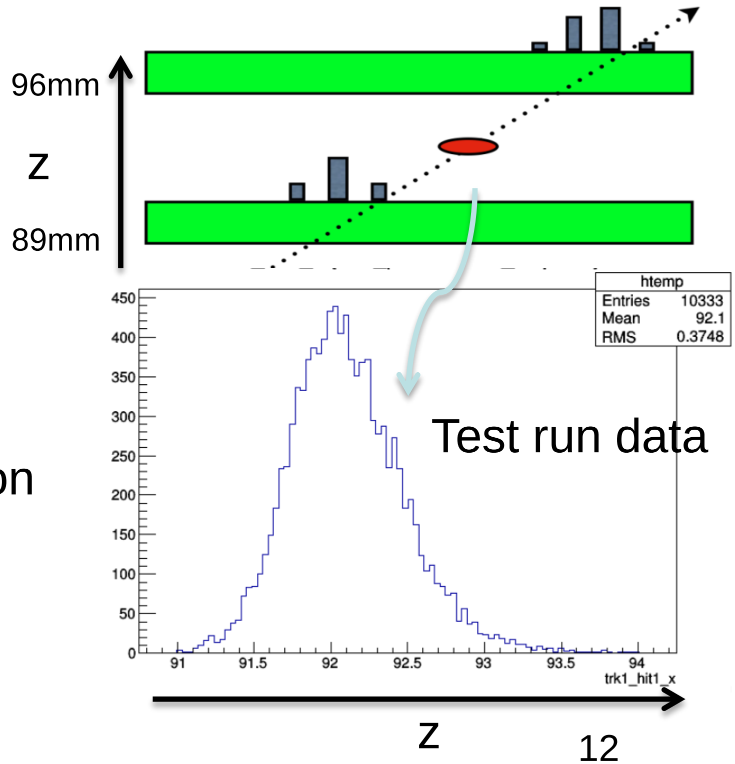


Test run stereo pair module



Take all combinations of clusters in adjacent stereo pair sensors to build "stereo hits"

- Starting 3D hit position is taken as midway between clusters
- Reject *very* bad combinations (not pointing to target)
- Stereo hit positions are updated with track direction in track finding/fitting



- Track Finding Inherited from linear collider simulation
- Seed-confirm-extend philosophy
  - Very fast: test often, reject early
  - Based entirely on stereo hits
- Track finding is governed using a "Strategy"

SeedTracker Track Finding Algorithm

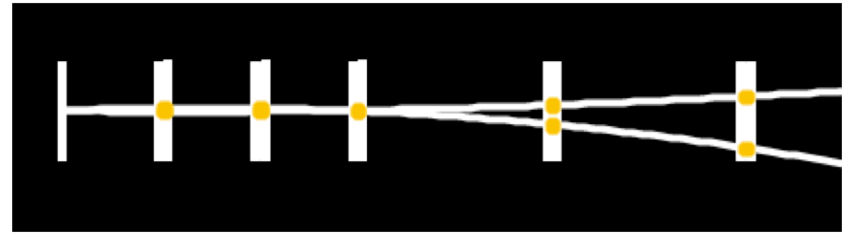
- Track finding begins by forming all possible 3 hit track seeds in the three “Seed Layers” (specified in the strategy)
  - Brute force approach to finding all possible track seeds
- Typically require the presence of a hit in a “Confirmation Layer” (specified in the strategy)
  - Significantly reduces the number of candidate tracks to be investigated
- Add hits to the track candidate using hits on the “Extension Layers” (specified in the strategy)
  - Discard track candidates that have fewer that the minimum number of hits specified in the strategy
  - If two track candidates share more than one hit, best candidate is selected
- Upon each attempt to add a hit to a track candidate, a helix fit is performed and a global χ^2 is used to determine if the new track candidate is viable
- Hooks for user-defined diagnostics at all decision points

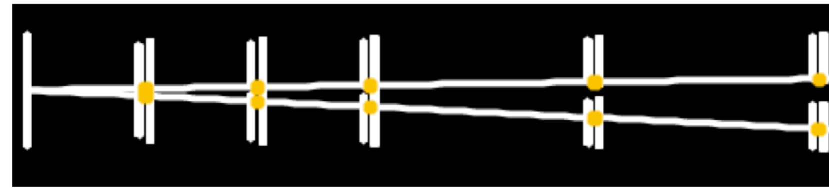
Track Fitting

- Fit track in two independent views (const. magnetic field)
- Circle fit in the “bend plane”
- Straight line fit in non-bend plane

- Both are fast non-iterative fit algorithms
- Parameter estimations
- Covariance matrix
- (Seed)Track finding uses these algorithms at each step

⇒ Merge final fit into a “helix” track object together with the hits of the track





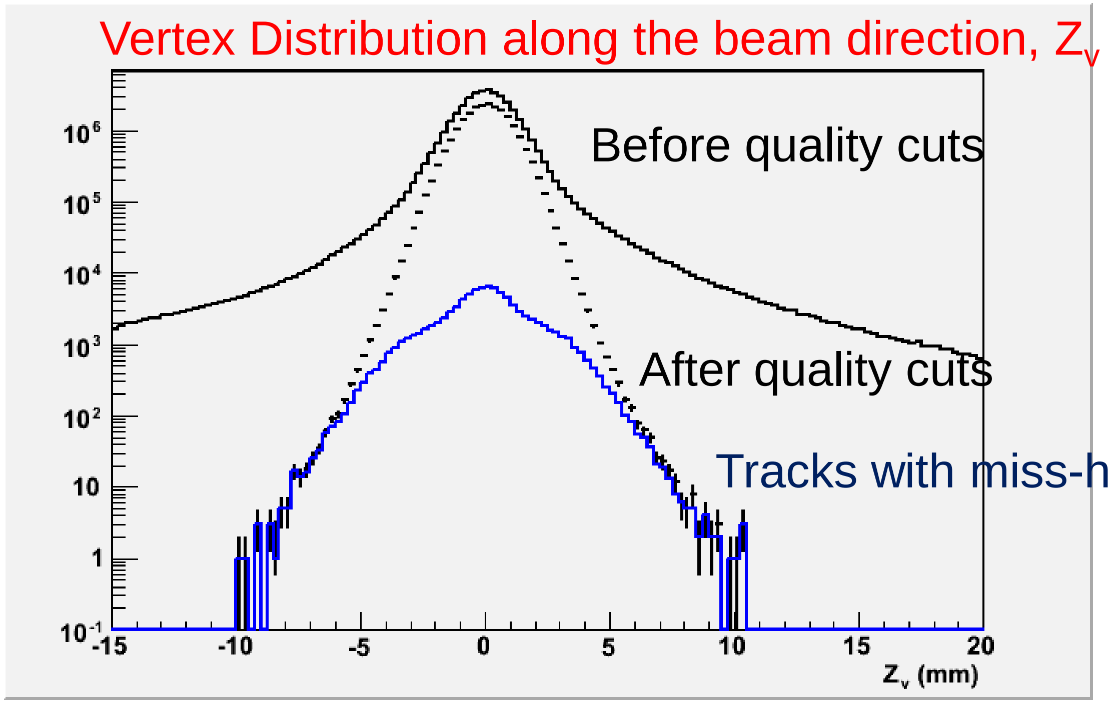
- Single hit efficiency > 99%
- Track efficiency > 95%
- Hit resolutions: $\sigma_x < 125\mu m$, $\sigma_y < 10\mu m$
- Momentum resolution ~5%
- Resolution dominated by multiple scattering

Track Re-Fitting and Alignment

- Found tracks are refitted using the General Broken Lines (GBL) approach
  - C++ code ported to Java
- Provides convenient link to alignment package Millepede-II
  - hps-java writes out binary format
- Alignment constants returned by millepede-II are fed into compact.xml file to provide aligned geometry
  - used for reco and simulation (if desired)

Vertexing

- Using the Billoir implementation of the Kalman filter vertexing with the perigee parameterization.
- Simulated tracking efficiency is >95% with beam backgrounds included. Only 5% of tracks have miss-hits, which can cause vertex tails, and spoil reach.
- Track quality, vertex quality, and trajectory cuts nearly eliminate vertex tails.

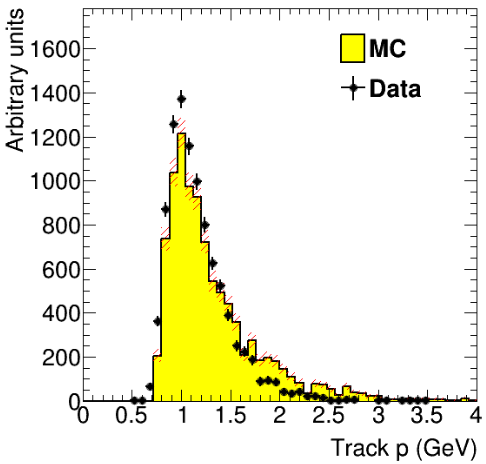


$m_{A'}$= 200 MeV
E_{beam}= 5.5 GeV

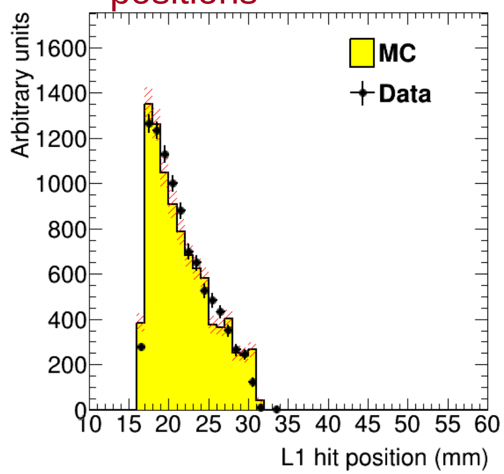
Test Run Data Analysis

The Heavy Photon Search Test Detector, NIM A (2015), pp. 91-101

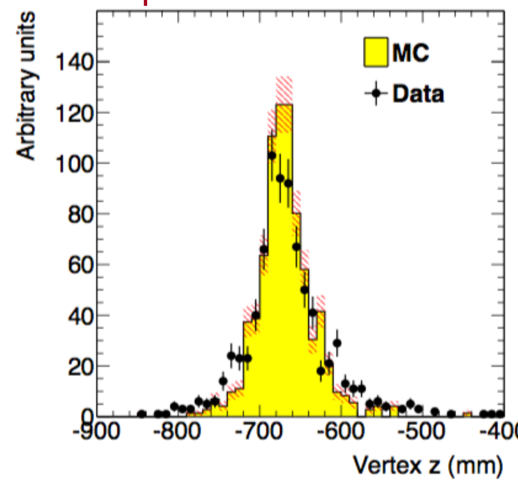
Track momentum



Vertical stereo hit positions

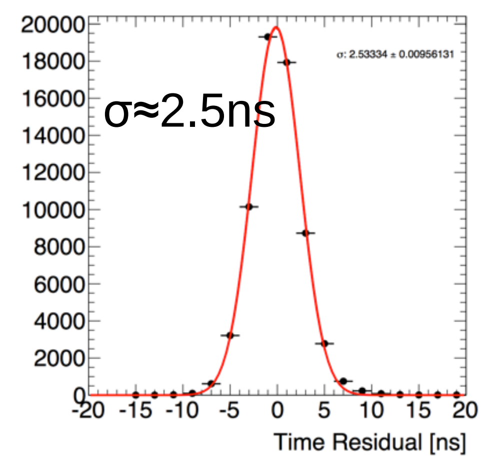


Converter (vertex) position

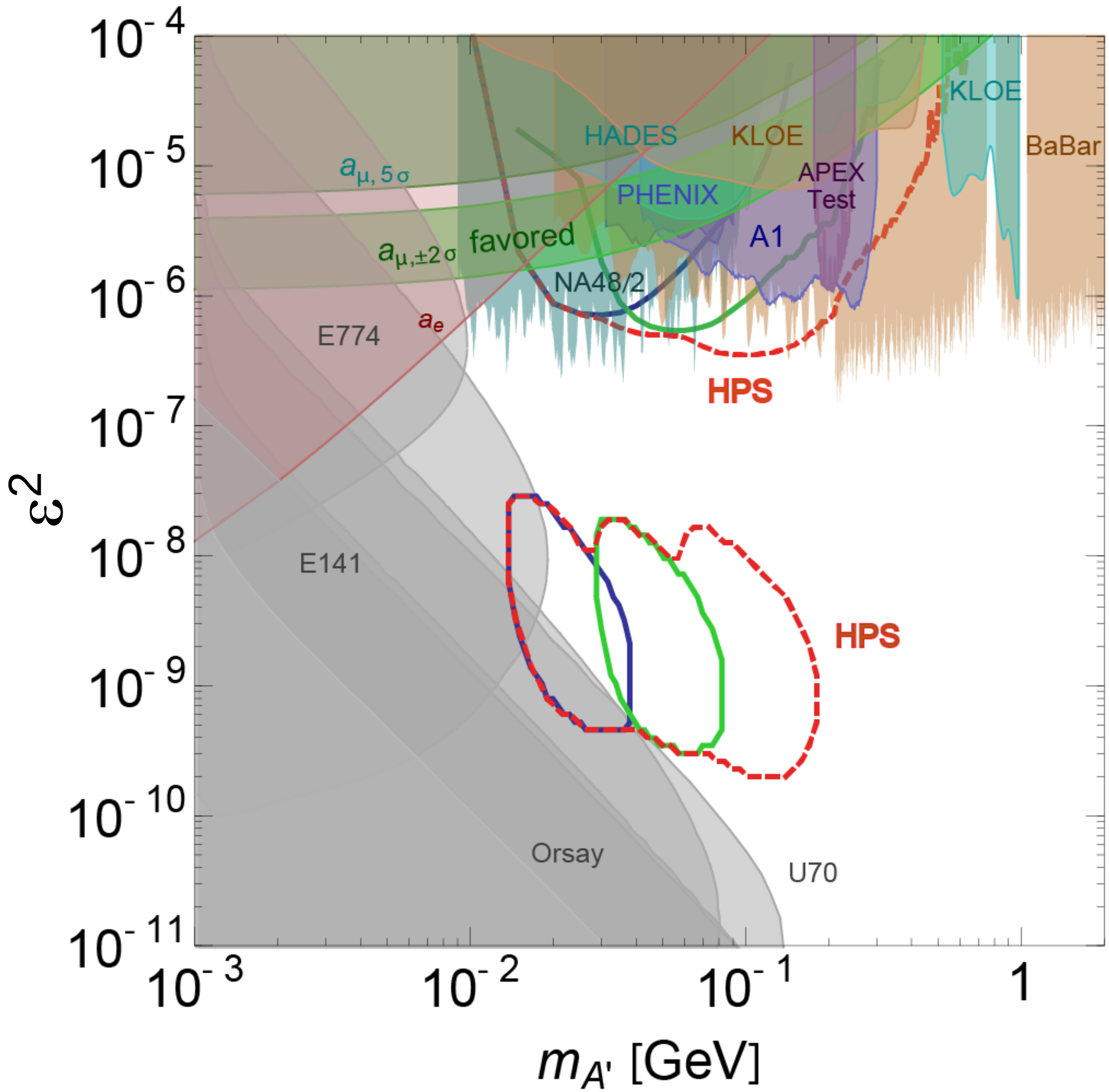


- Data taken during a short parasitic test run (2012) with a photon beam
- Conceived, built and installed detector in ~14 months!
- Demonstrated FADC, trigger and DAQ rates
- Good performance then, tracking code now even better.

Hit time residuals



HPS Reach



One week @ 1.1 GeV

One week @ 2.2 GeV

Two weeks @ 4.4 GeV

Conclusions

- HPS is a new experiment at JLAB, dedicated to searching for heavy photons with masses 10-200 MeV and couplings $10^{-3} < \varepsilon < 10^{-5}$ in unexplored regions of parameter space.
- HPS uses a large acceptance forward spectrometer, operating close to the incident electron beam. It depends on the accelerators' ~100% duty cycle and high-rate electronics and DAQ to integrate large luminosities in this environment.
- Use of existing simulation and reconstruction software (developed for the ILC collider detectors) minimized the time needed to design and optimize detector.
- Proximity to the high-current electron beam at JLab forced careful review of background simulations, especially multiple scattering in Geant4
- Java-based reconstruction software working well
- Invariant mass and vertexing signatures let HPS achieve sensitivity to very small values of the A' coupling. Using invariant mass alone, HPS covers ε^2 > few x 10^{-7} for $10 < m_{A'} < 200$ MeV.
- HPS is installed in Hall B at JLAB and is currently being commissioned.
- Beam is imminent.
- Looking forward to physics data run!