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Single-Volume Neutron Scatter Camera

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SNM detection/imaging

We develop systems for eventual application in a range of scenarios:

Standoff detection

Cargo screening

SNM detection applications

- Low signal rate
  - Need large area detectors!
- Low signal to background
  - Need background discrimination!

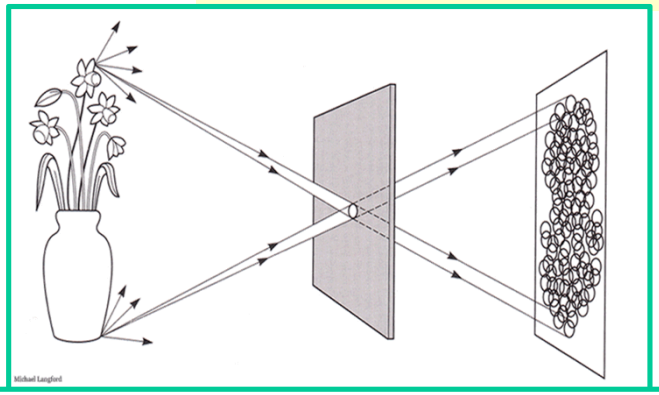
Arms control treaty verification

Emergency response

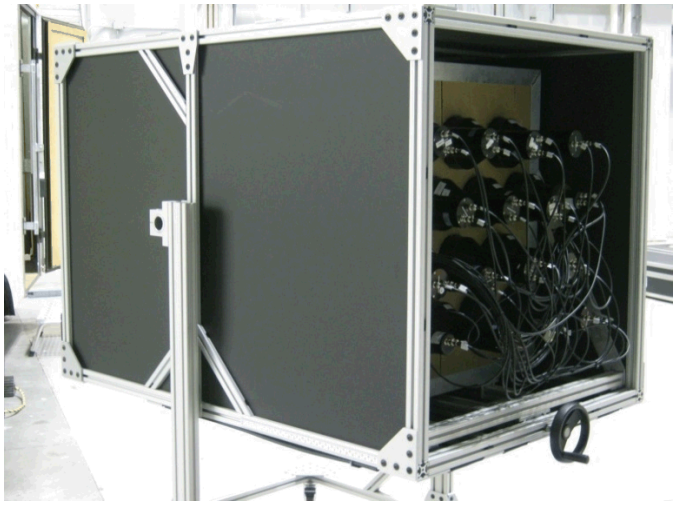
SNM imaging applications

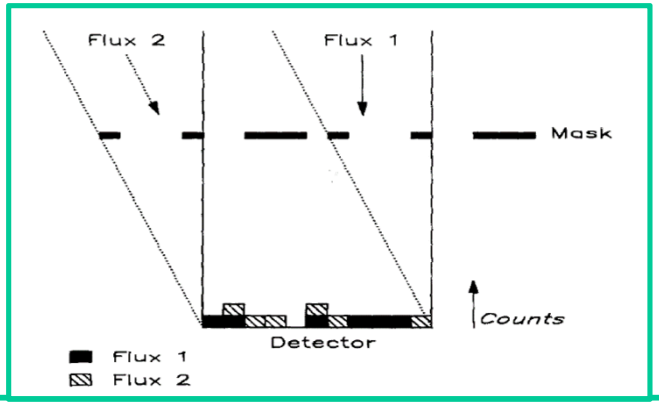
- High resolution required
  - Fine detector segmentation
- Multiple or extended sources

Neutron camera approaches

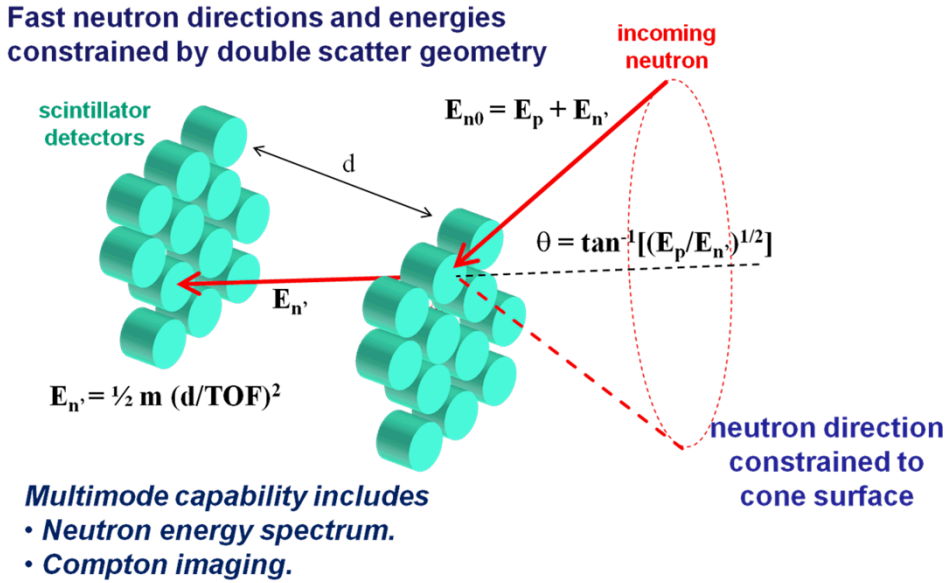


Pinhole: High Resolution, Low Throughput

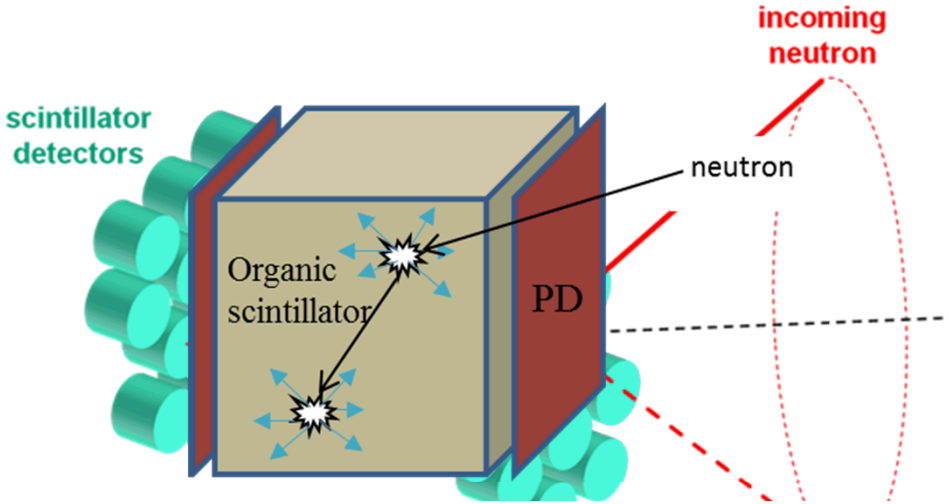


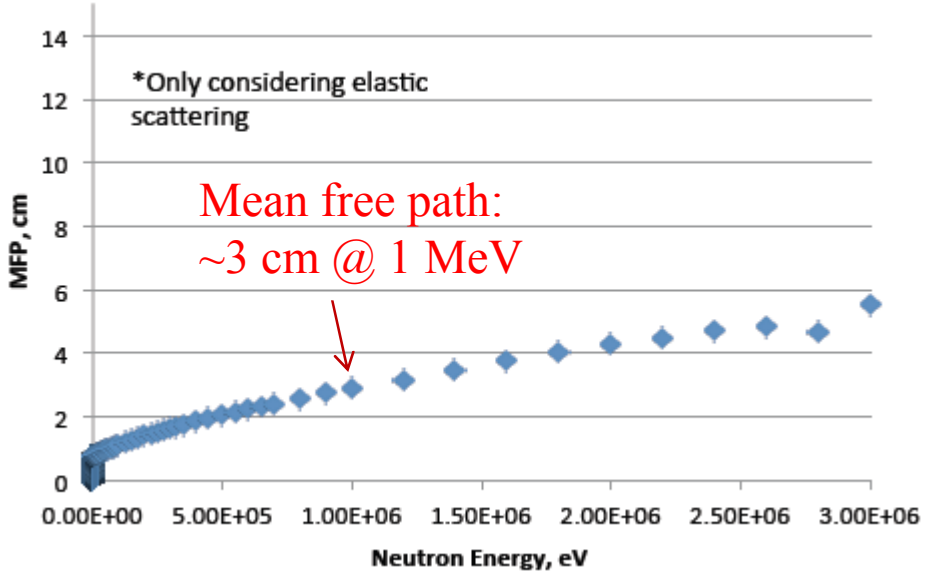


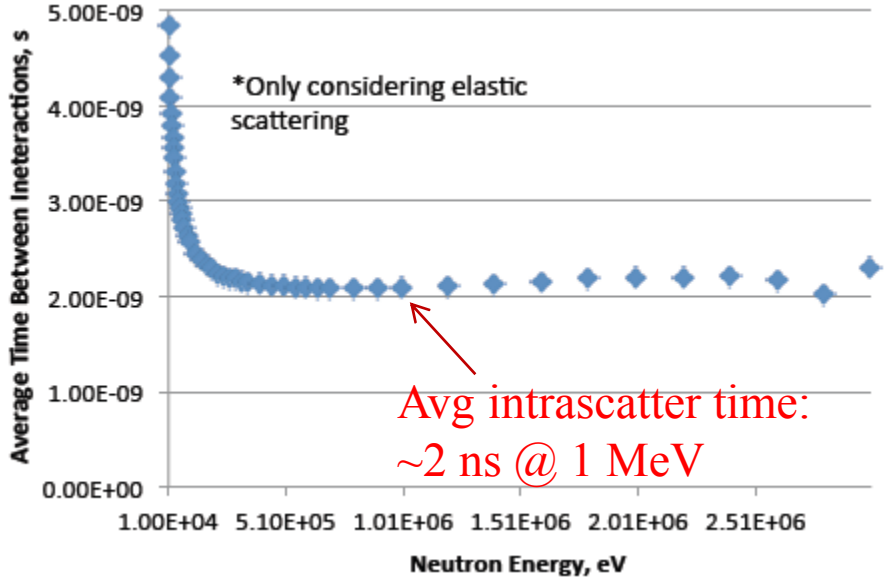
Coded aperture: High Resolution, High Throughput



Single-Volume Neutron Scatter Camera

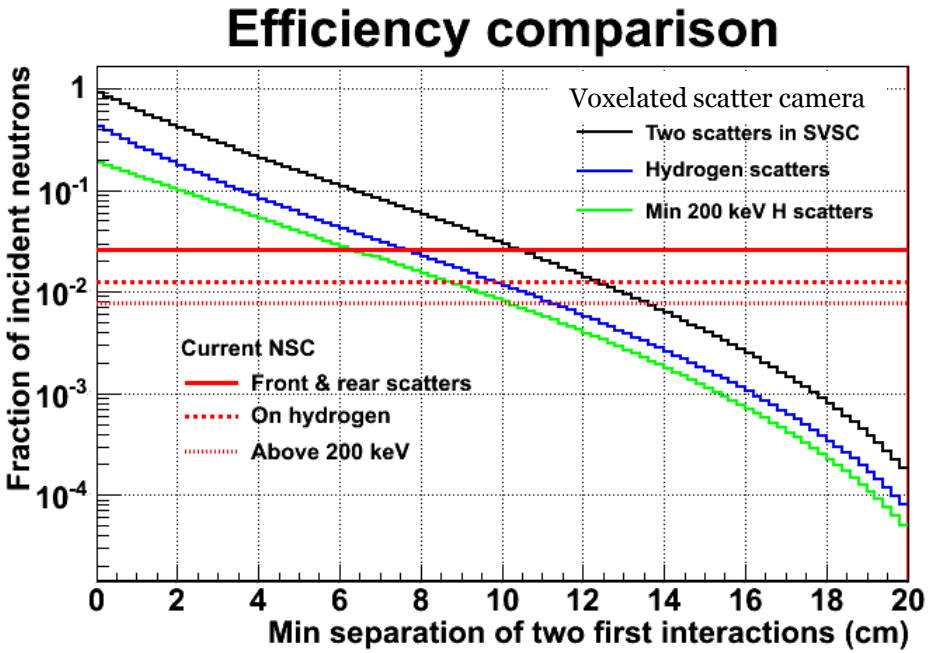


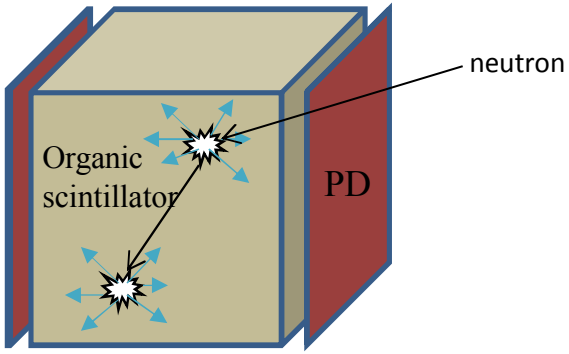




Single-Volume Neutron Scatter Camera

- A scatter camera built from a highly voxelated volume can recover more than an order of magnitude of efficiency if nearby interactions can be resolved.
- Resolving multiple interactions of a neutron separated by O(cm) and O(ns) is difficult!
- Excellent spatial and temporal resolution of photodetectors based on microchannel plates is the key enabling technology.





If successful:

- Spectroscopic capability
- Good per-event angular resolution
- High efficiency
- Compact form factor

Direct reconstruction

Probability multiplies over all observed photons

Extended ML for accurate energy uncertainty

Probability to observe a photon is summed over all interactions

$$\mathcal{L} = \frac{e^{-\mu}\mu^n}{n!}\prod_{i=0}^{n}\sum_{j=0}^{N}\frac{\mu_j}{\mu}P_j(x_i)$$

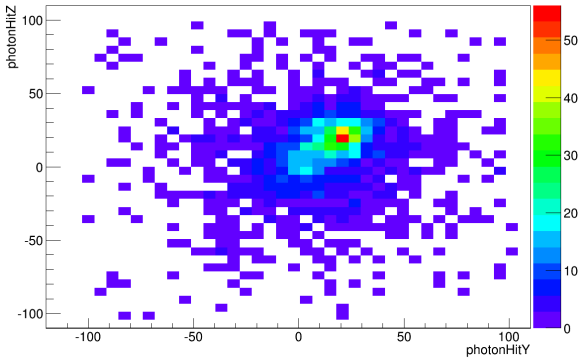
$$P_j(x_i) = \left[\frac{\cos\phi_{ij}}{4\pi|\vec{x}_i - \vec{x}_j|^2}e^{\frac{-|\vec{x}_i-\vec{x}_j|}{\lambda}}f(t;\mu,\sigma,\lambda)\right]$$

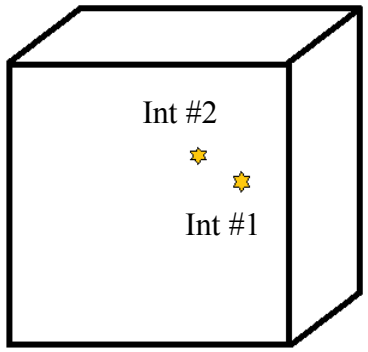
Solid angle

Optical attenuation

Pulse shape

list of photon arrival positions and times





(x,y,z,t,μ) for each int

Event reconstruction via likelihood maximization.

- MINUIT: SIMPLEX, MIGRAD
- Deterministic Likelihood Maximization

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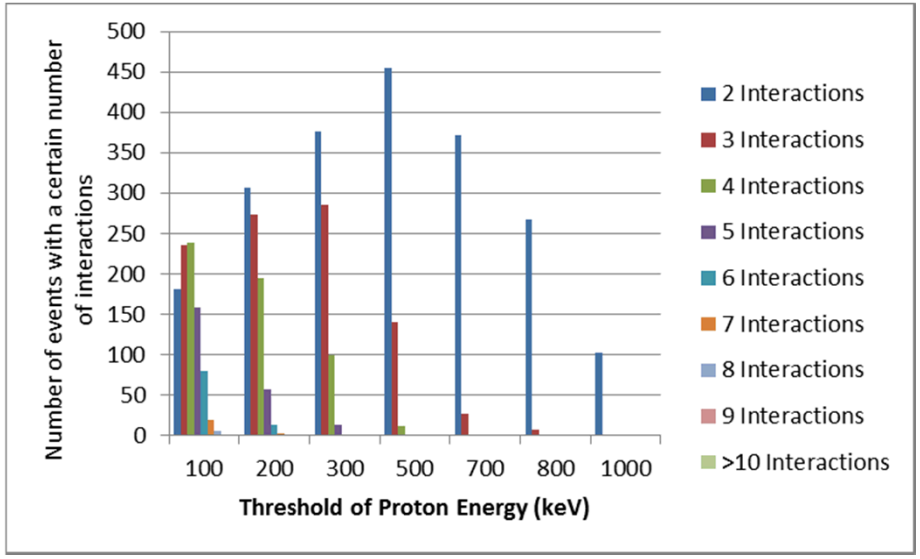
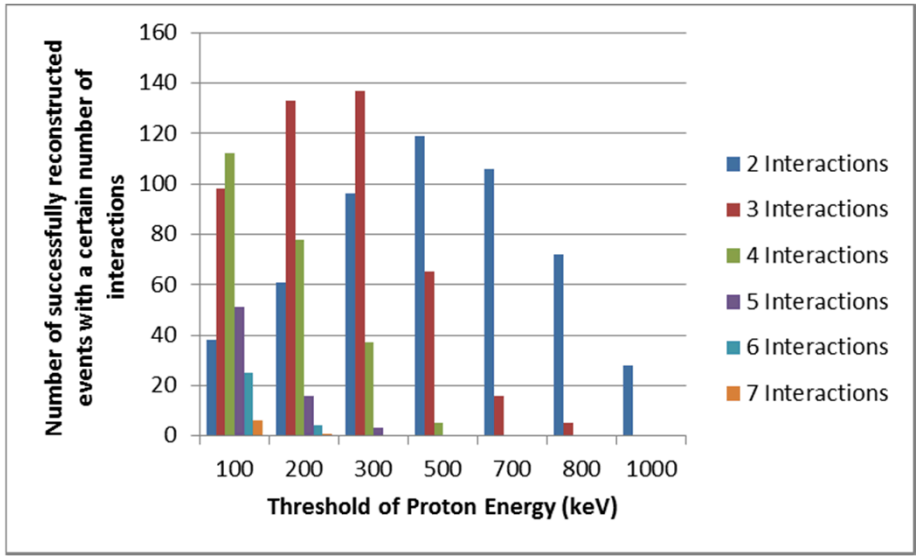
Simulations

- GEANT4 simulation of neutron transport, scintillation photon generation and transport
- 20 cm x 20 cm x 20 cm detector
- Six faces instrumented with MCP-PMT
- 3 MeV neutrons (reasonable fission energy)
- Count N interactions above 300 keV deposited
  - Require N >= 2
  - Reconstruction assumes N interactions, but all photons are used
- Gaussian pulse shape, 1 ns FWHM

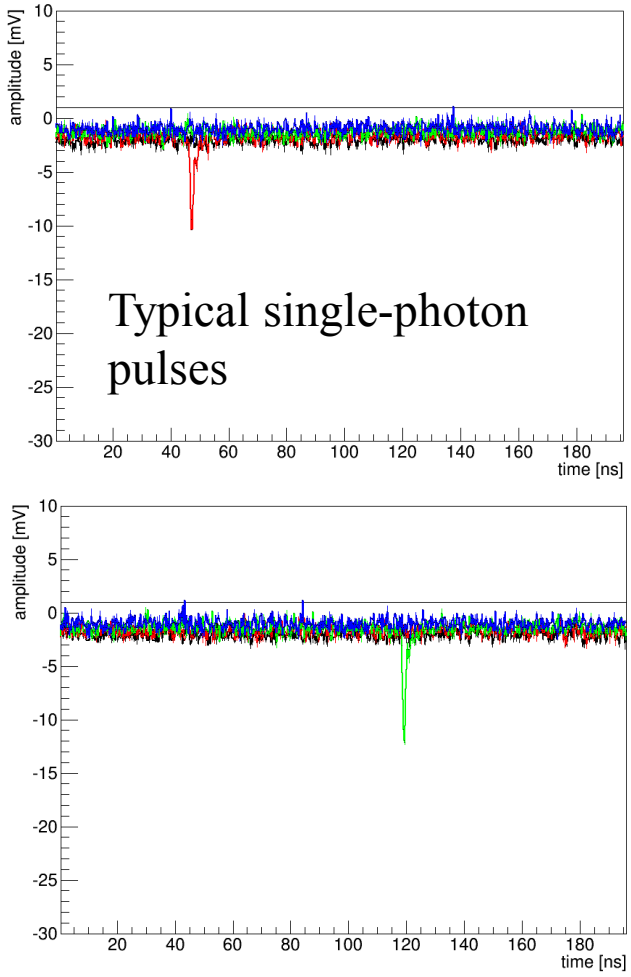
Where is the gap?

- Misreconstructed events tend to be due to photons from subsequent interactions "polluting" the results.
- Higher fraction of 3-interaction events successfully reconstructed than 2-interaction events.
- Suggests avenue for improvement: allow some photons not described by interaction likelihood.

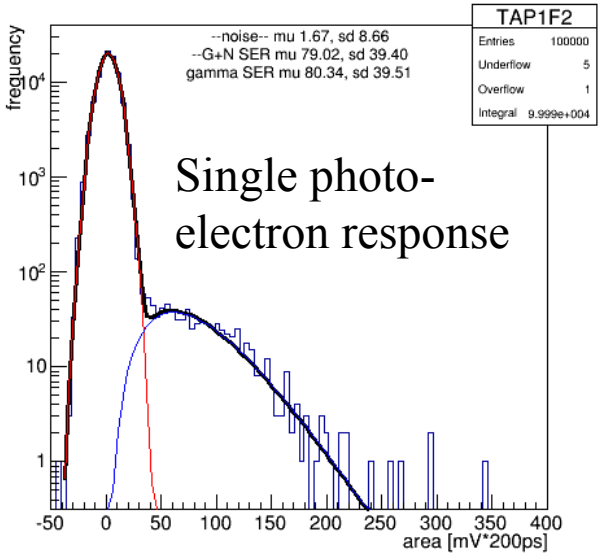


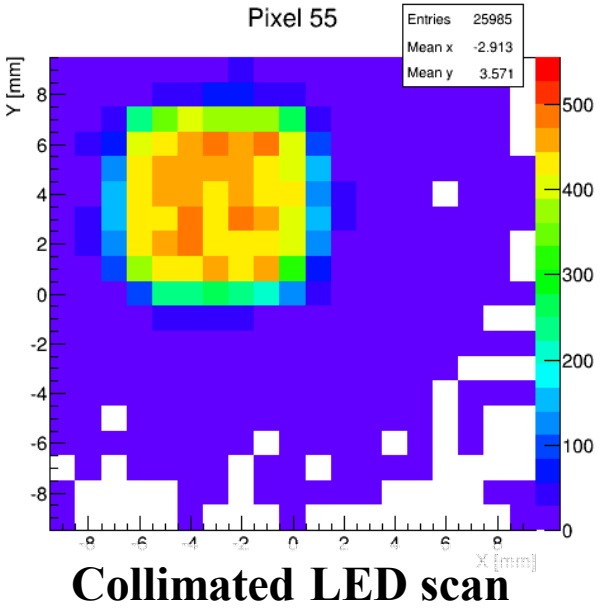


Low-level studies



- Photonis Planacon XP85012 + DRS4 eval board
- In-house DAQ & analysis code
- LED tuned to $\lambda << 1$.

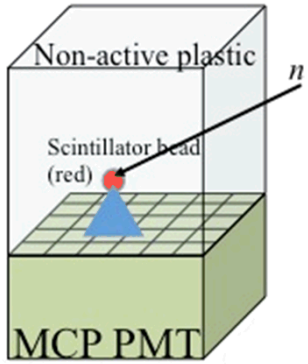


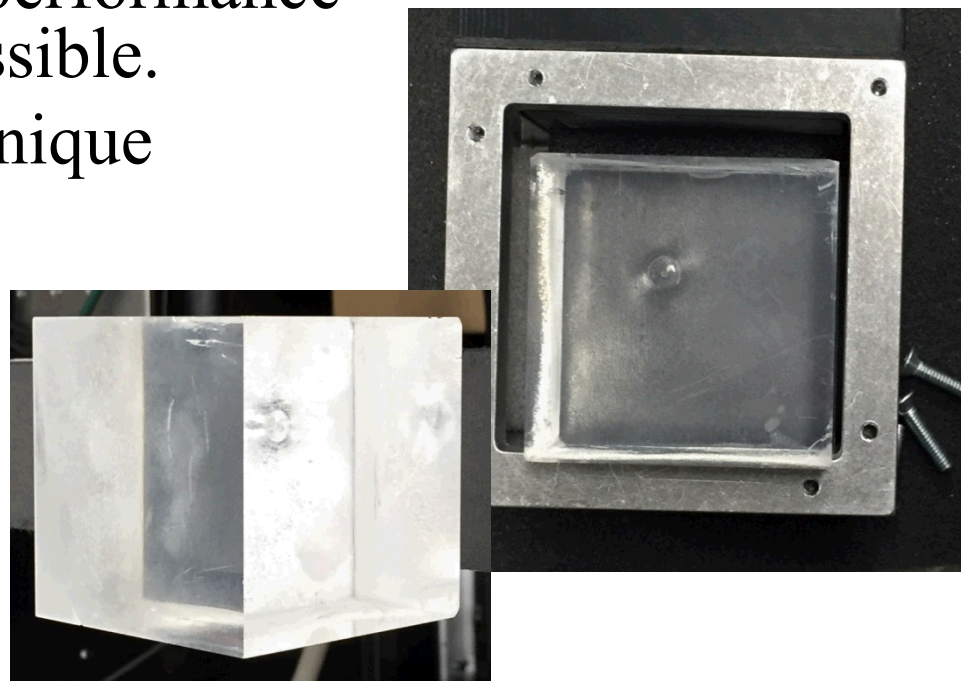


Collimated LED scan

Bead scintillator

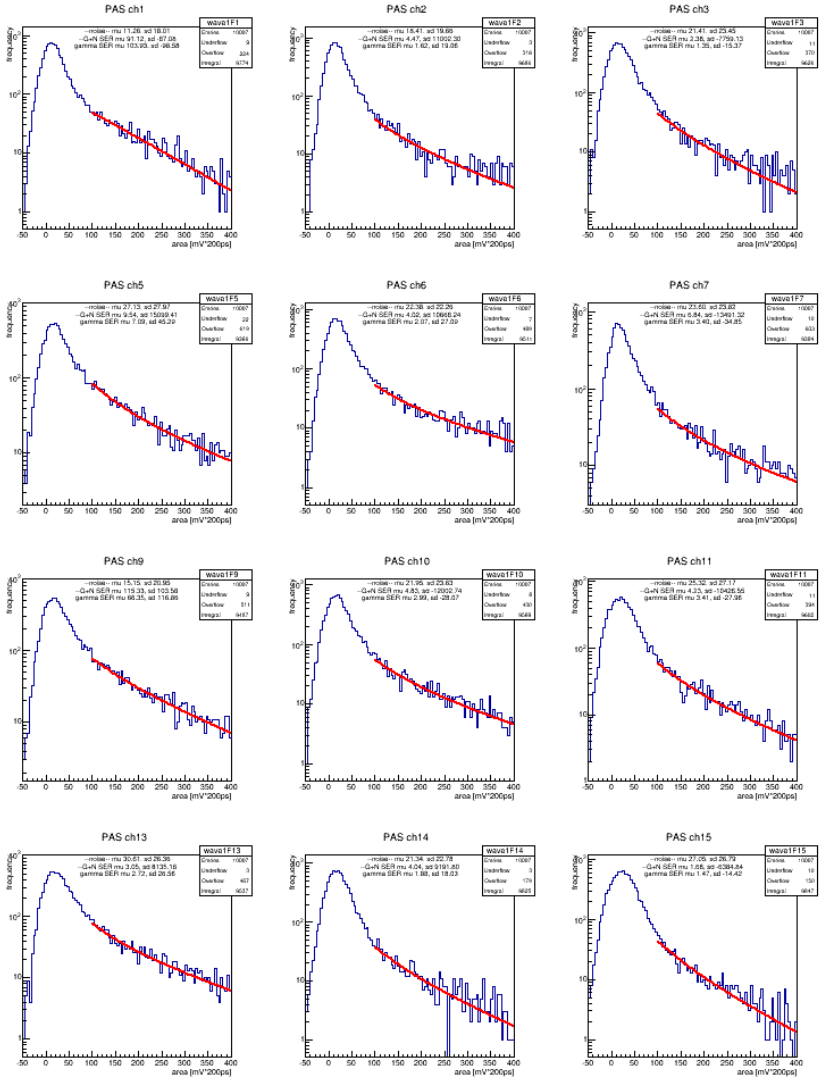
- Now look at multiple photons incident on multiple channels simultaneously.
- Simulation results indicate difficulty in understanding complex event structures.
- Need to understand photon transport, PD characteristics, electronics performance in as simple a system as possible.
- Use "scintillator bead" technique
  - ~5 mm dia. active plastic
  - 2" x 2" x 2" inert plastic
  - Allows testing of optical transport and detection from *known* interaction location.



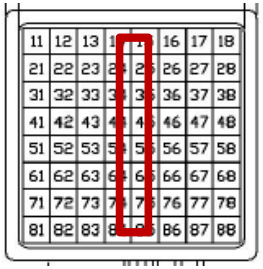


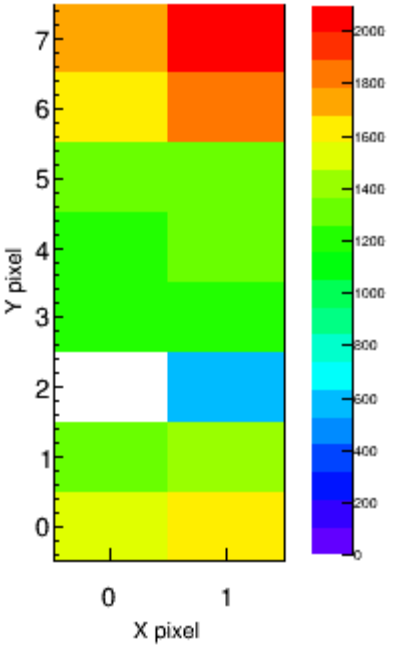
Experimental results

Channel used for trigger signal

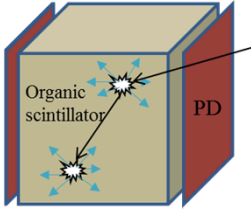


- 15 anode channels instrumented with DRS4 readout
  - 5.8 cm^2
- Preliminary results are inconclusive.
- Analysis is ongoing.

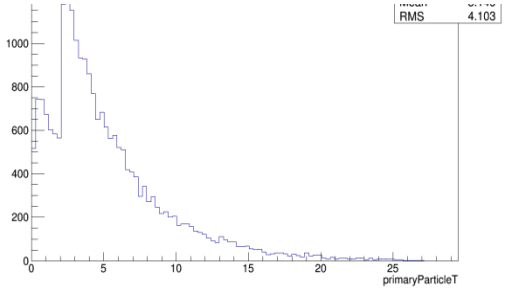




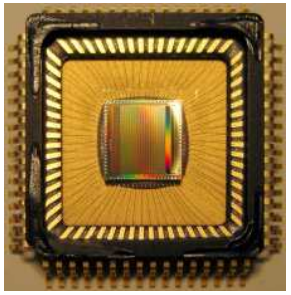
Prototype Implementation



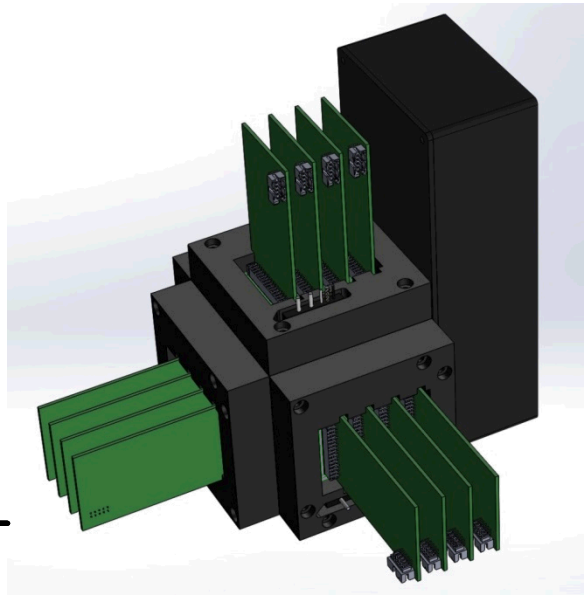
- Active material
  - Fast organic scintillator
  - O(ns) decay time
- Photodetector
  - MCP-PMT, e.g. Planacon
  - Position resolution depends on anode structure (8x8)
  - 35 ps transit time spread
    - Equals 8 mm photon travel
- Electronic readout
  - Switched capacitor array
    - e.g. DRS4 (5 GS/s, 950 MHz, 11.5 enob)
  - High bandwidth: take advantage of MCP-PMT
  - Long reset time
  - Scale to many channels

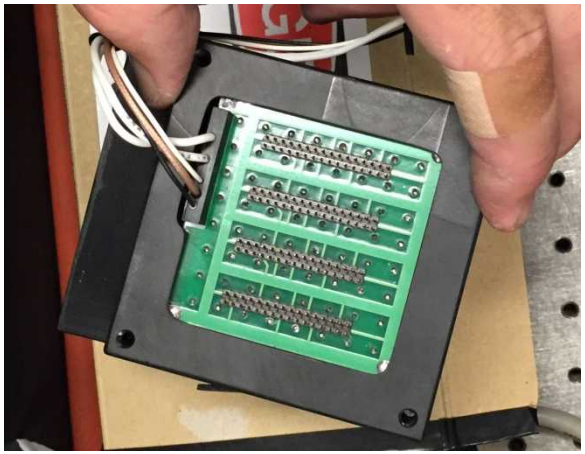


Photonis



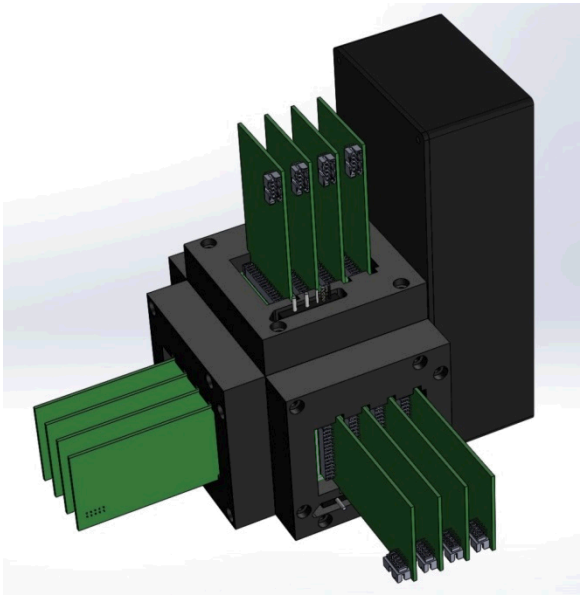
PSI

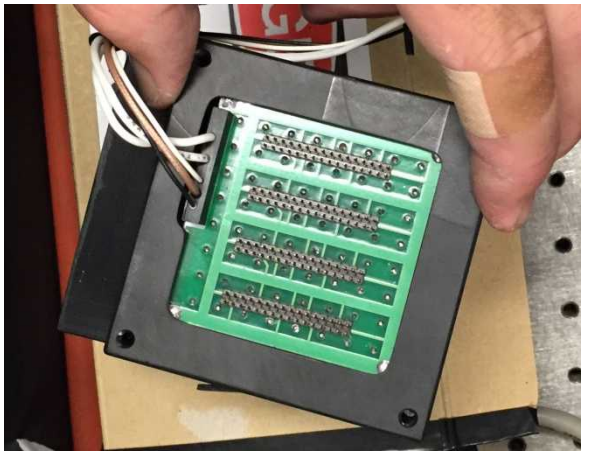




Prototype plans

- 2” x 2” x 2” quenched plastic.
- 3x – 4x Planacon, 8x8 anode.
- 216 – 288 channels DRS4 readout.
- + HV distribution, calibrations, data concentrator, firmware, DAQ software.
- Integration early 2016.
- Test with 14 MeV, 2.5 MeV, fission sources.





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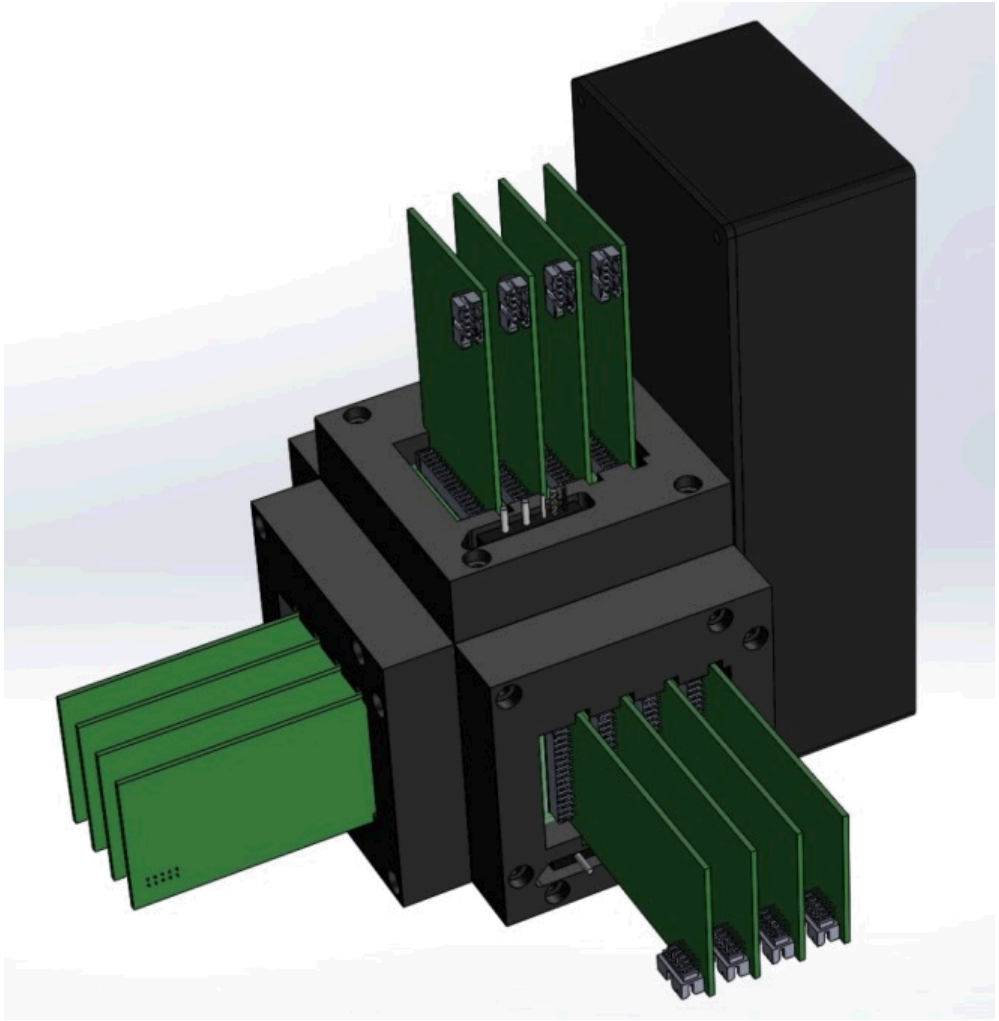
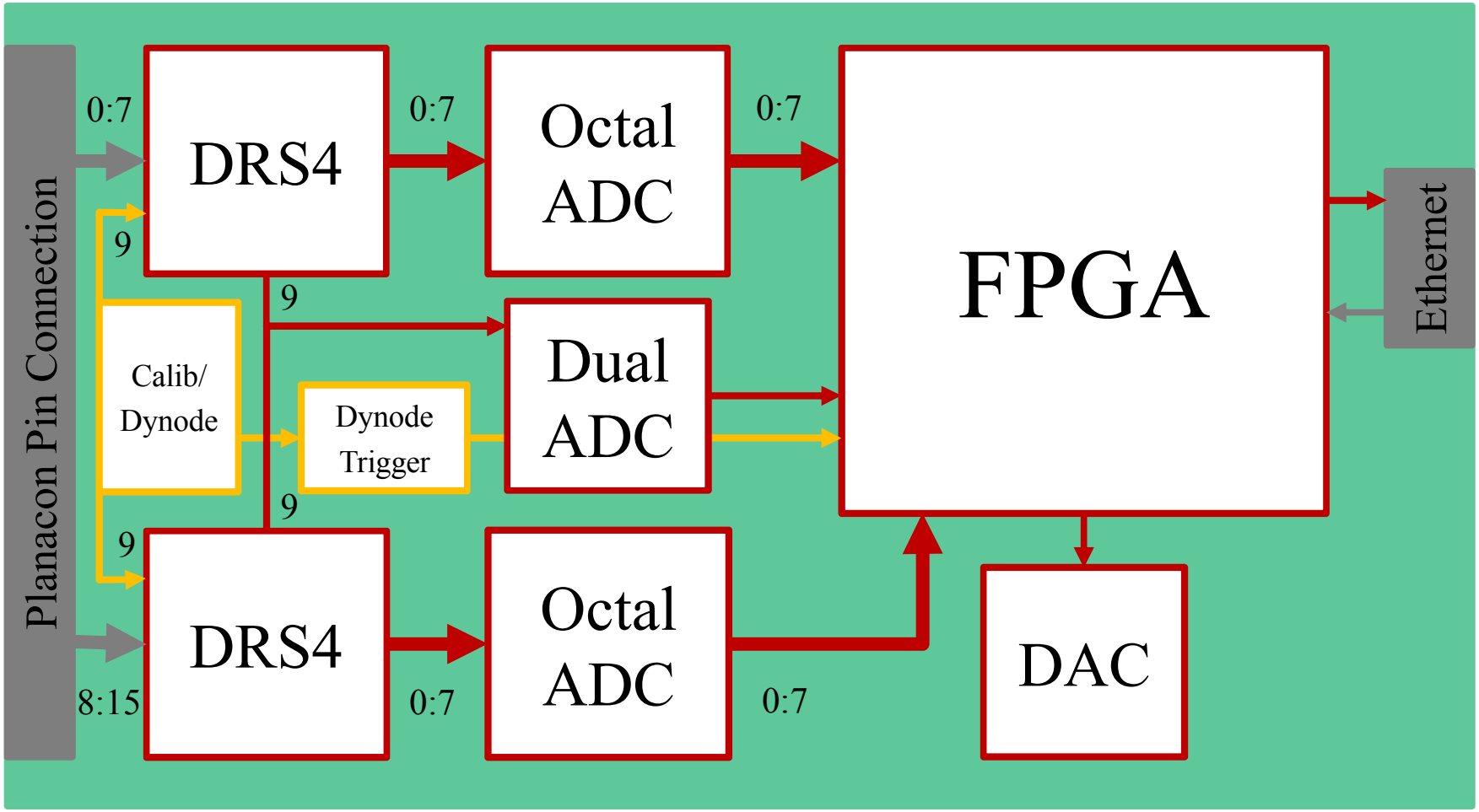
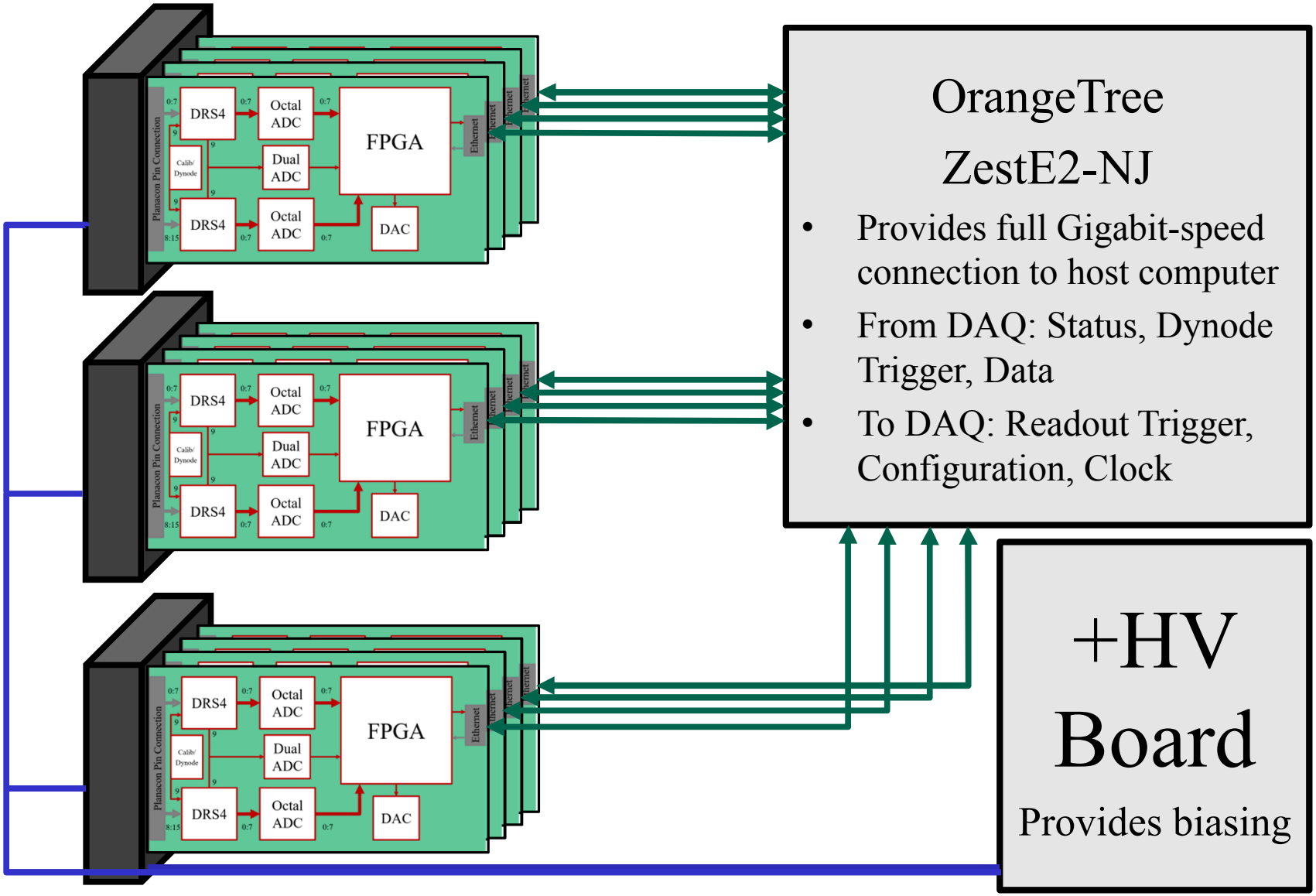
Prototype Design



Data Acquisition Board



System Design



Summary & Conclusions

- Direct reconstruction technique to localize neutron interactions in a bulk scintillator volume.
- Simulation and experiment are converging:
  - Added more realism to simulations.
  - Applied conclusions from simulation studies to develop design of lab prototype.
- Neutron interactions after first two have a significant impact on performance.
- Goal is Single-Volume Neutron Scatter Camera for high-efficiency double-scatter imaging.
  - Prototype under construction.

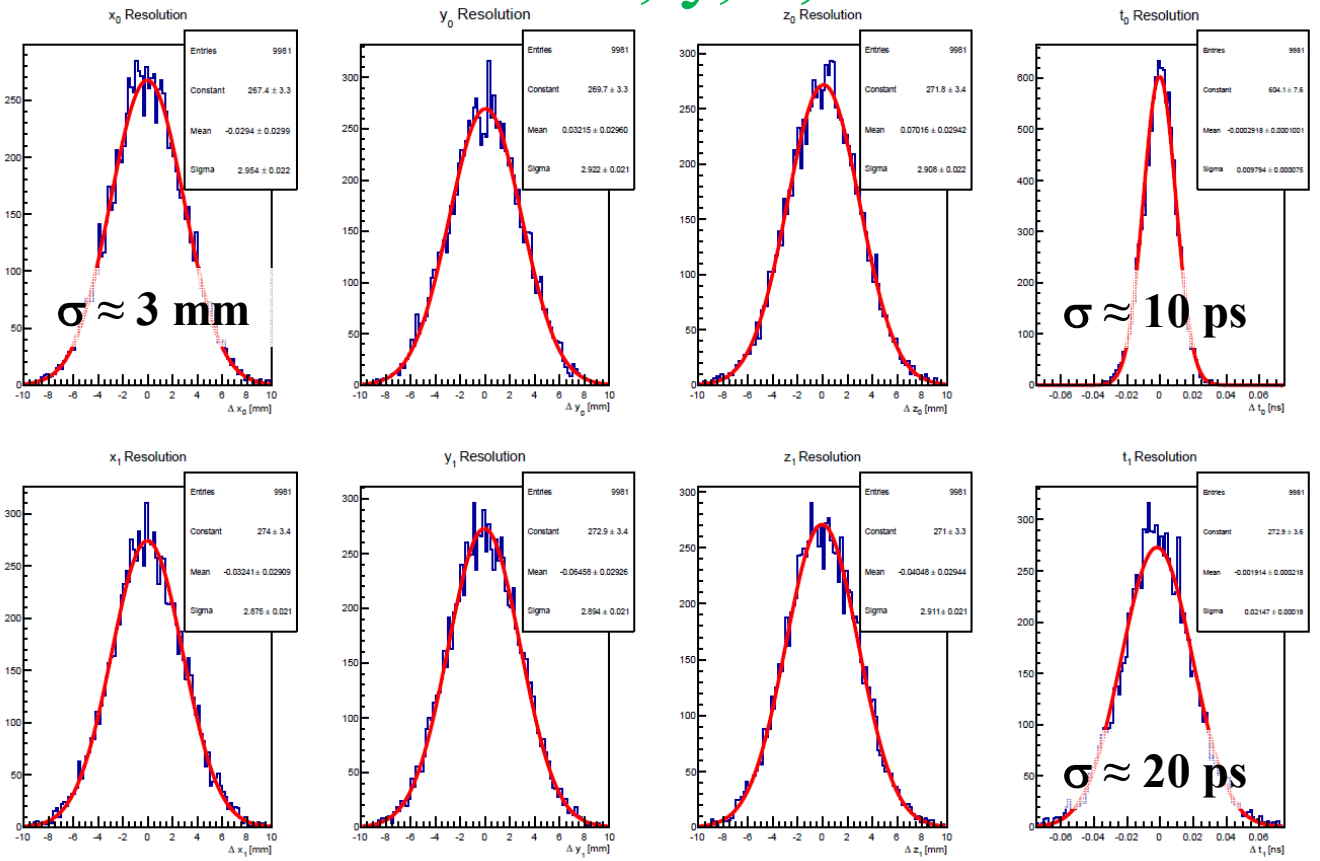
Acknowledgments
- SNL LDRD funding
- LAPPD collaboration
- mini Time Cube

Additional Slides

Simulation/Reconstruction

- GEANT4 simulation incl optical photons
- $(10\ cm)^3$ detector, PD on all six sides
- Fixed event: 3 cm/2 ns separation, ~1 MeVee each recoil
- Stilbene pulse shape (0.1 ns rise, 4.5 ns decay)
- Idealized PD response/resolution

First Interaction x, y, z, t

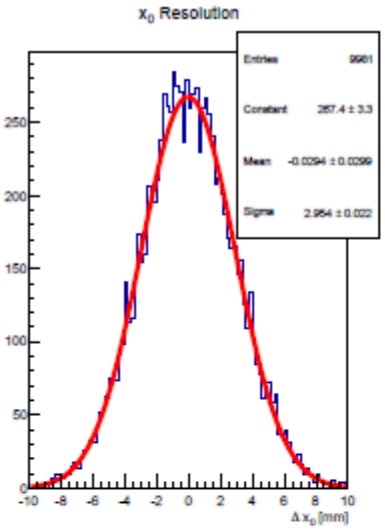


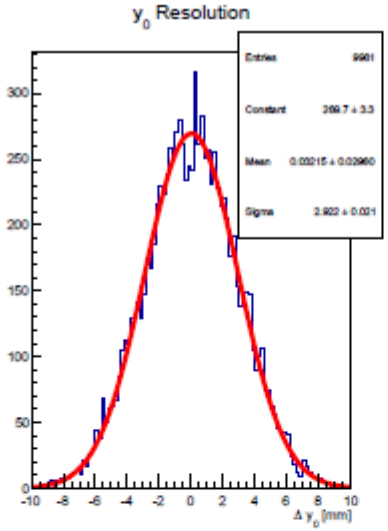
Second Interaction x, y, z, t

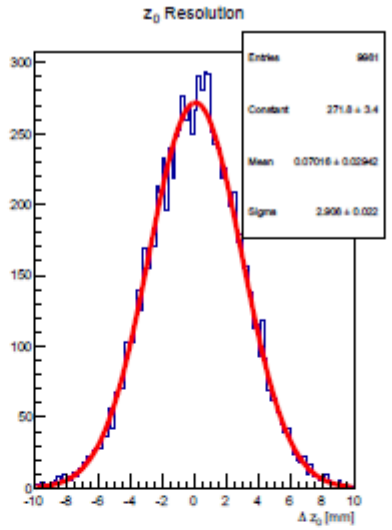
Ideal case, **NOT** predictions of experimental resolutions!

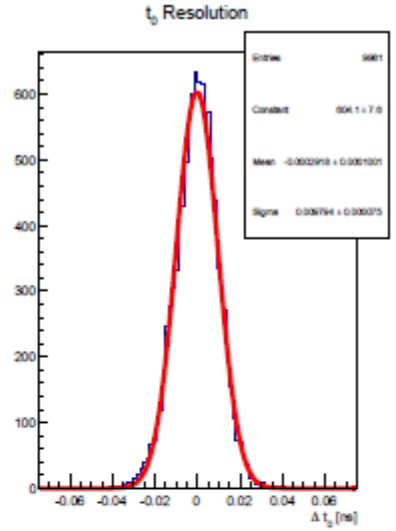
Central event

(10,0,0,0) [mm,ns]

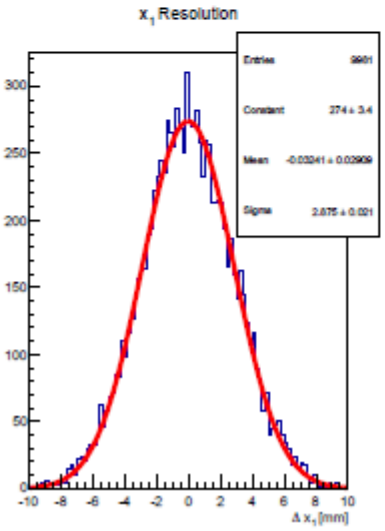


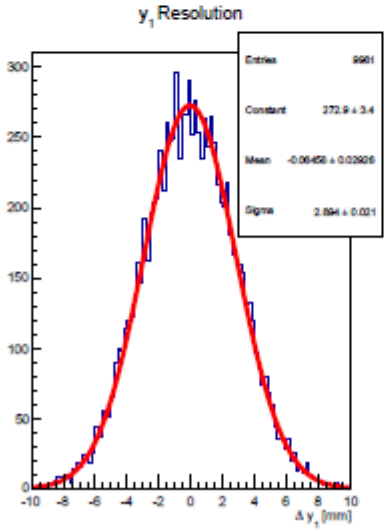


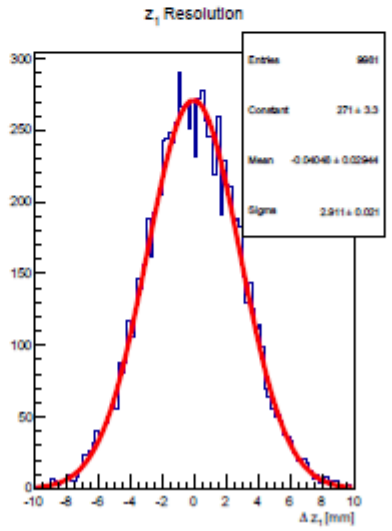


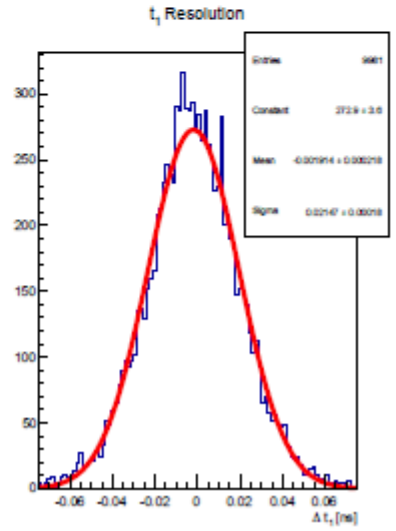


(20,20,20,2) [mm,ns]



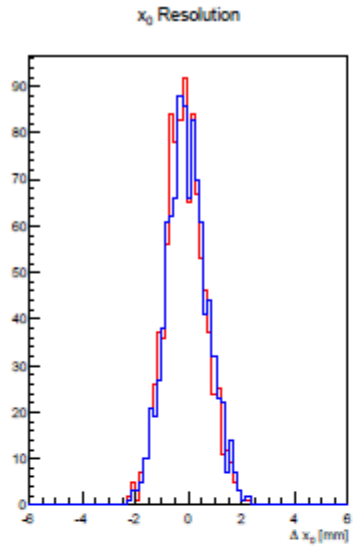


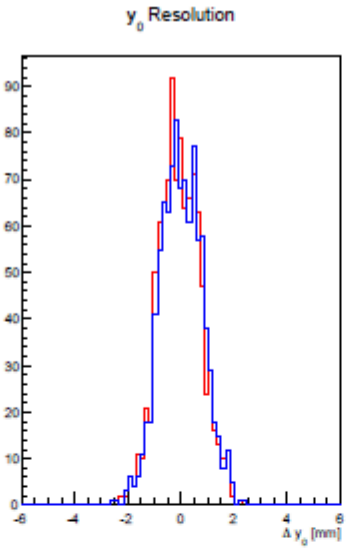


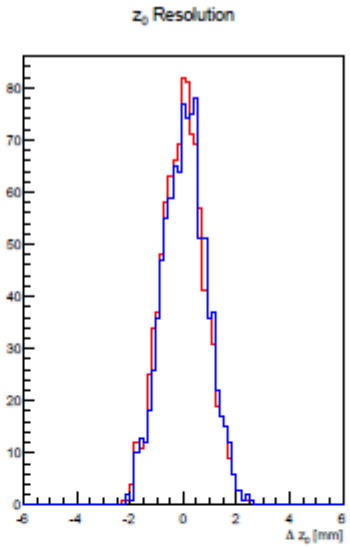


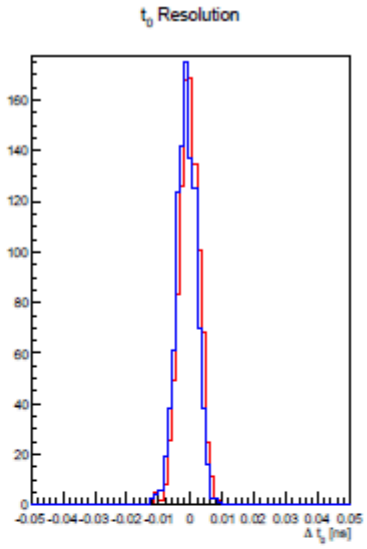
Shifted event

(80,0,0,0) [mm,ns]

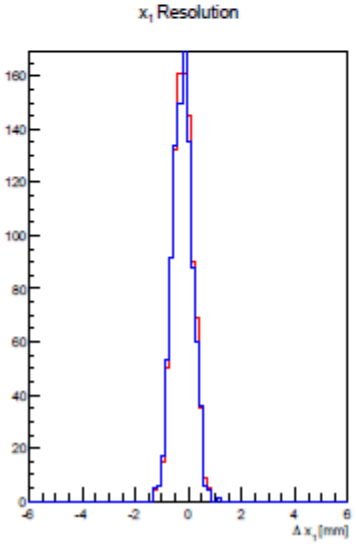


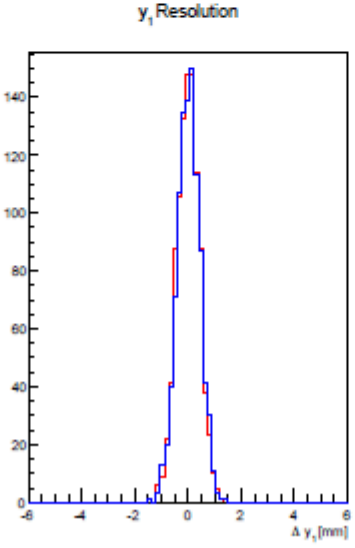


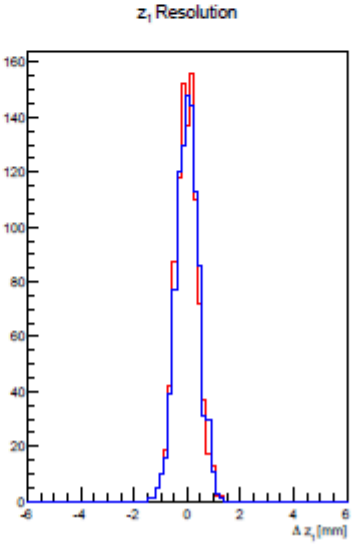


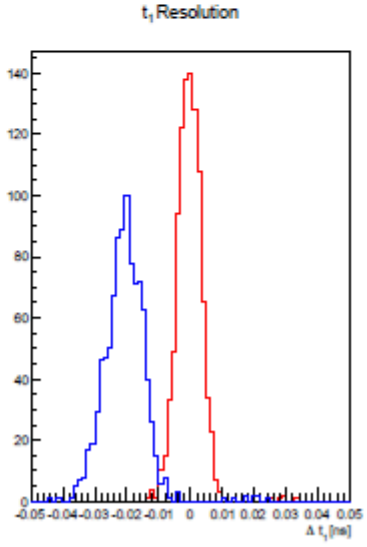


(90,20,20,2) [mm,ns]

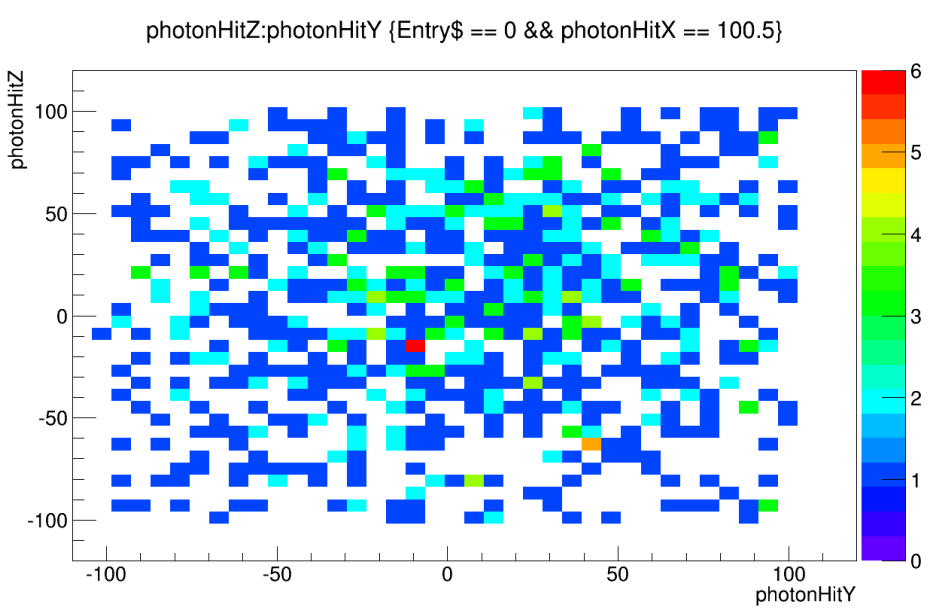


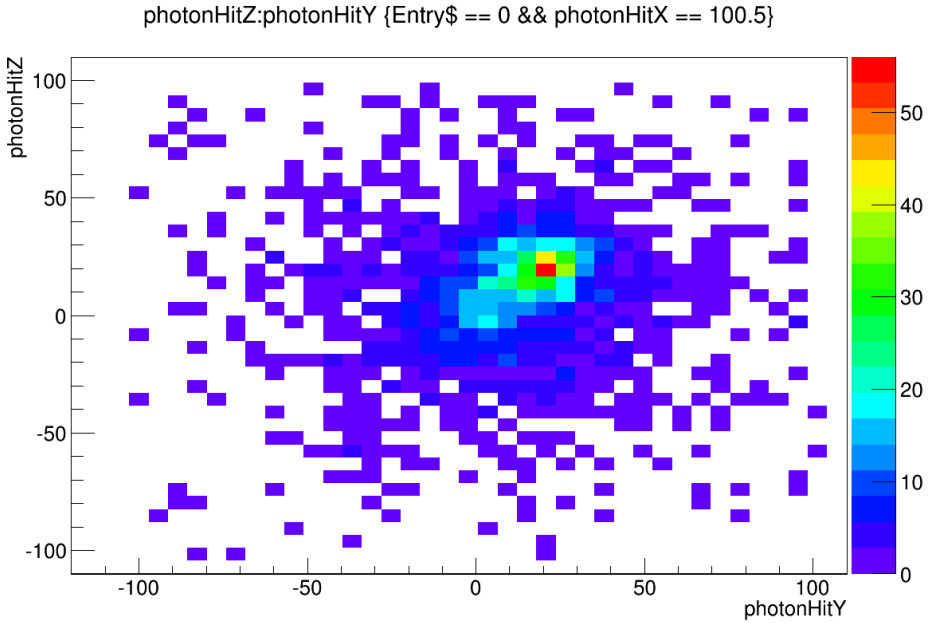




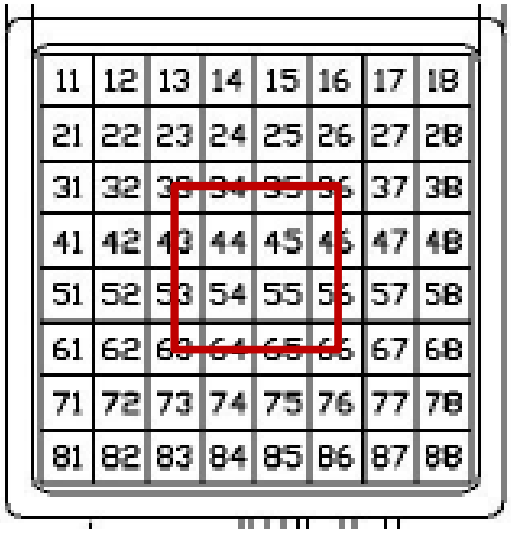


Pixel populations

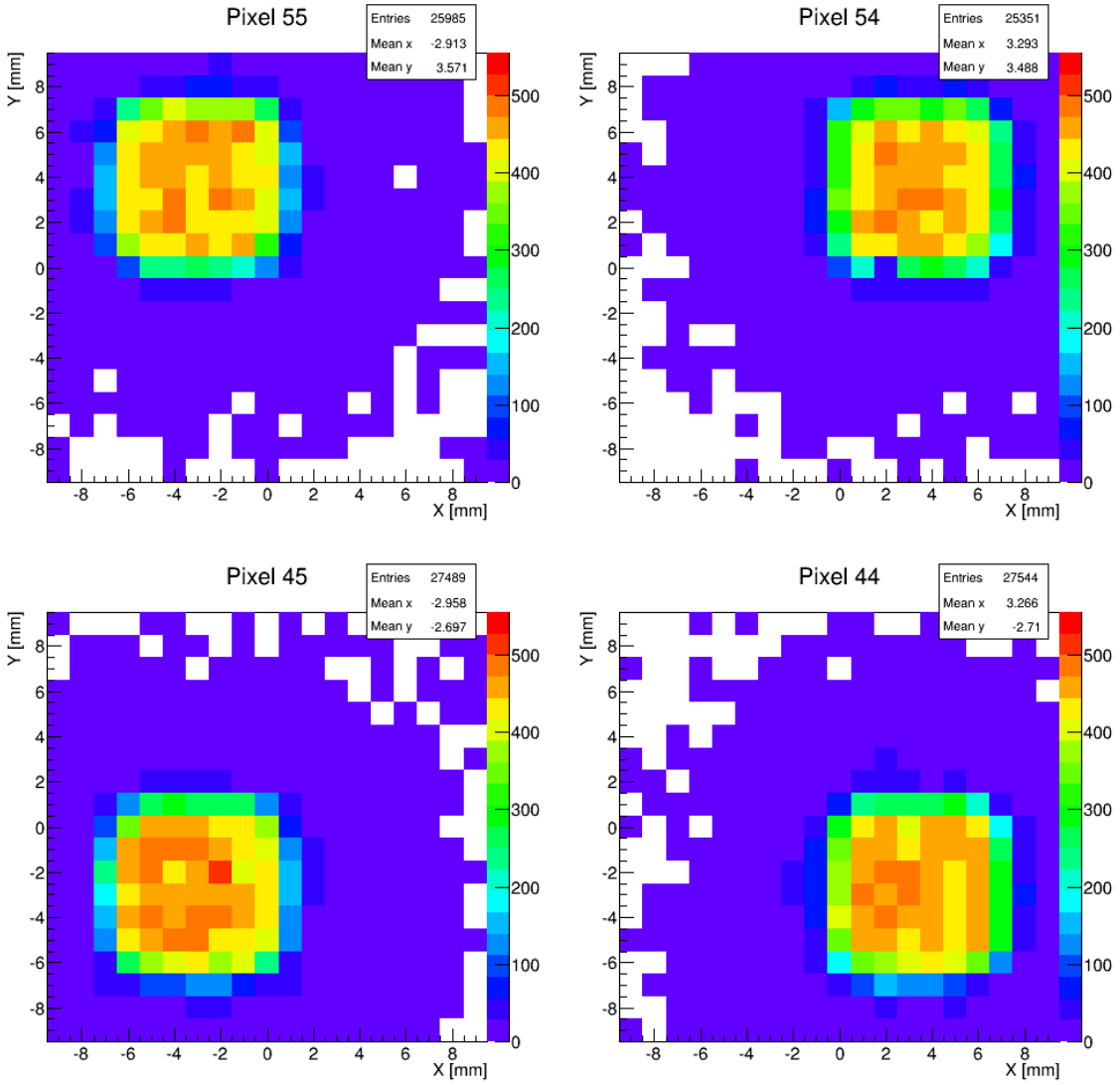




Collimated LED scan

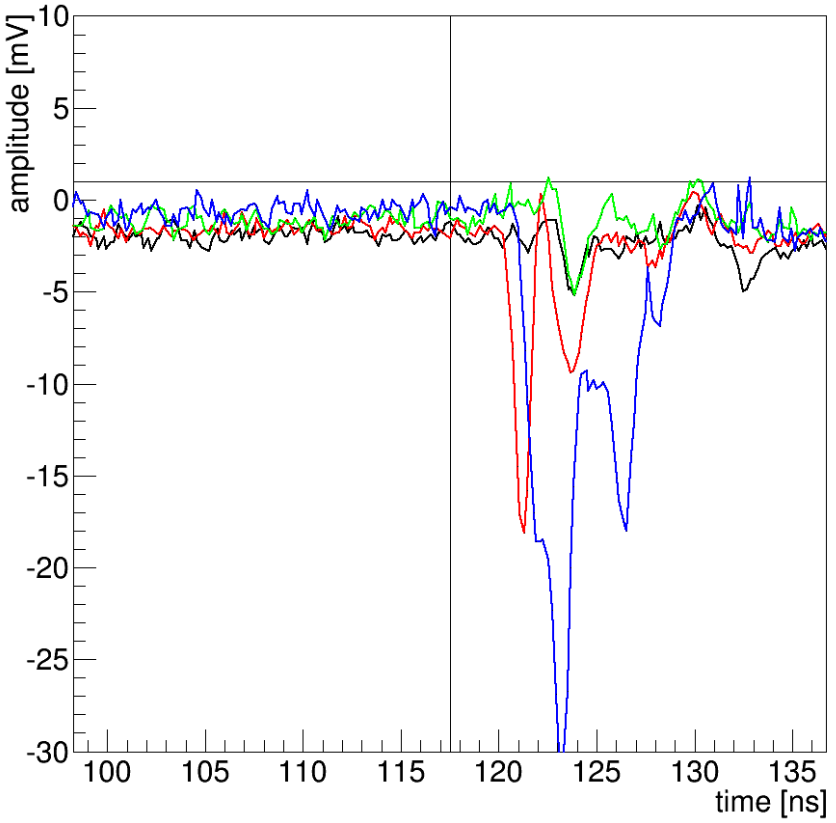


- QE quite flat (over small region)
- Sharp anode pixel boundaries
  - 1 mm collimation
- Some PE scatter

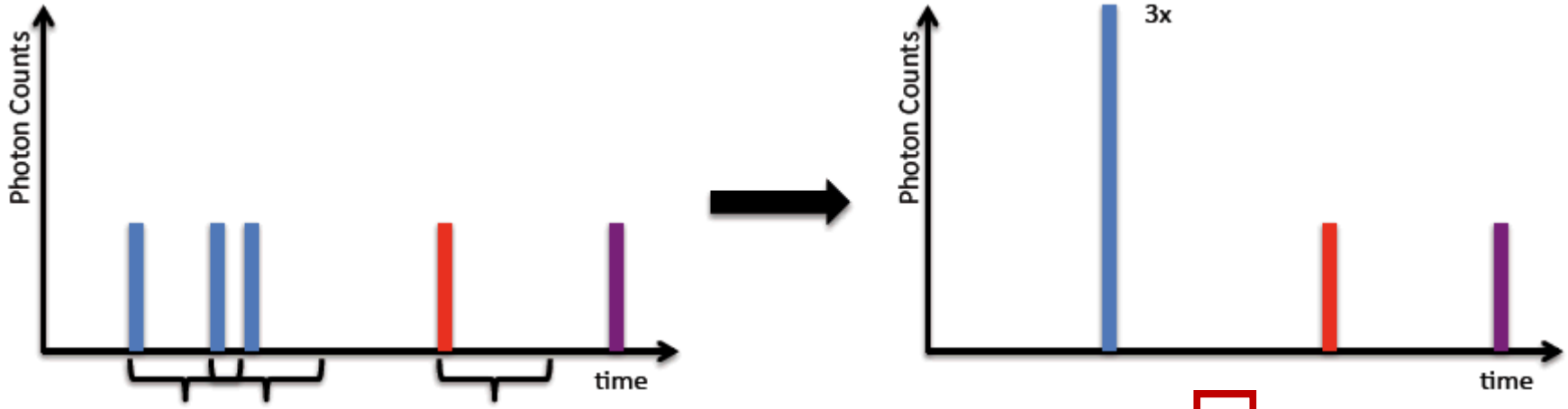


Signal readout/processing

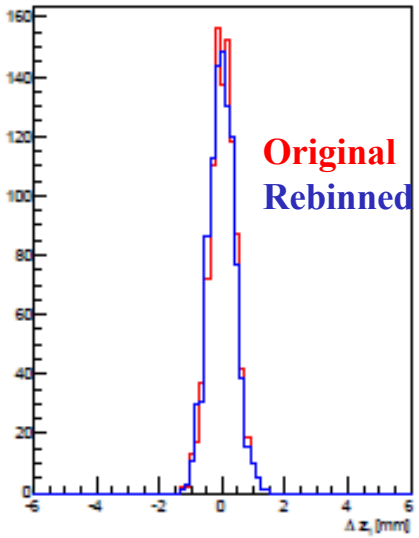
- Not all pixels see well separated single photons.
- Reconstruction algorithm assumes it is handed a list of photon arrival positions & times.
- How to analyze signal trace?



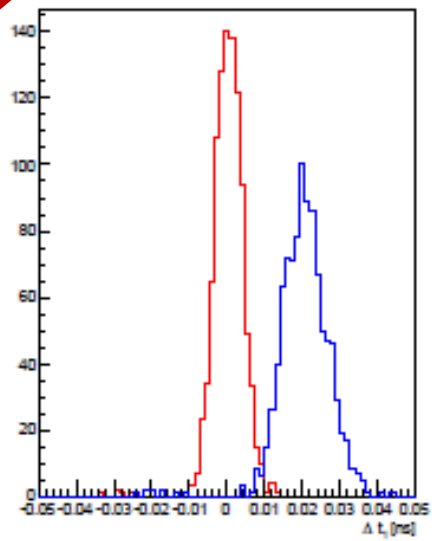
Signal readout/processing



- What if the best we can do for overlapping photons is count them?
- Check in simulation study.
- For t_{window} = 300 ps, time is shifted but reconstruction still reasonable.



$z_2 - z_2^{true}$



$t_2 - t_2^{true}$

Active material studies

- Study effect of pulse shape on Δt resolution
- Same default event as earlier slide
- Pulse width important, especially rise time
- Quenched plastics?
  - Short decay
  - But slower rise
  - Low light output