The Heavy Photon Search Experiment

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on behalf of the HPS Collaboration

LDMA2015, Genoa

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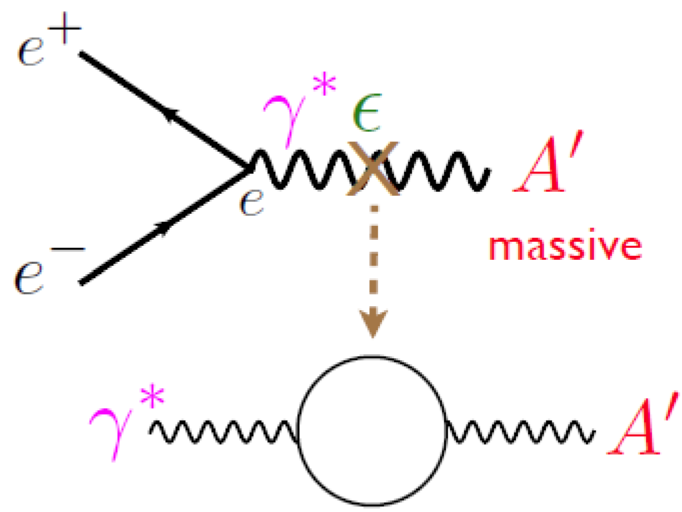
Outline

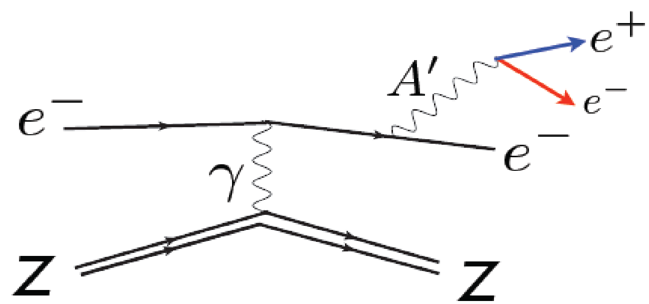
- Motivation
- Construction
- Simulation
- Reconstruction
- Commissioning
- Calibration
- Prospects

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.**



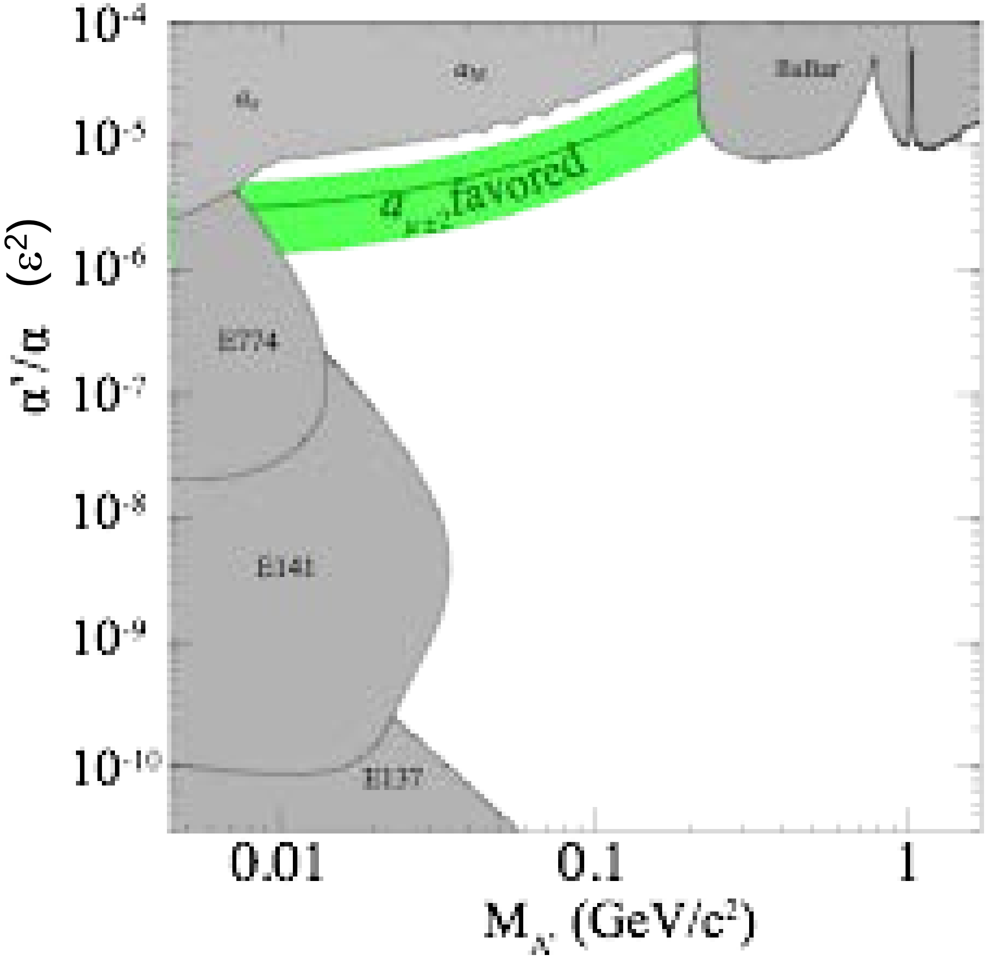
Produced by bremsstrahlung off heavy targets and subsequent decay to e+e-



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

Increasing Interest

- 2010 limits set primarily by beam dump experiments.



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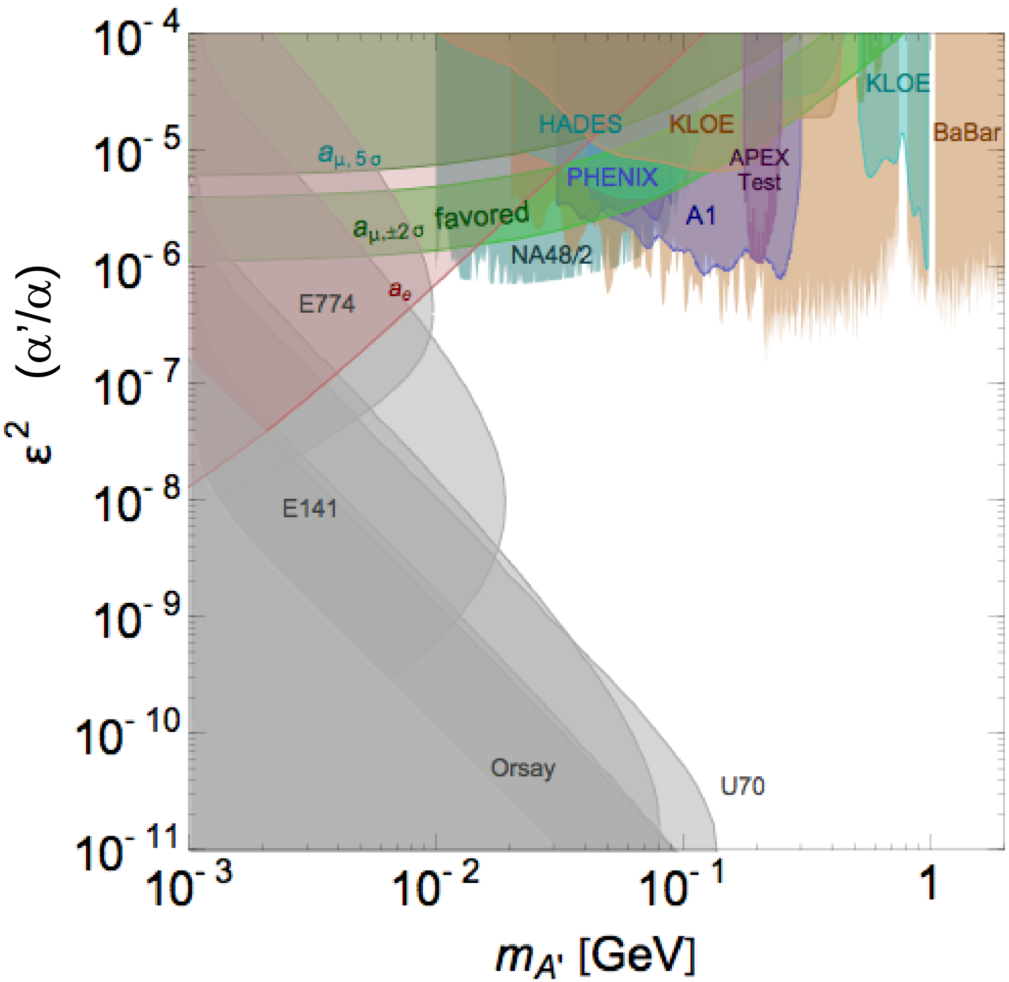

- By 2015 multiple approaches extending limits

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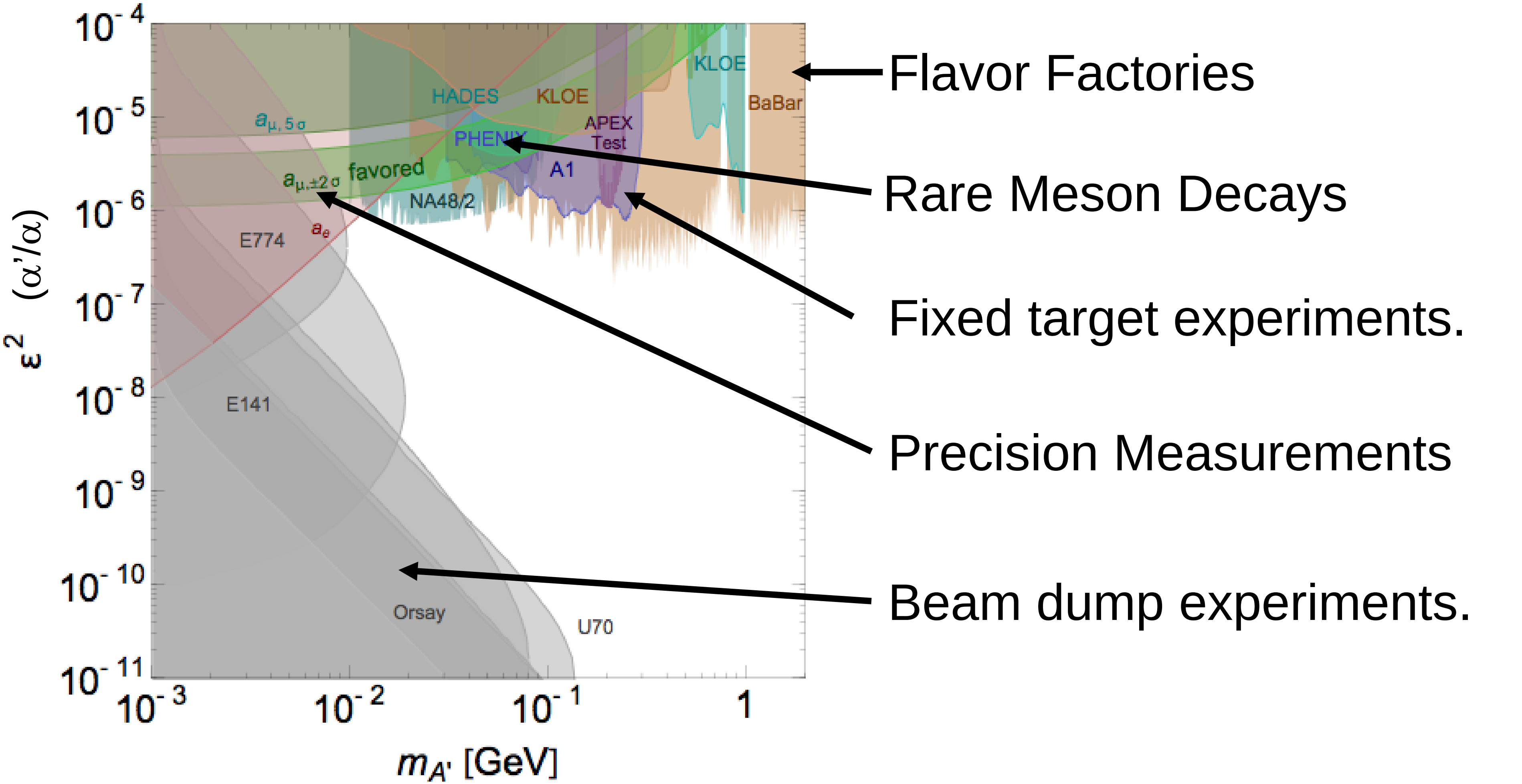
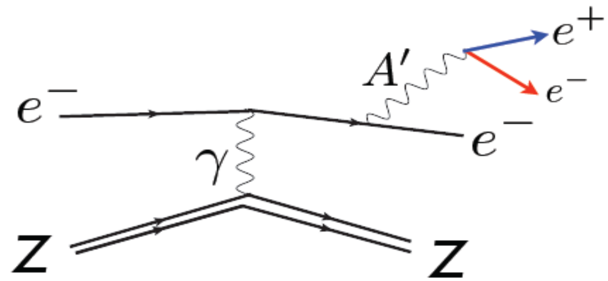


- By 2015 multiple approaches extending limits

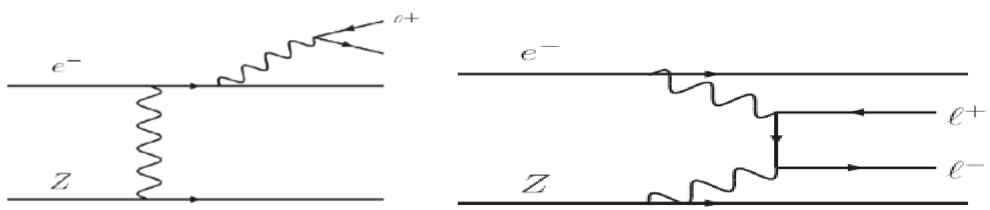
Searching for an A' with HPS

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

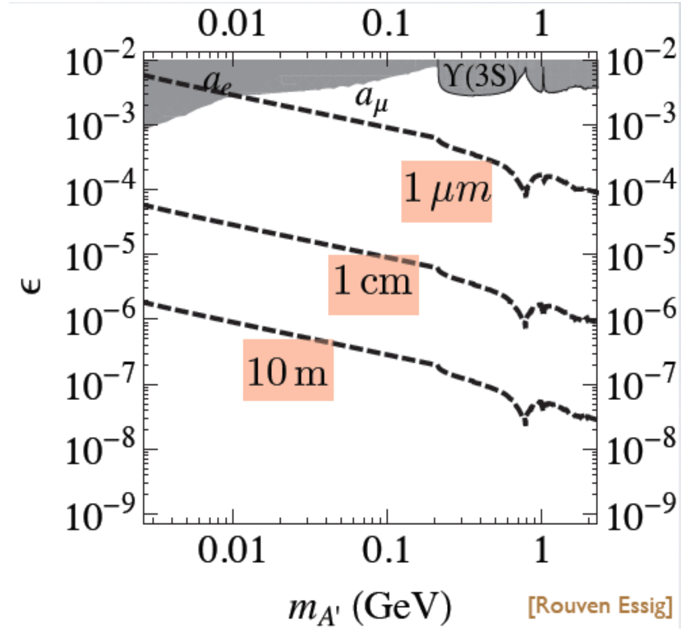
Signal



Background

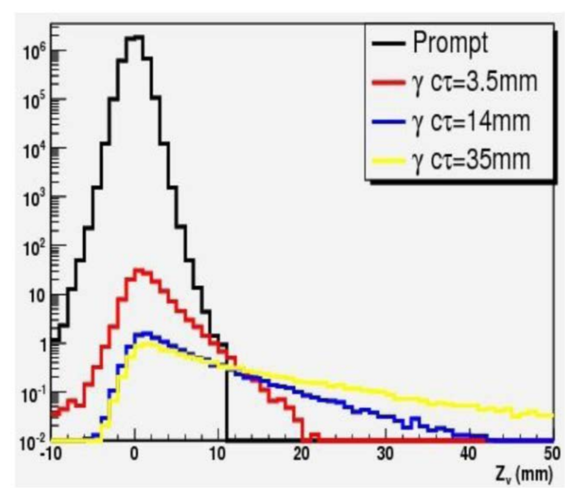


Decay Length cτ

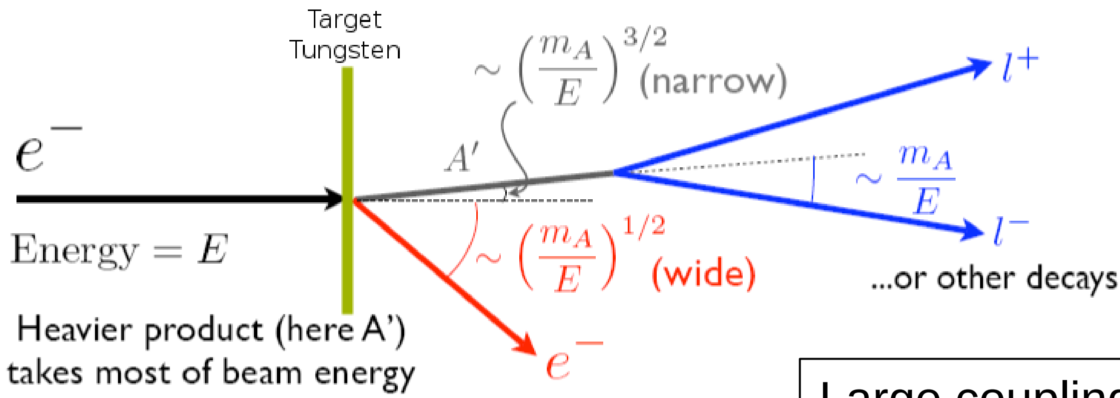


- **Precision Tracking and Vertexing essential** Invariant mass peak and secondary vertex signatures powerfully discriminate against the prompt trident background.
- **Precise simulation essential** The A' decay length signal is in the tails of the prompt trident signal. HPS must understand and control the tails of the trident vertex distribution. Full simulation confirms this is possible.

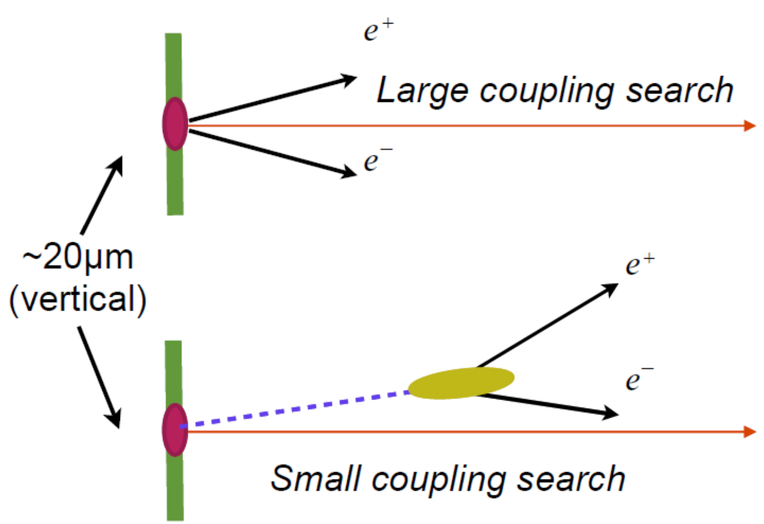
Vertex Distribution



A’ Searches: Bump-Hunt and Vertexing



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



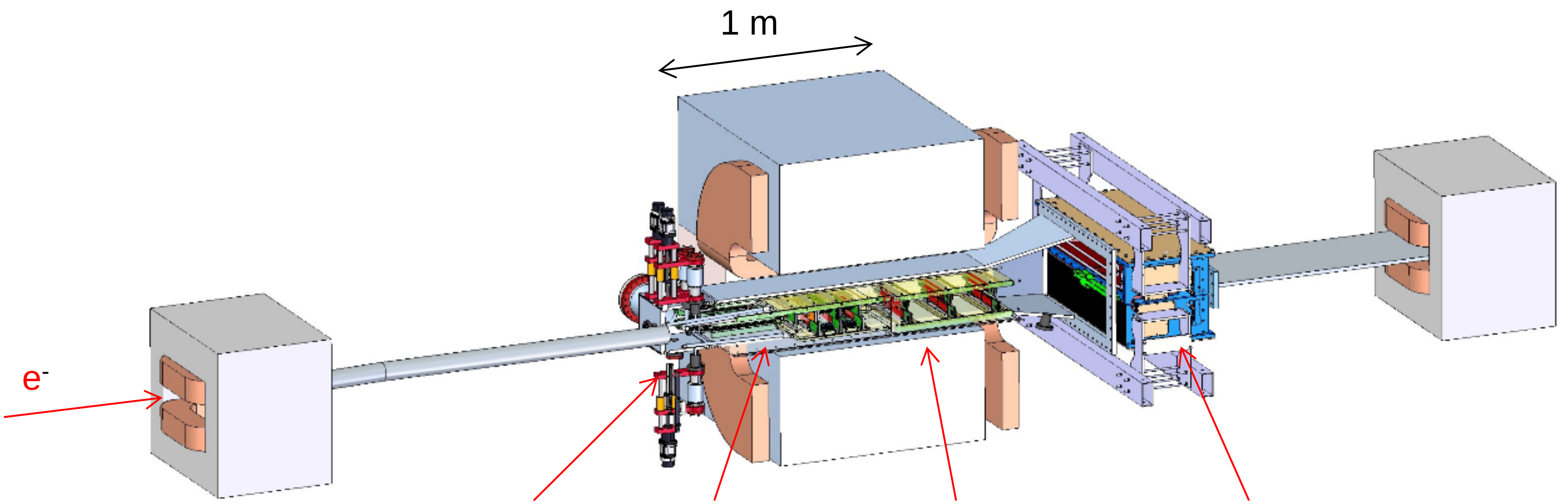
Large coupling regime:
A’ decays in target ∴ constrain e+e- to originate from beamspot
Search for peak in invariant mass plot

Small coupling regime:
A’ decays outside of target ∴ constrain A’ to originate from beamspot
Search for displaced vertex + mass peak

Including recoil e- along with e+e- pair would improve mass resolution

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

HPS Detector



- **Thin Tungsten Target** (10^{-3} X_0) to reduce backgrounds
- **Dipole Analyzing Magnet** small bore (16”x7”), 0.24T for 1.056GeV 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** provided 20kHz readout

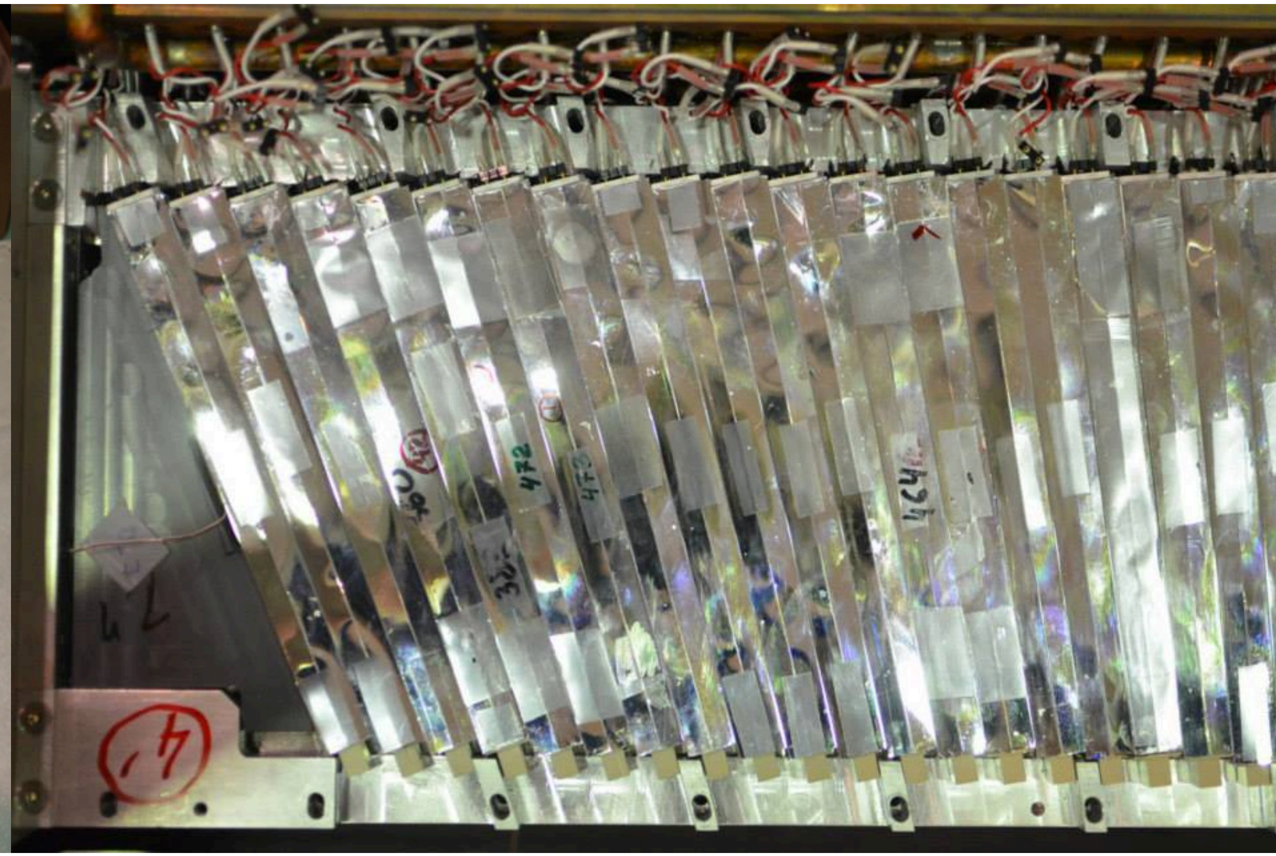
HPS Construction

- Conceived, built and installed HPS proof-of-concept detector in ~14 months.
- Data taken during a short parasitic test run (2012) with a photon beam, demonstrated FADC, trigger and DAQ rates.

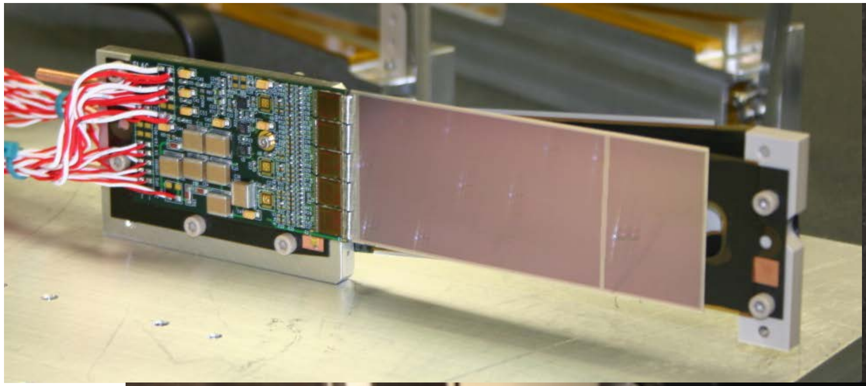
The Heavy Photon Search Test Detector, NIM A (2015), pp. 91-101

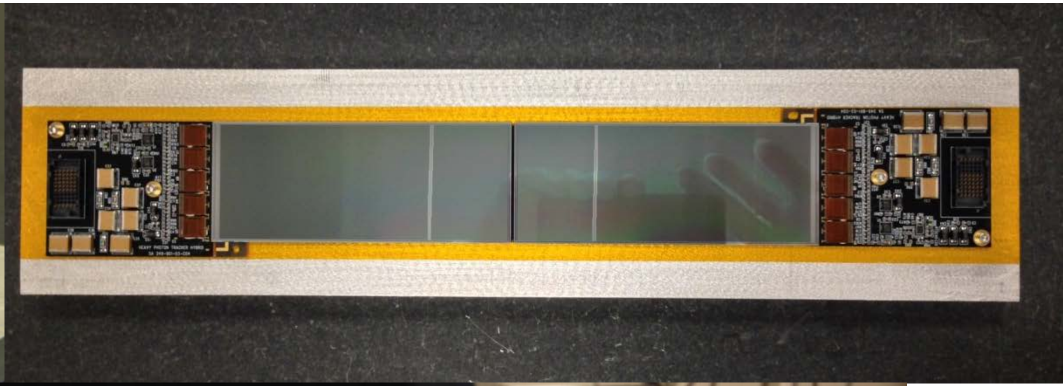
- Upgraded $PbWO_4$ Ecal installed September, 2014
- Improved six-layer Si Vertex Tracker installed February 23, 2015

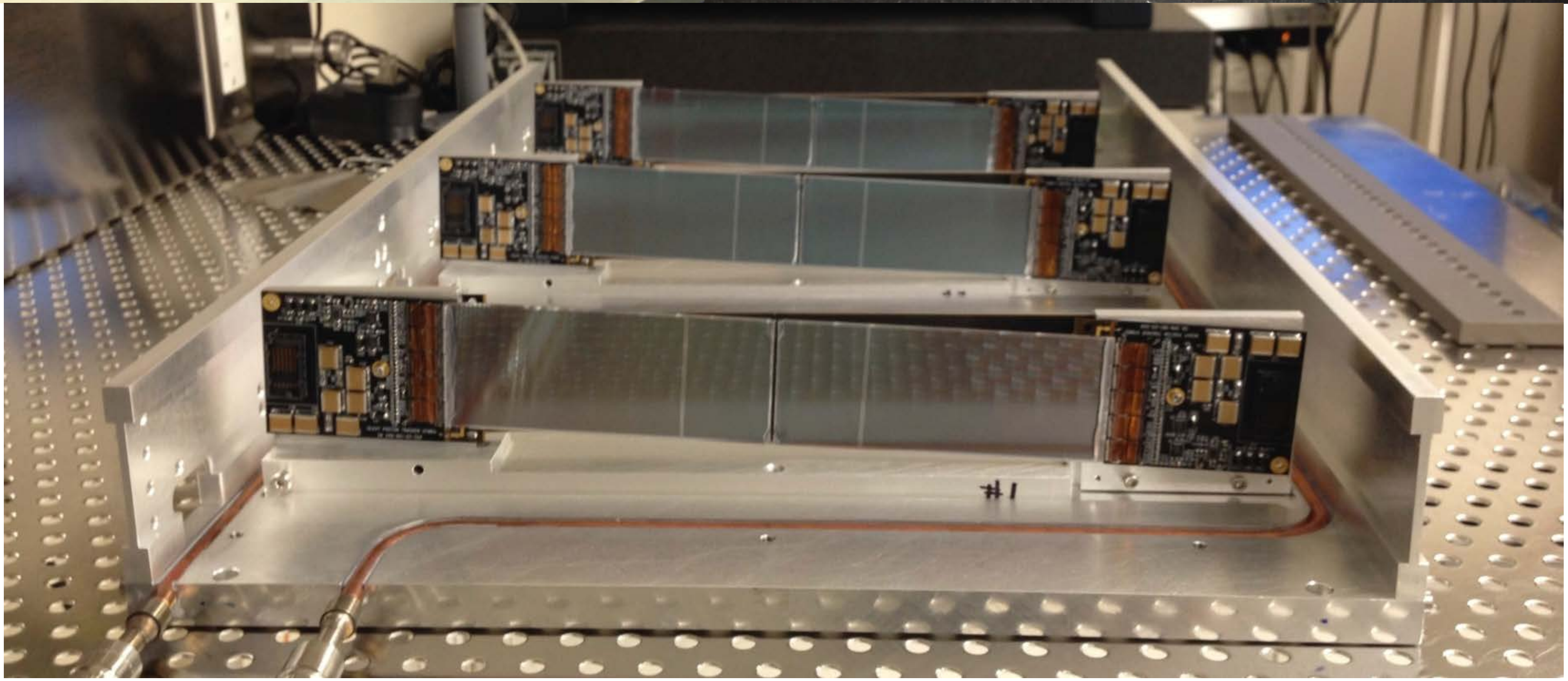
Crystal ECal



Silicon μ-strip Tracker







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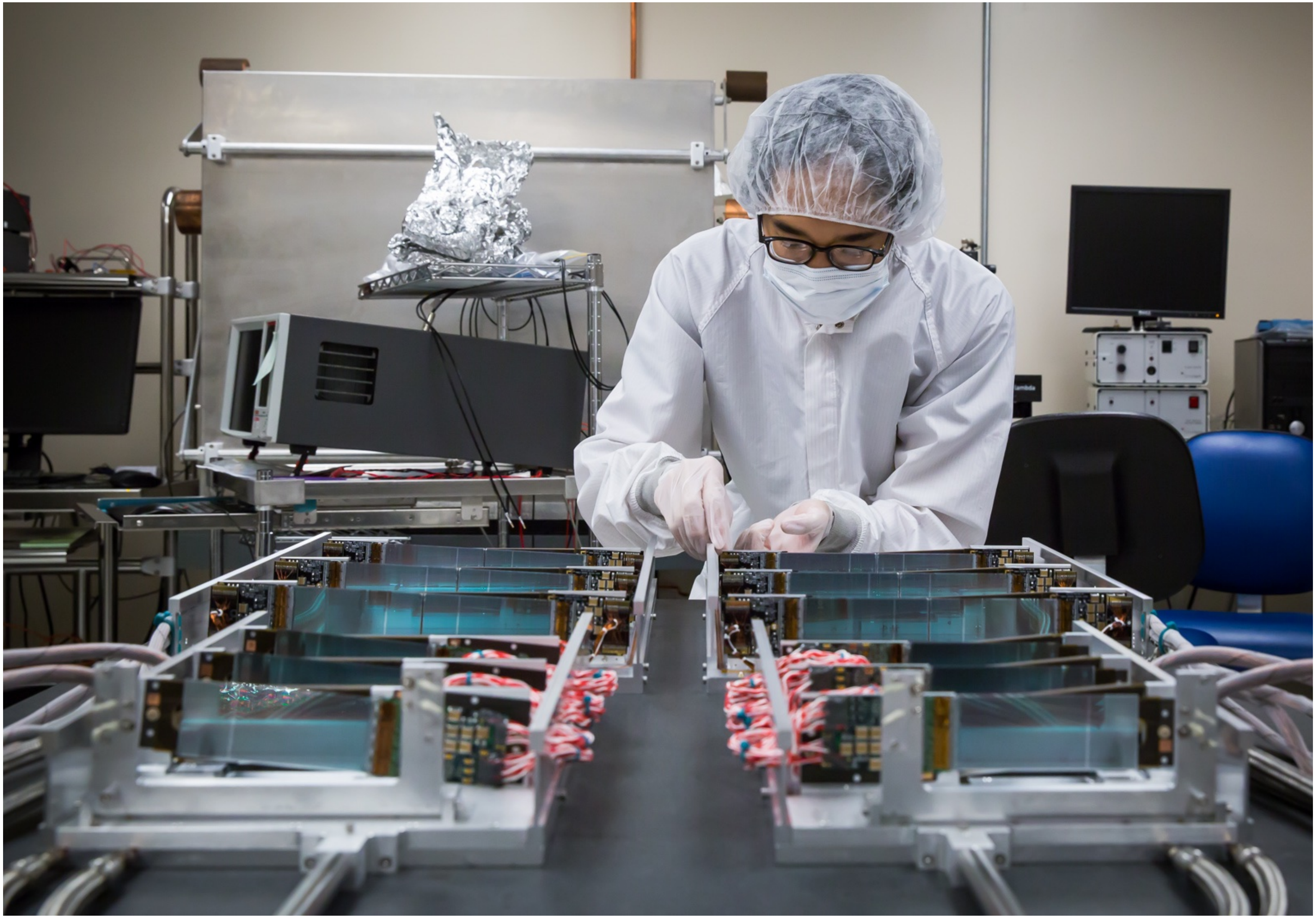
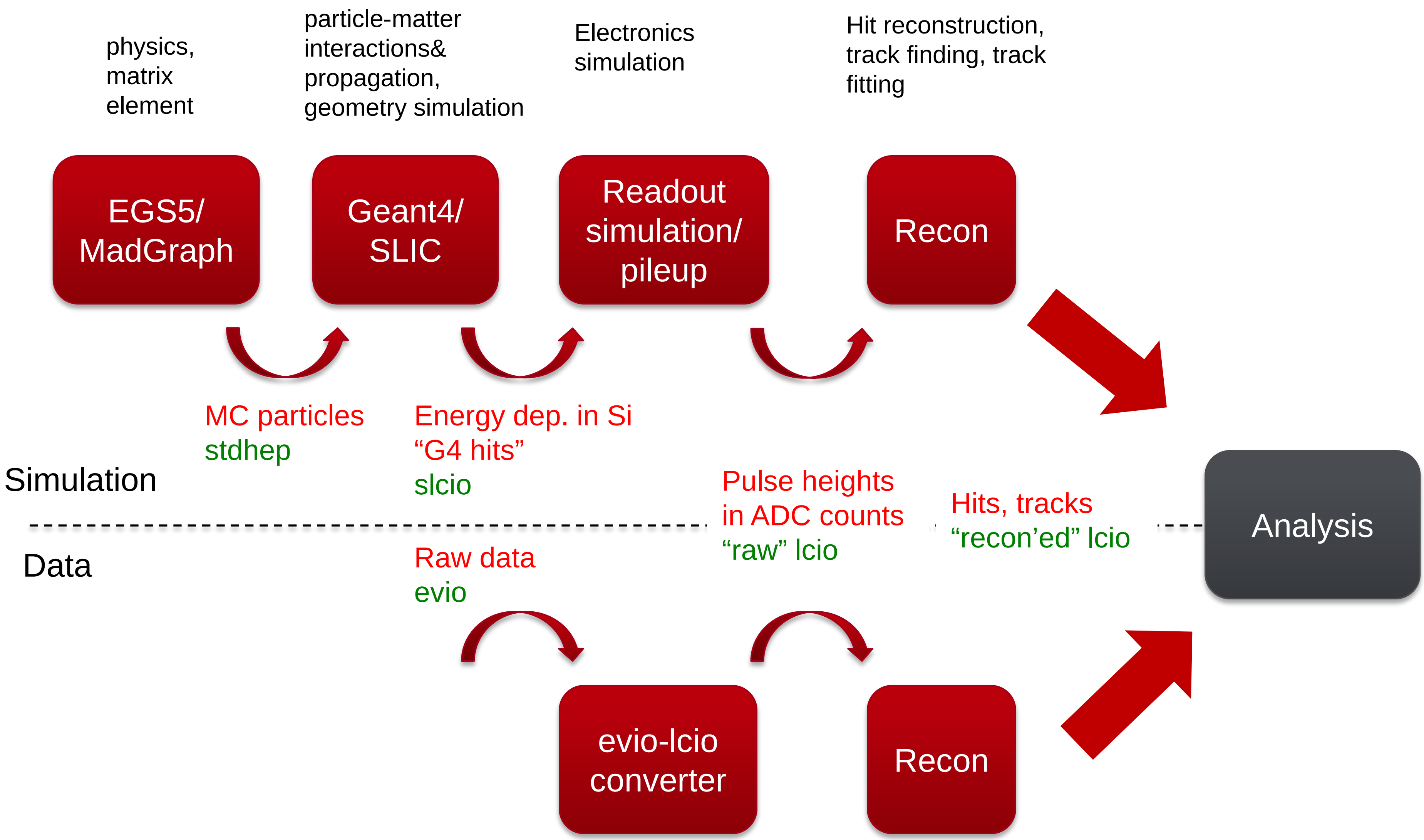
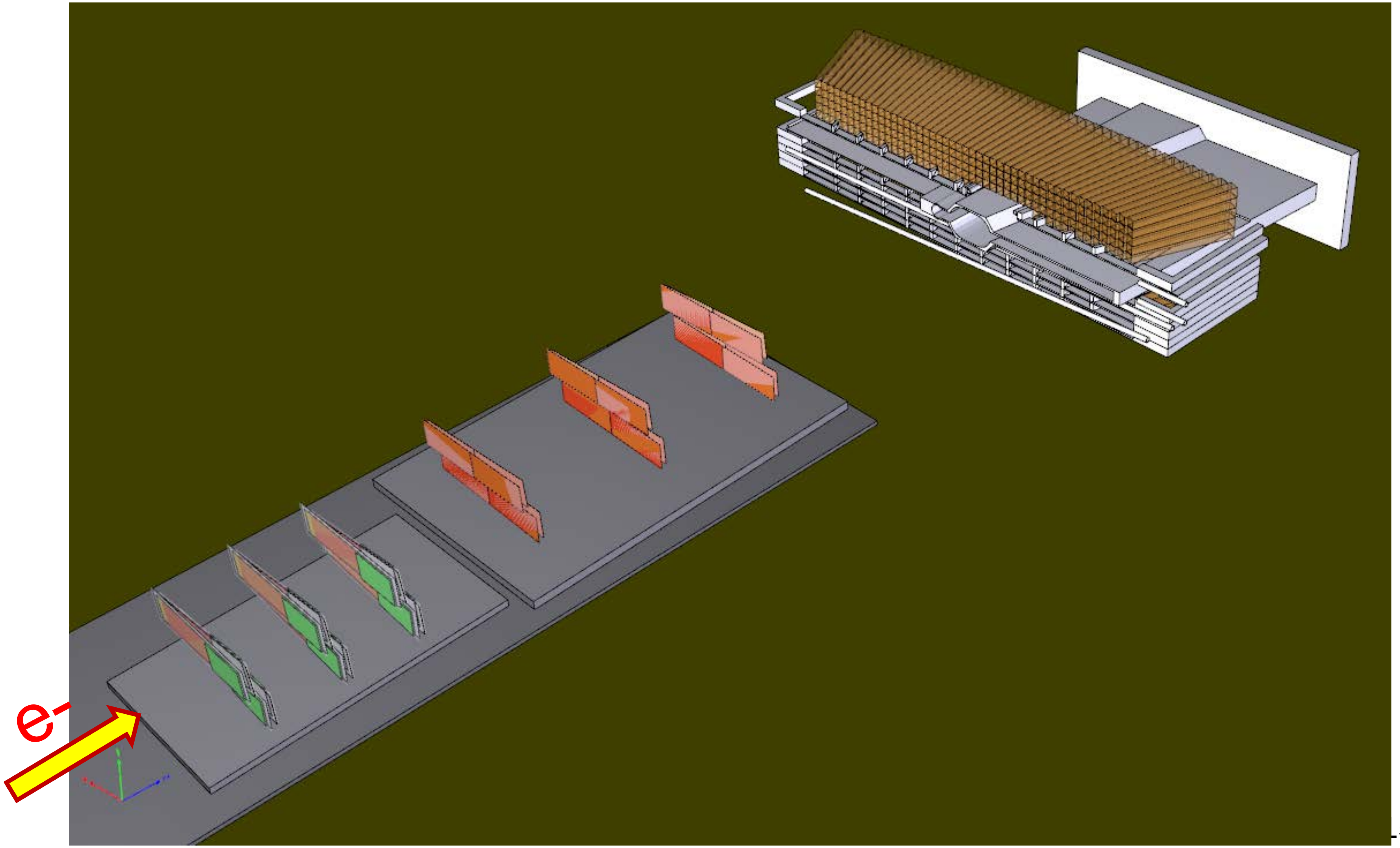


Simulation & Reconstruction



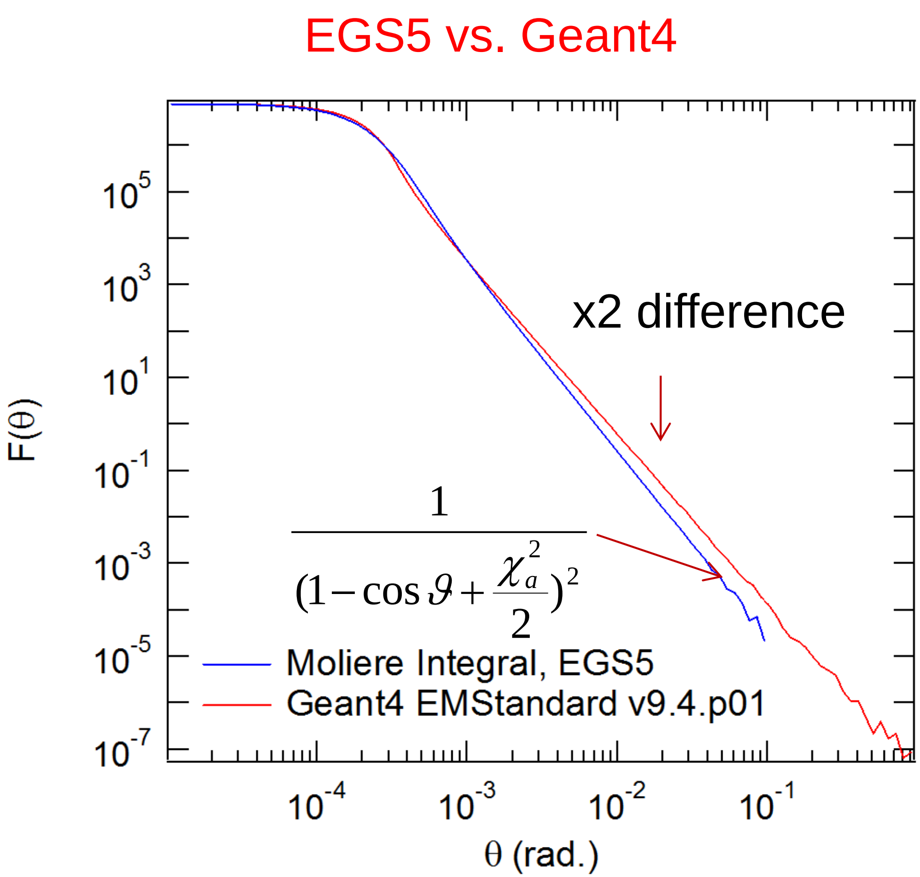
Detector Response Simulation

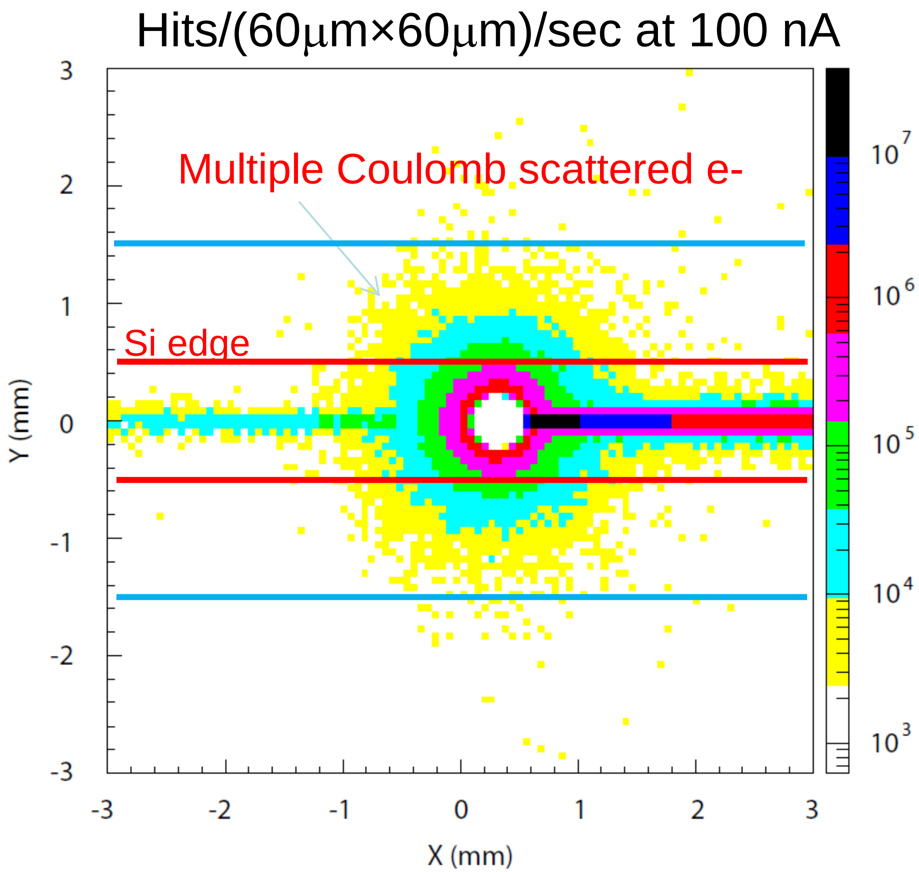
- **Detector response simulation uses the slic and org.lcsim software framework developed for physics and detector studies at the ILC and CLIC.**
- **Geometry defined in xml file, fed into slic, produces output collections of SimTrackerHits, SimCalorimeterHits and MCParticles.**



Multiple Scattering

- **Silicon Trackers were placed 0.5mm from the beam. Important to understand backgrounds very well in order not to destroy the sensors**



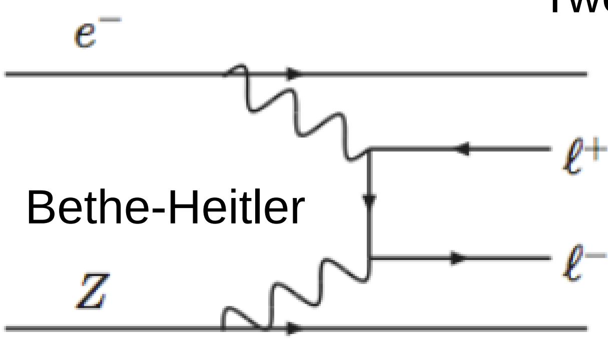


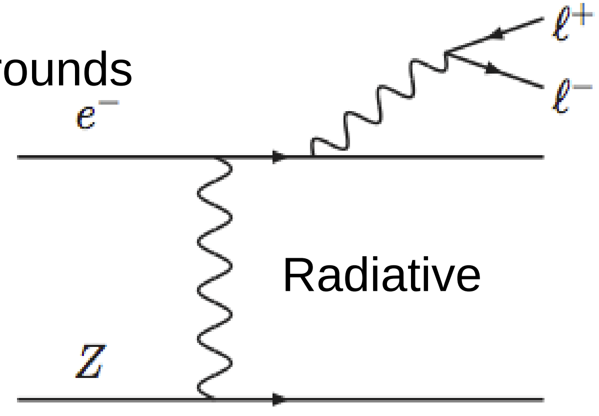
- **Took time to understand differences between Geant4's Urban model and EGS5 / analytic calculation (Geant4 single scattering model agrees)**
- **Pair production and Bremsstrahlung must also be understood**

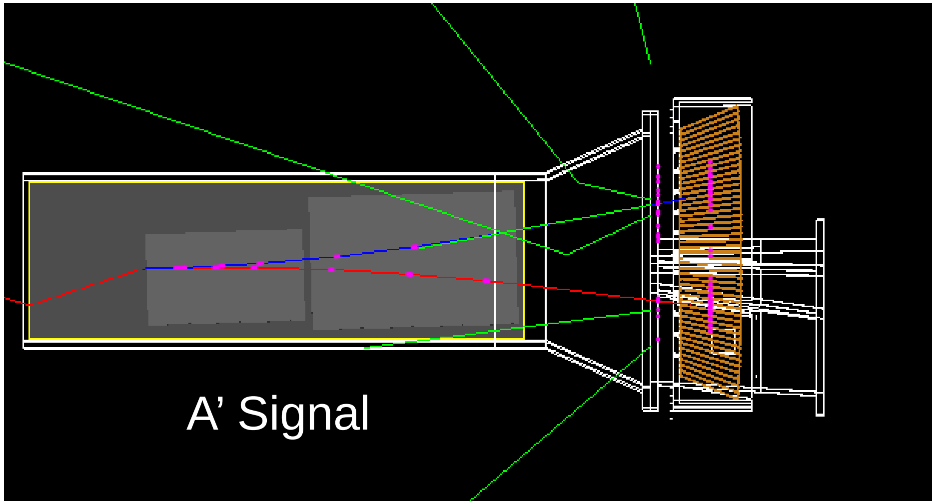
Detector Response Simulation

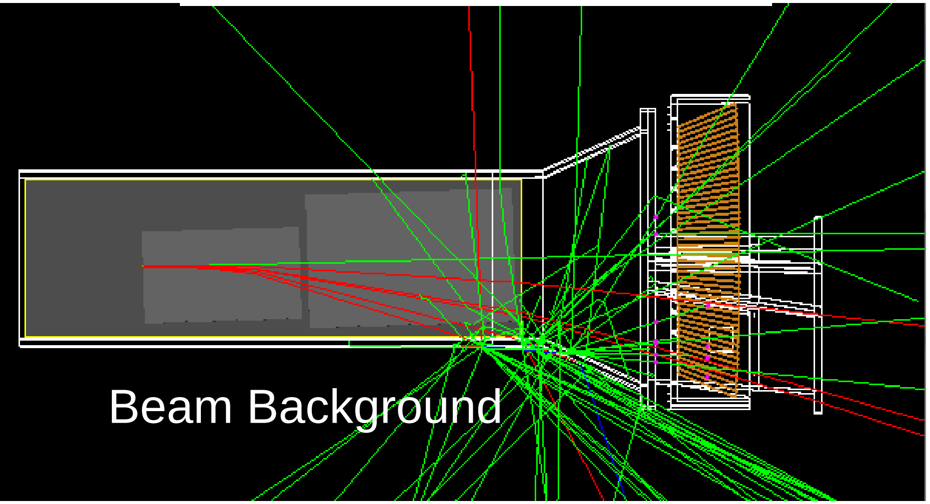
- Generate the full gamut of beam backgrounds, tridents and A' signals
- Merge generated particles into simulated beam bunches accounting for beam current, size and position.
- Run beam bunches through the detector geometry in slic
- Process hits through readout simulation to get simulated raw data

Two Main Backgrounds



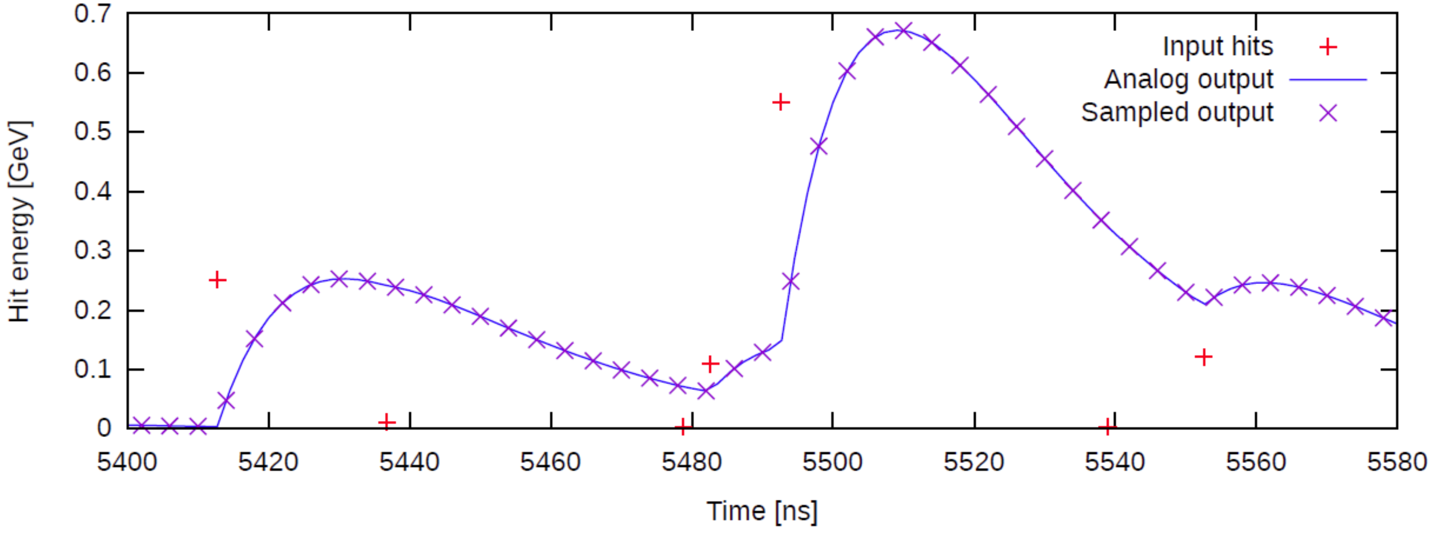






EM Calorimeter and Trigger

- **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

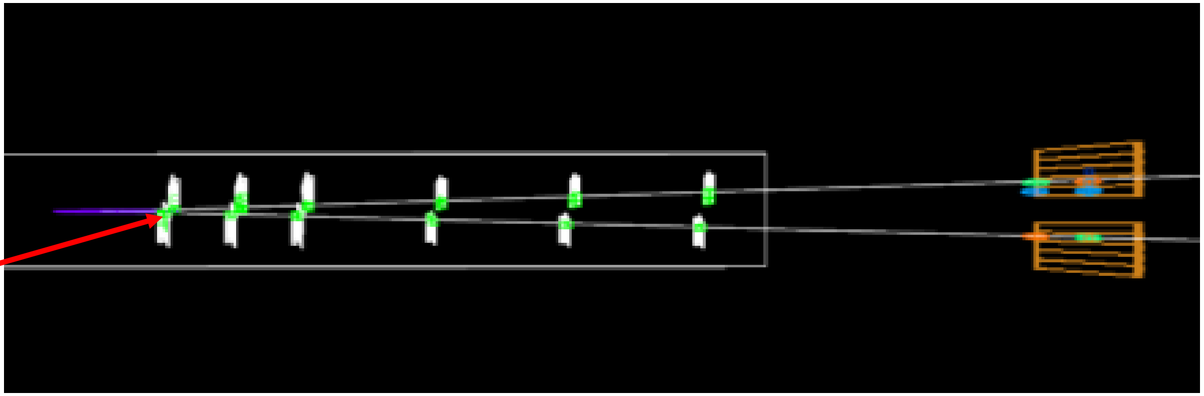
Forming hits from Geant4 energy depositions:

- 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

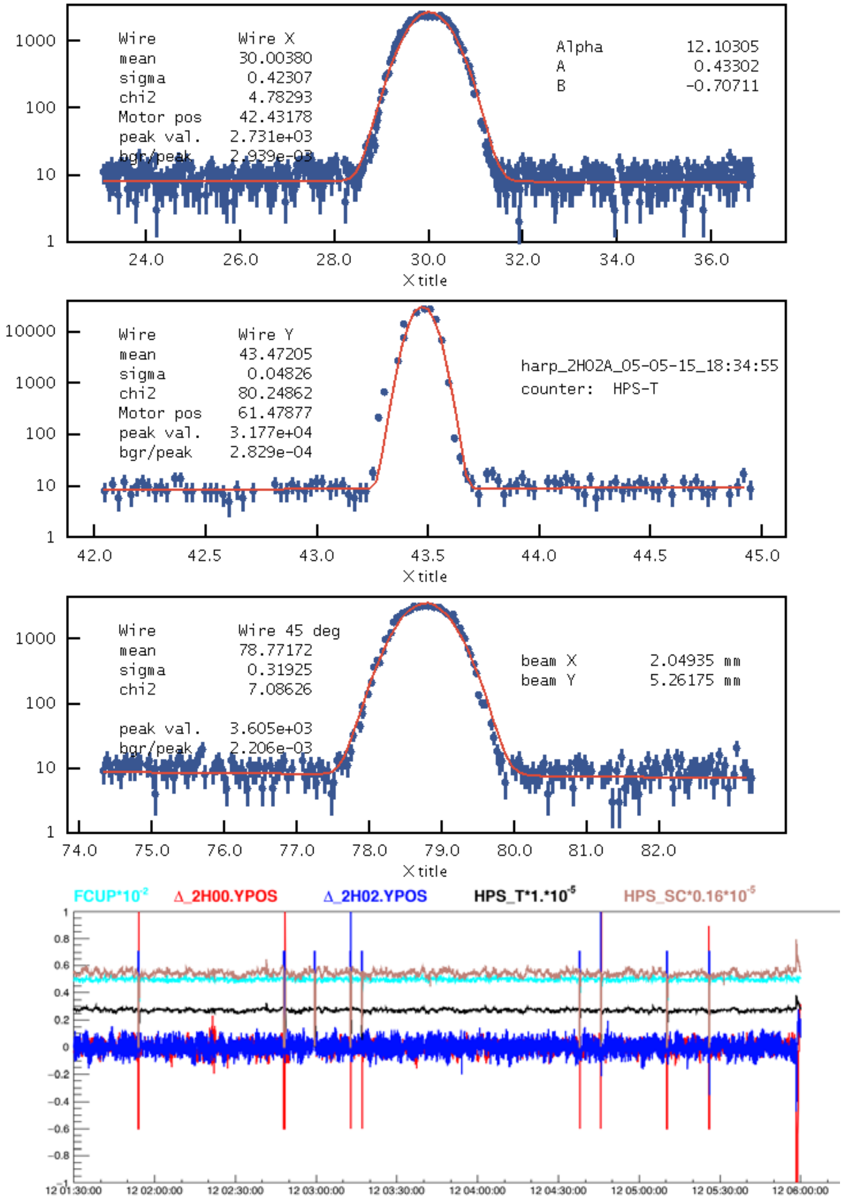
2015 Engineering Run

- Installed SVT end of February
- Commissioned Hall B beamline March-April
  * Calibrated beam position monitors & established orbit locks
  * Set up SVT Protection Collimator
  * Checked beam position stability
- CEBAF down after power outage
- Commissioned Trigger and integrated SVT DAQ late April
- Explored SVT backgrounds as SVT moved closer to beam
- Production running at 1.5 mm started May 1
- Production running at 0.5 mm started May 12
- Run ended May 18th.

Layer 1 silicon sensors are just 0.5 mm above and below beam. Min opening angle is θ_y= 15 mrad.



Beam Quality



HPS requires high-quality, stable beam.

Small Beam size:

- σ_X ~ 300 to 500 µm
- σ_Y ~ 15 - 50 µm

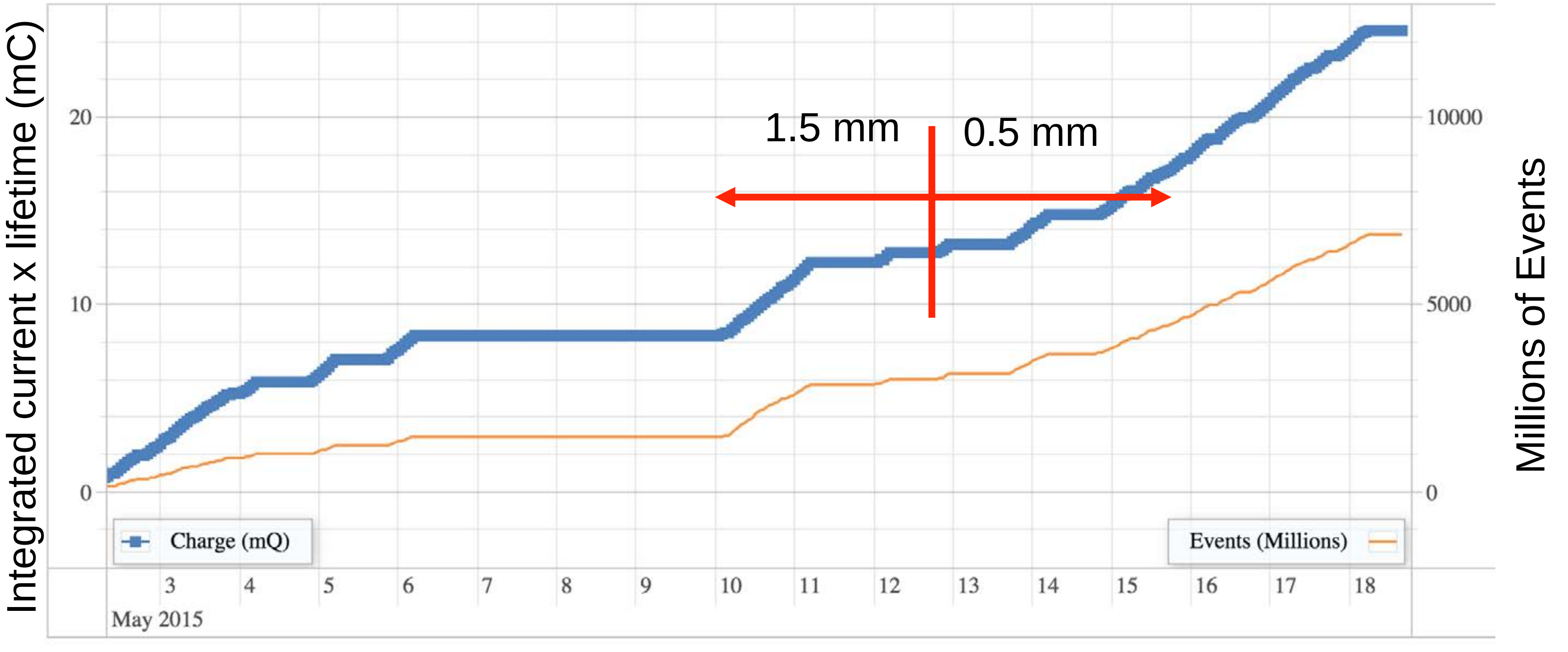
- Very low halo
- Fast shutdown triggered by beam halo monitors

- Stable, reproducible beam conditions achieved on May 12 allowed SVT to run at 0.5mm

1.056 GeV Run

- Proposal: 1 week of 50nA beam, 30mC
- Achieved: ~10mC with SVT @ 1.5mm

  ~10mC with SVT @ 0.5mm

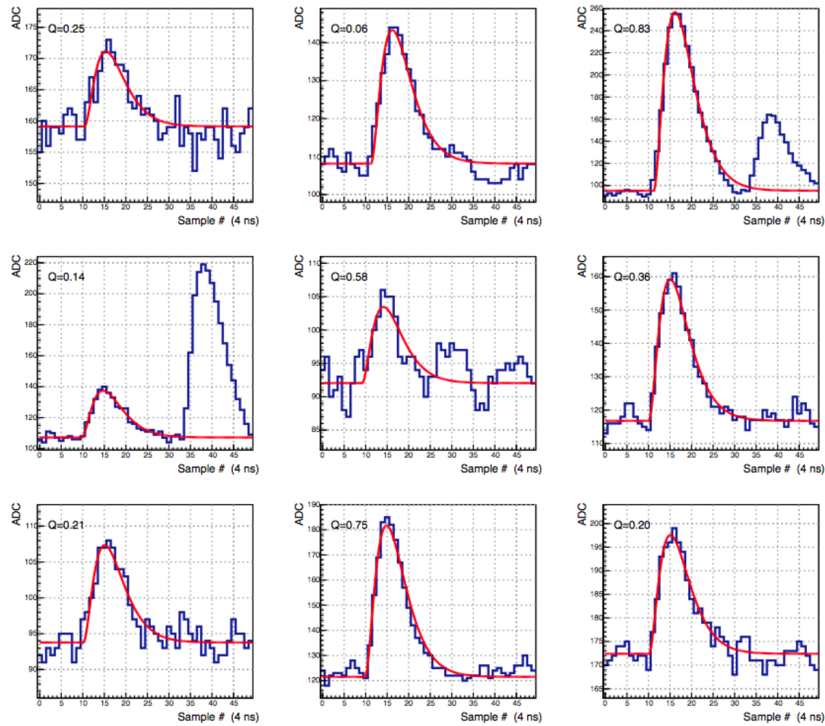


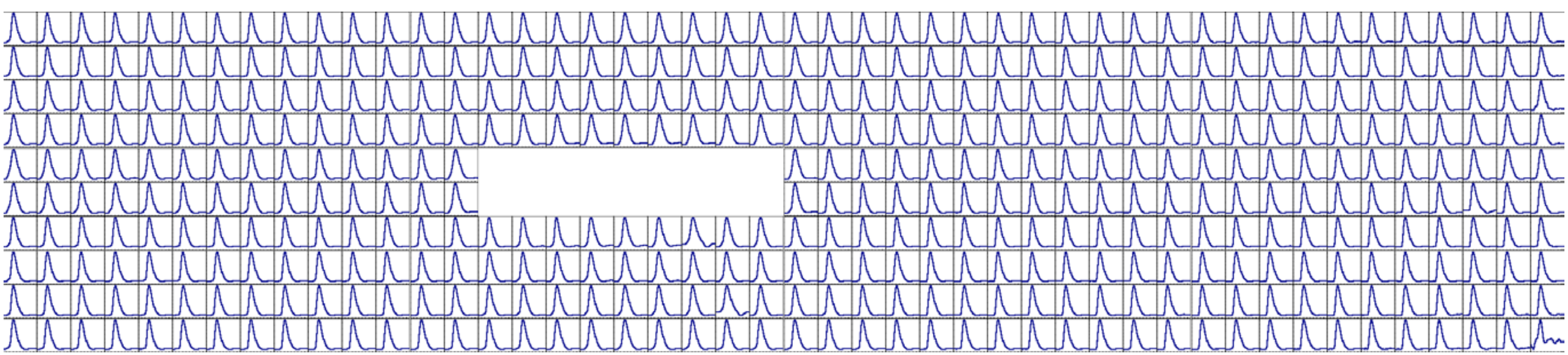
Data!

- Took over 5 billion events with single electron and pairs triggers.
- Detector and data acquisition system performed very well.
- Employing a “blinding” technique for physics analyses.
- Currently analyzing a fraction of the data (10%) to calibrate the detector response
  - Coulomb scattered e- provide full beam energy calibration
  - Møller scattered e-e- pairs and tridents provide correlated energy and position calibration
- Calibrating:
  - Time
  - Energy
  - Position

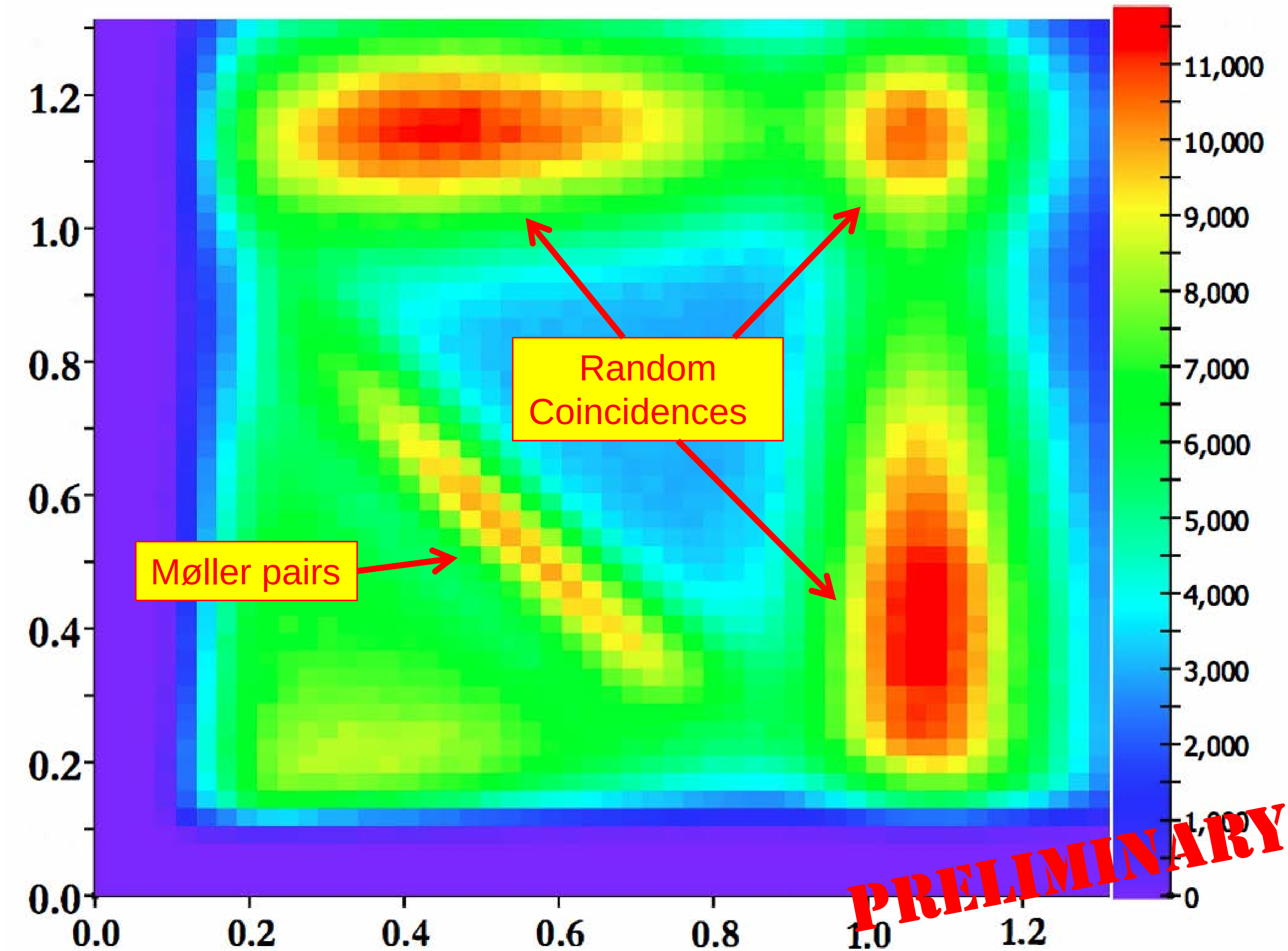
ECal Time/Energy Calibration

- Fit crystal FADC spectra to derive hit time and energy deposition.
  - Fits account for time walk and include pedestal.
- Neighboring crystals clustered
  - Cluster energy includes MC-derived corrections



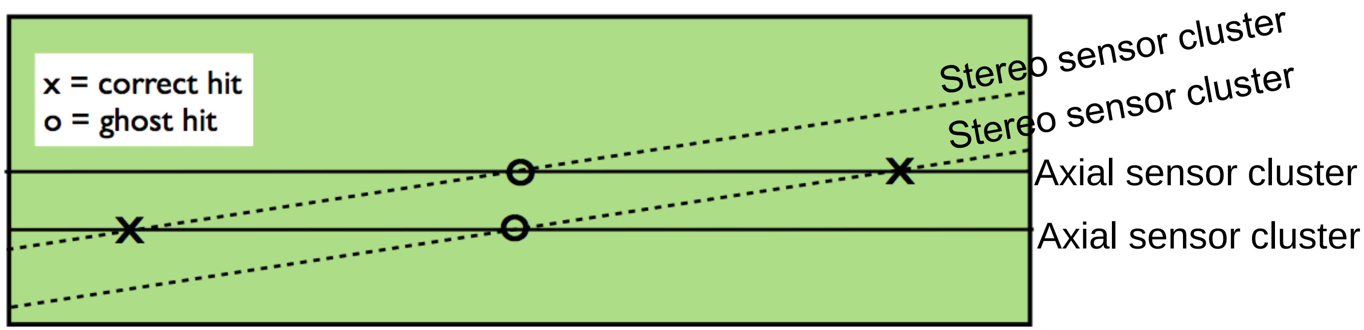


e- Cluster Energy vs e- Cluster Energy

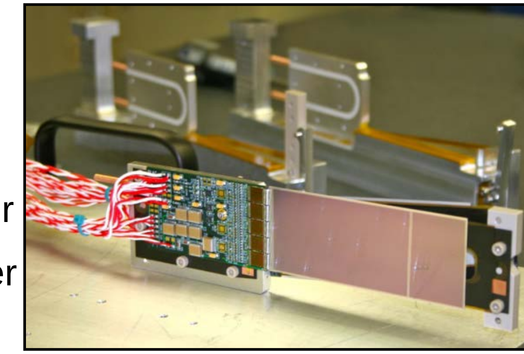


Hit and Track Finding

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

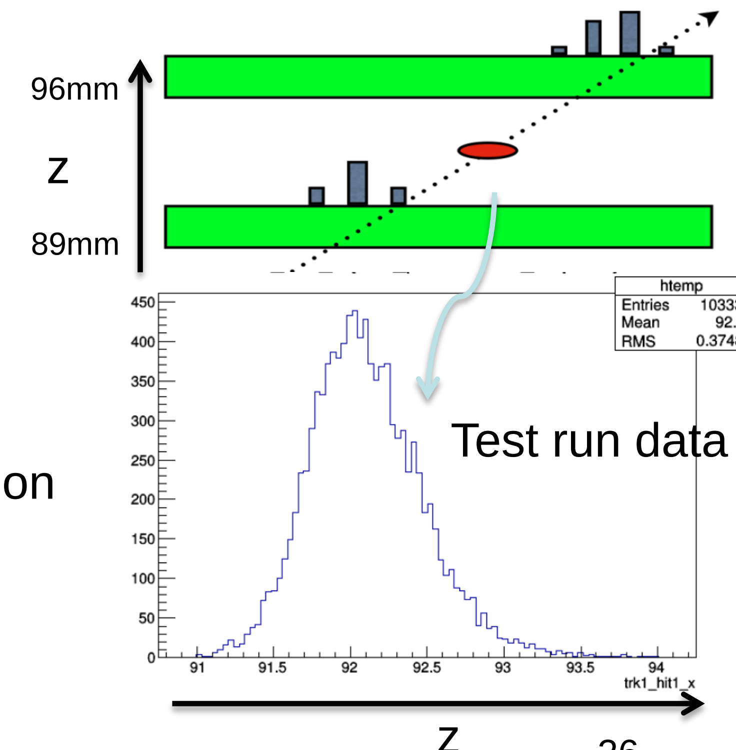


Test run stereo pair module



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"

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

$\Rightarrow$ Merge final fit into a “helix” track object together with the hits of the track

- MC Single hit efficiency > 99%
- MC Track efficiency > 95%
- MC Hit resolutions: σ_x<125μm, σ_y<10μm
- Momentum resolution ~5%
- Resolution dominated by multiple scattering

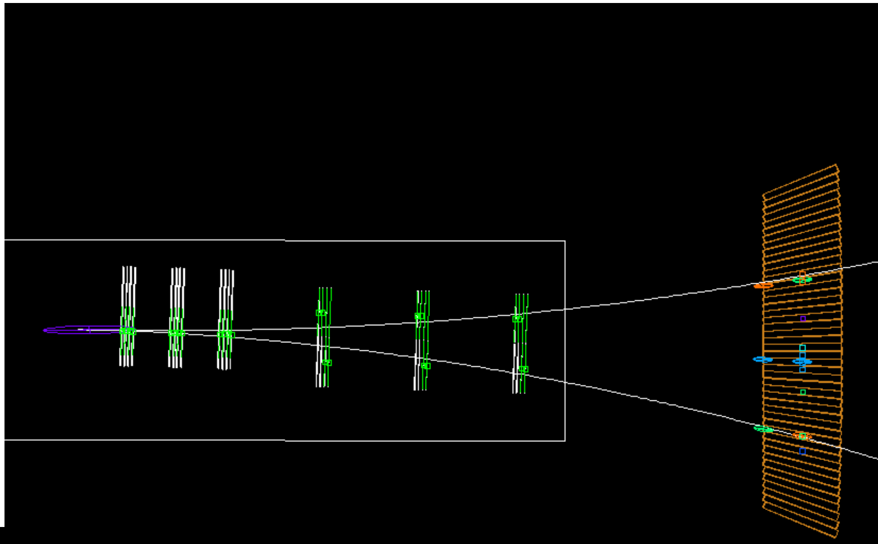
Track Re-Fitting and Alignment

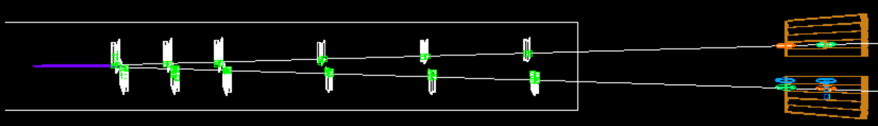
- Found tracks are refitted using the General Broken Lines (GBL) approach
  - C++ code ported to Java
- Provides convenient link to alignment package Millepede-II
  - hps-java writes out binary format
- Alignment constants returned by Millepede-II are fed into compact.xml file to provide aligned geometry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

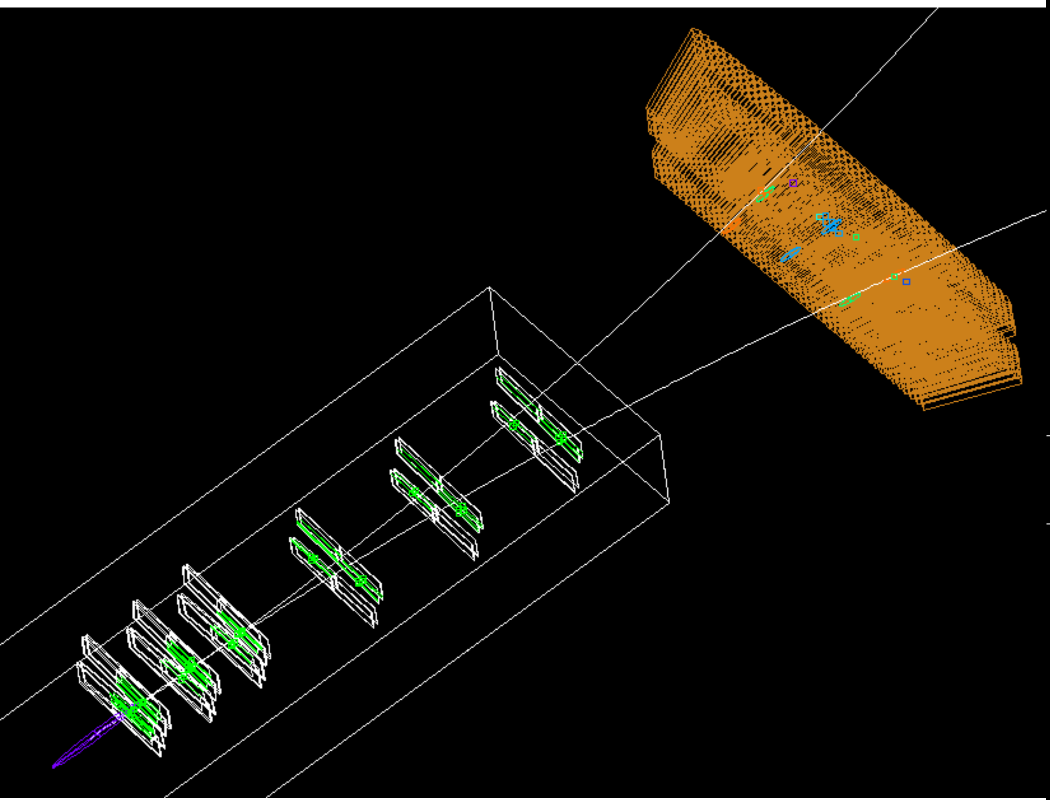
Events very clean, even within 0.5mm of the beam

Track momentum / cluster energy calibration ongoing

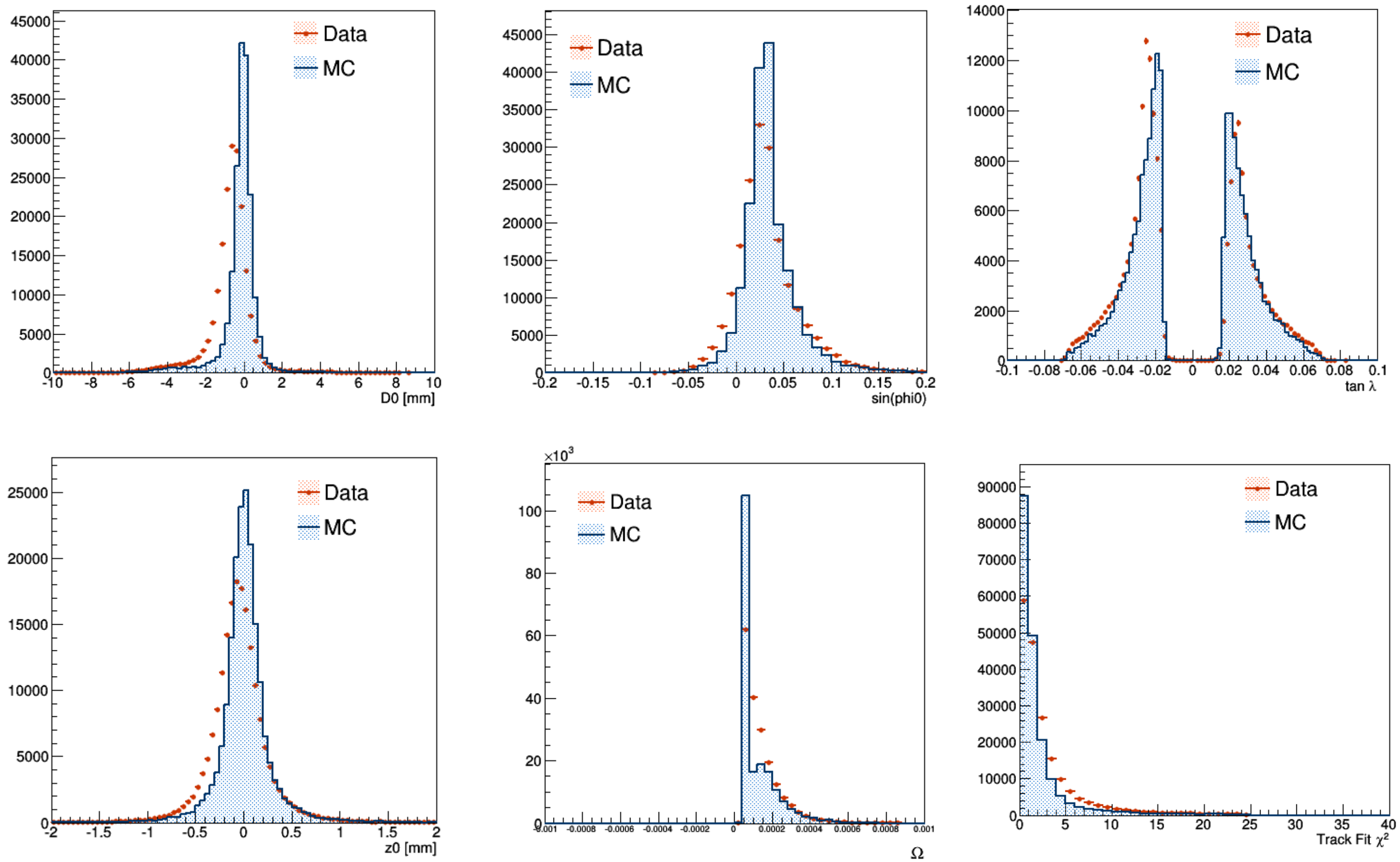
Track/cluster position calibration ongoing





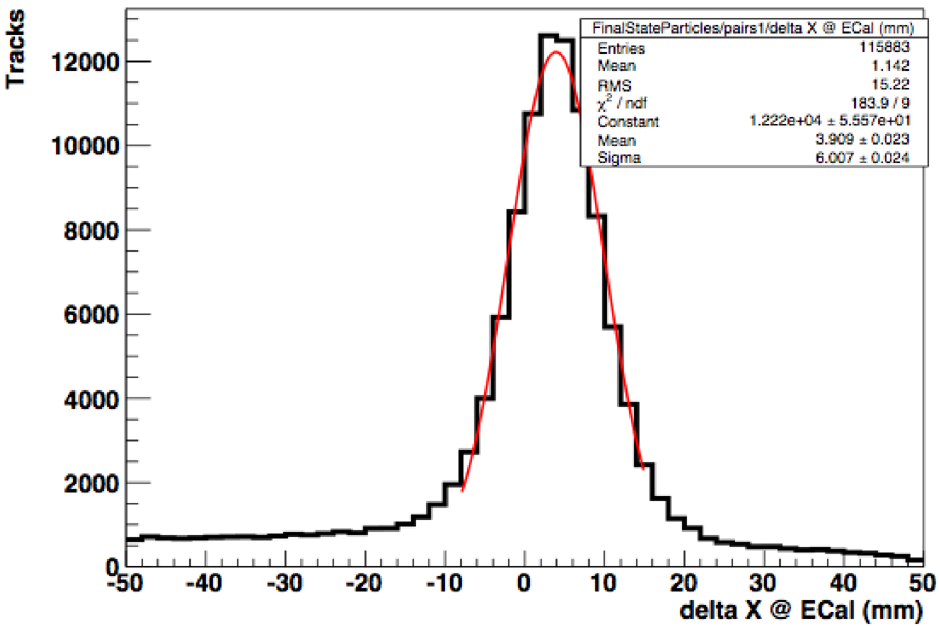


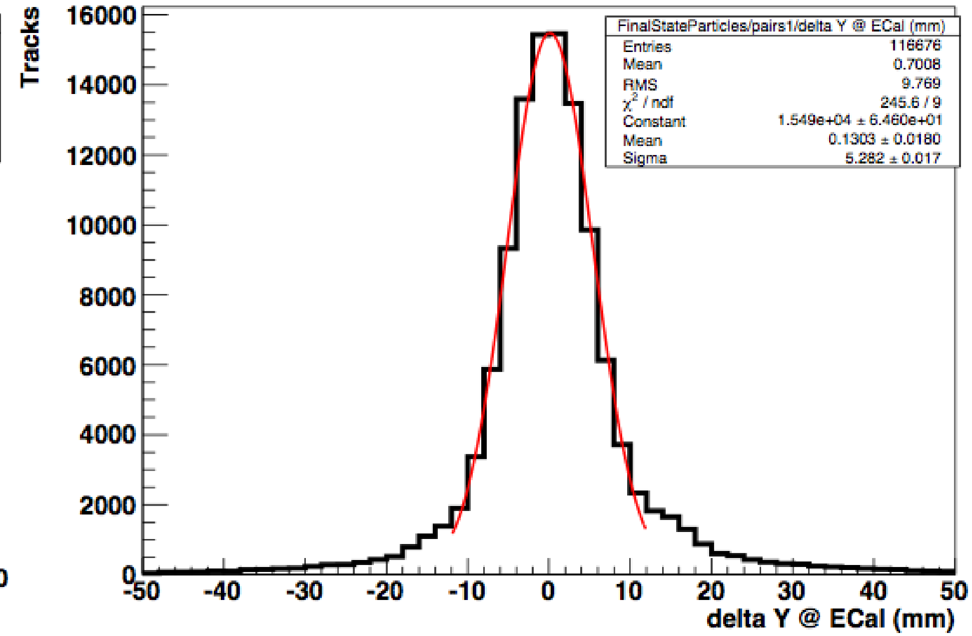
Electron Track Data vs MC

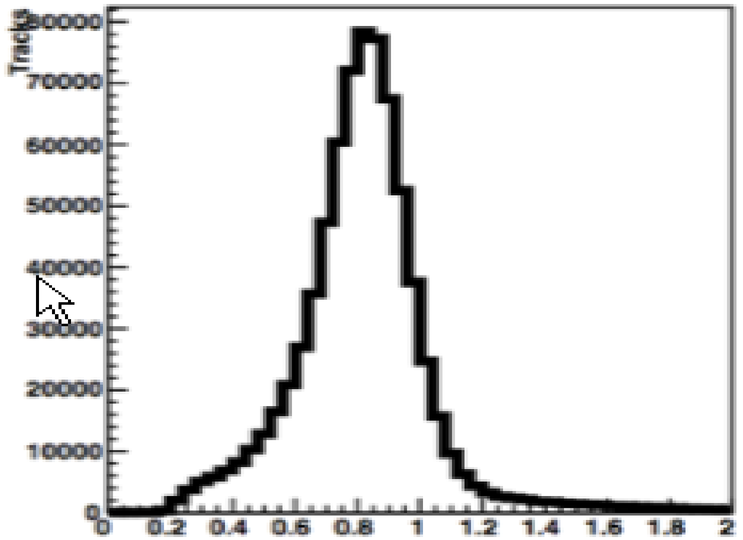


PRELIMINARY

Track Matching at ECal







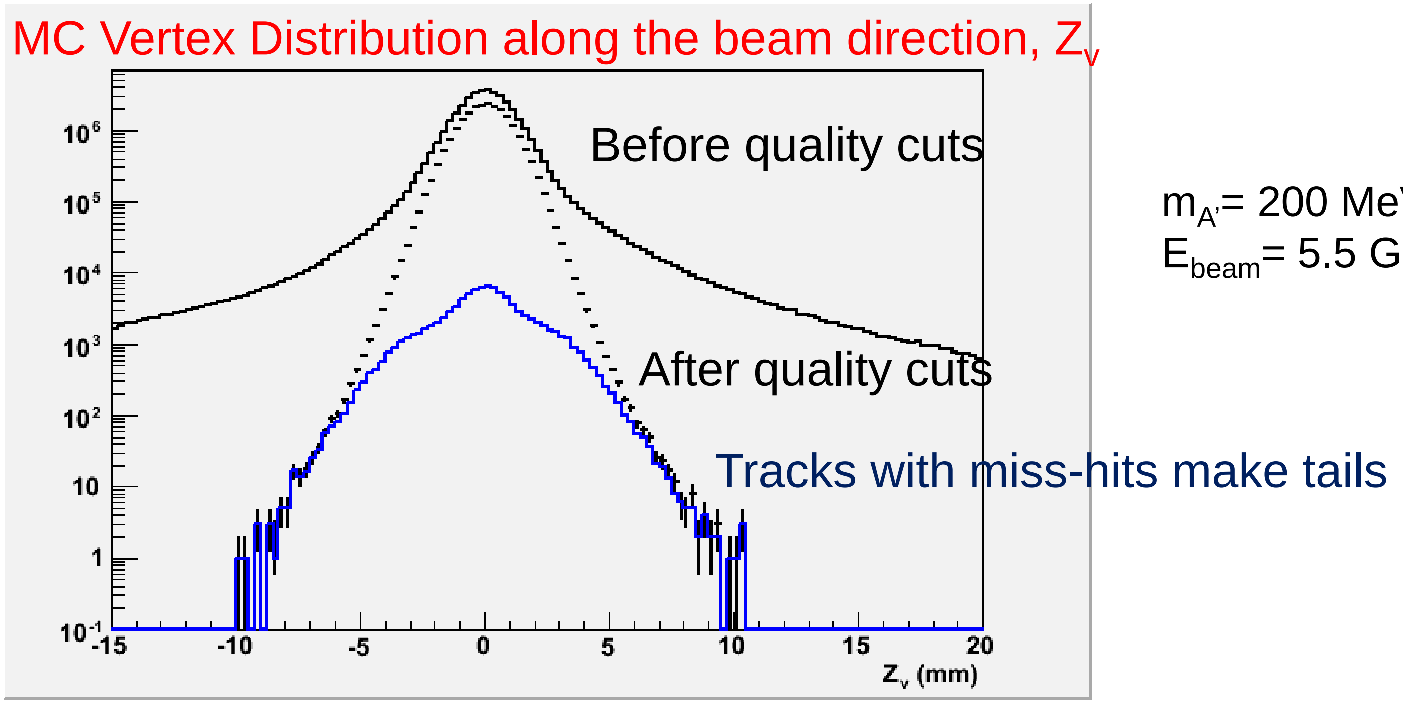
Cluster energy/track momentum

Detector is not yet fully calibrated!
Alignment fine tuning needed, but close.
Gain calibrations need improvement.

PRELIMINARY

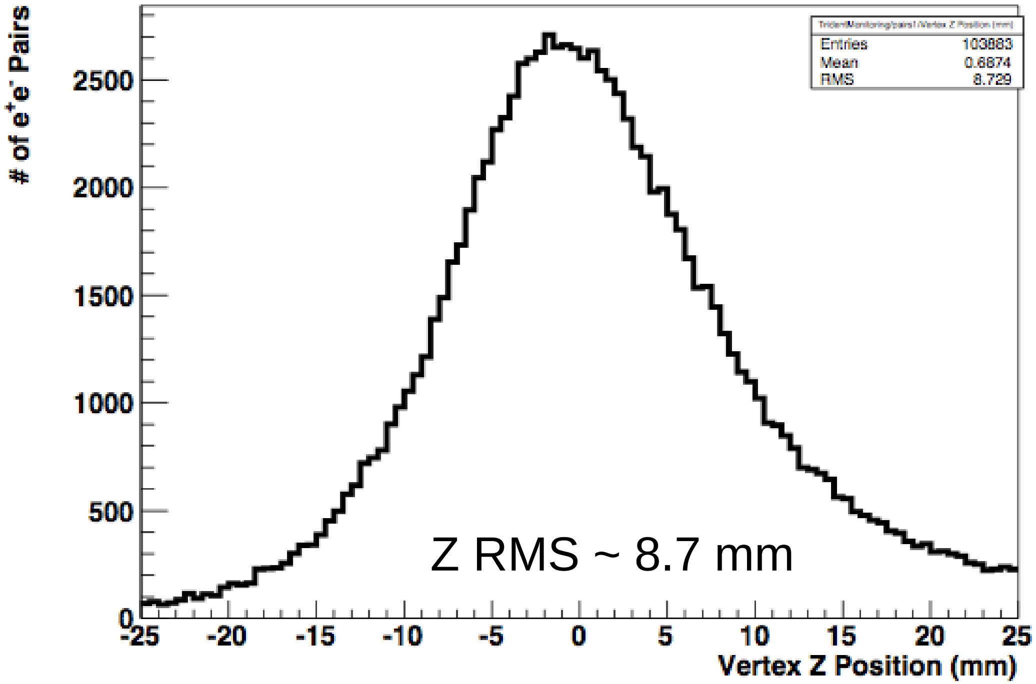
Vertexing

- 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

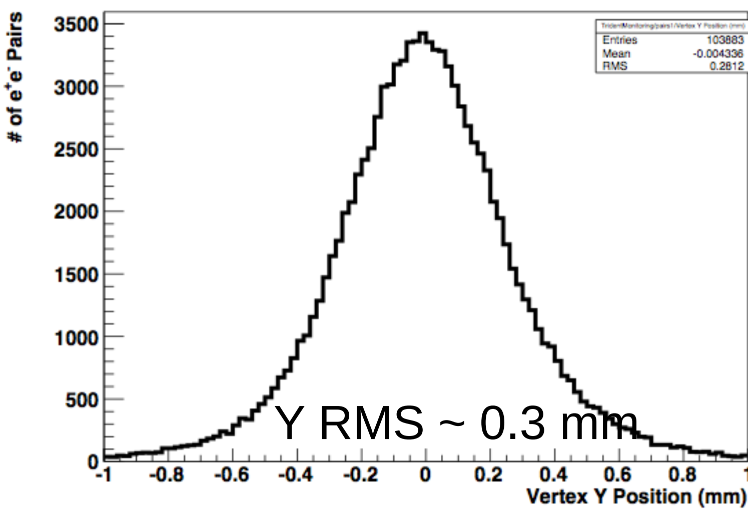
Pairs Vertex at the Target

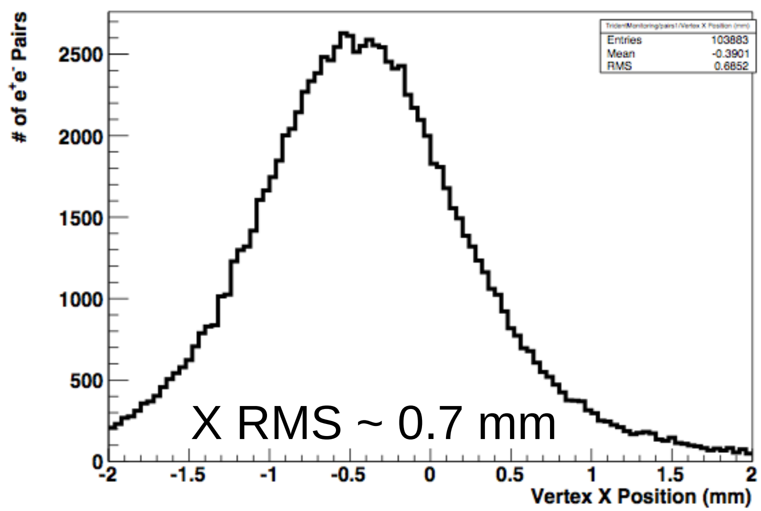


Z-vertex is critical for the experiment.

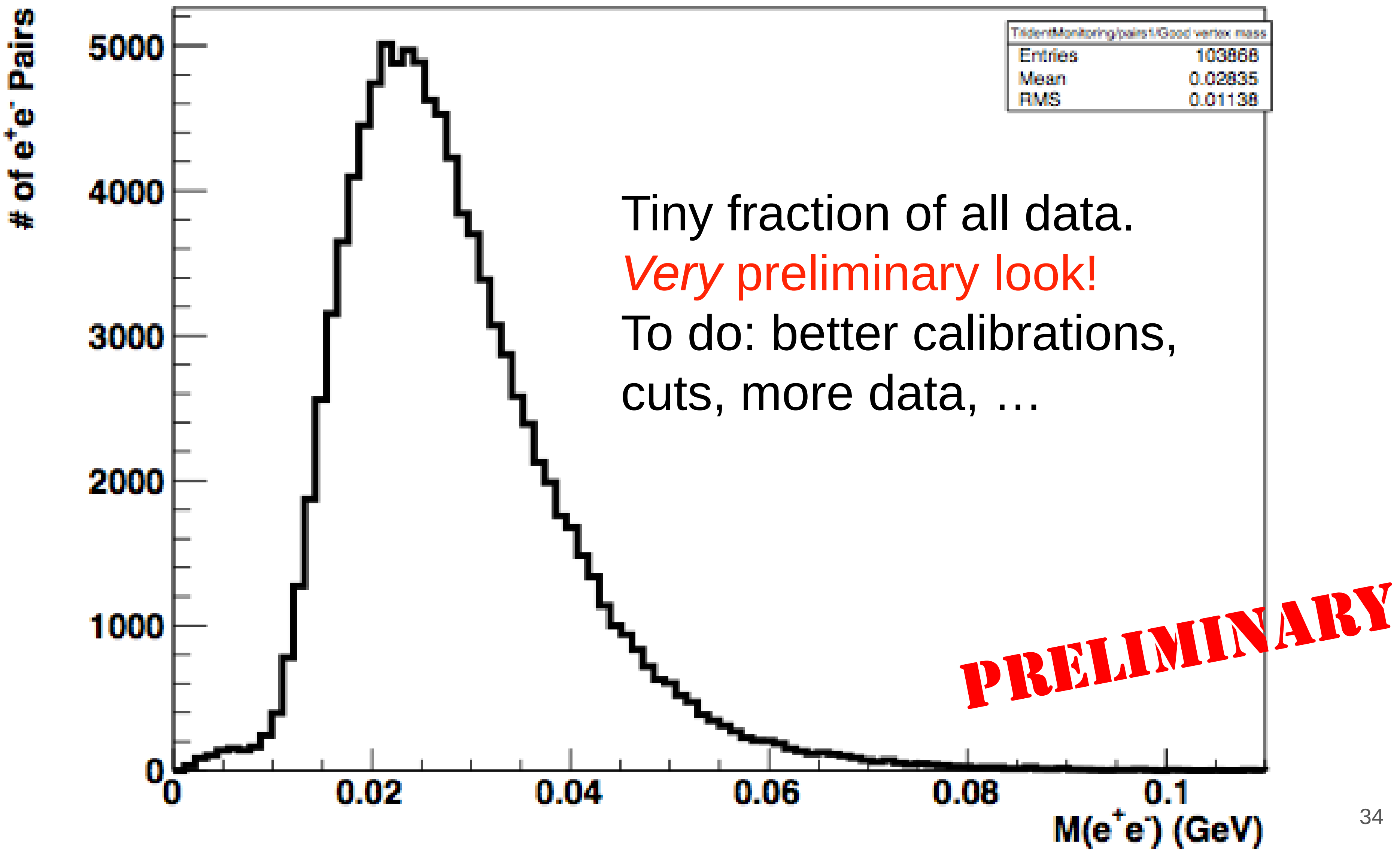
- Also the hardest @ 15 mrad.
- Requires very good SVT alignment (not yet done!)

PRELIMINARY



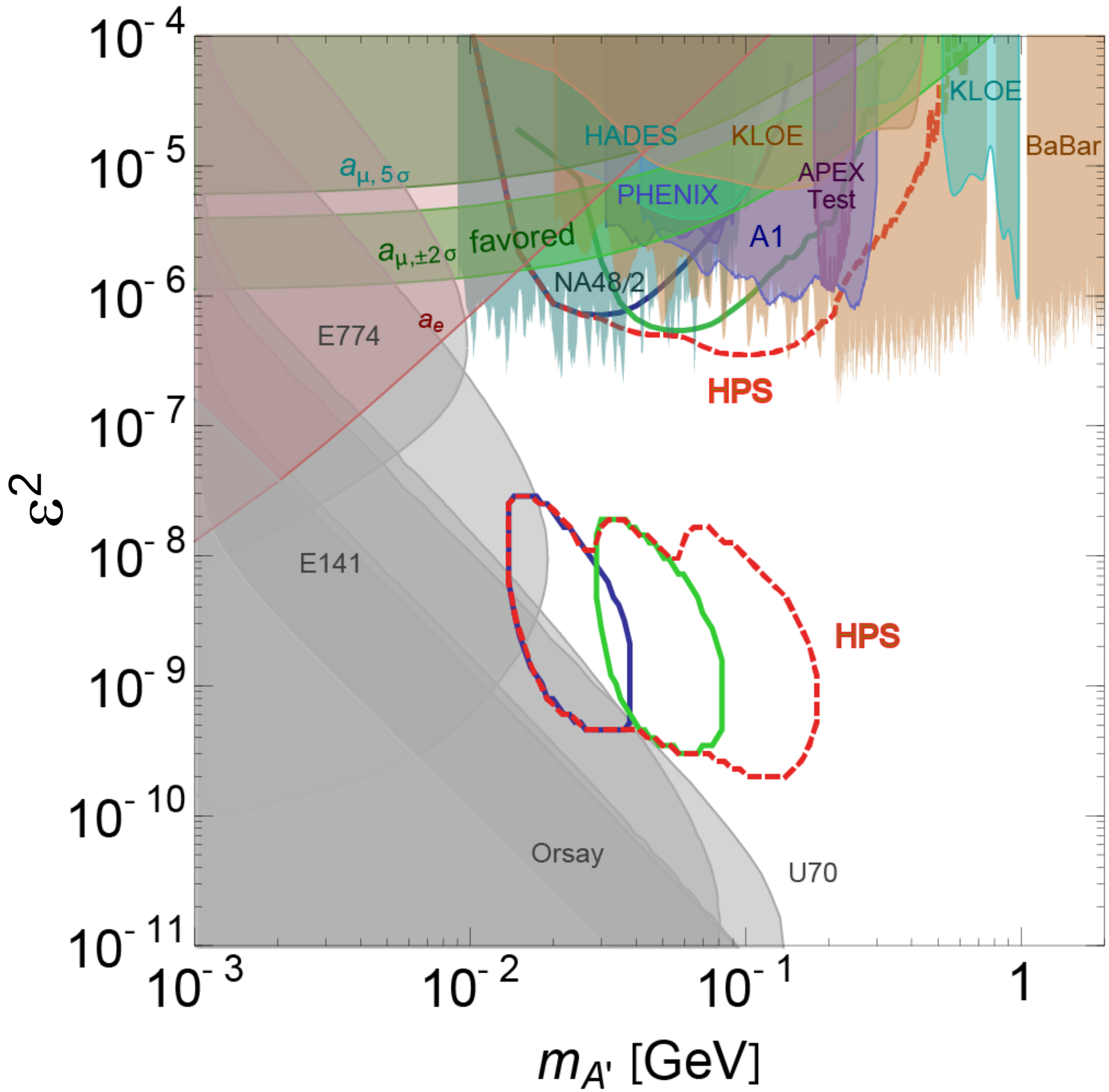


e^+e^- Pairs Mass Distribution



Tiny fraction of all data.
Very preliminary look!
To do: better calibrations, cuts, more data, …

Expected HPS Reach



One week, 50nA @ 1.1 GeV

One week, 200nA @ 2.2 GeV

Four week total reach = above
+
Two weeks, 300nA @ 4.4 GeV

Times are PAC times
(Clock time/2)

2015 Spring Engineering run accumulated 1/3 PAC week at 1.056GeV

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.
- 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 recently completed a successful engineering run, exercising all aspects of the experiment.
- Roughly 1/3 PAC week of data accumulated with nominal detector configuration.
- Initial analysis of a fraction of the data looks very encouraging. Pursuing a "blind" analysis where only 10% of the data is available before final unveiling.
  - Detector calibration and alignment ongoing
  - Reconstruction being improved
  - Analyses being developed
- Looking forward to physics data runs!