University of Chicago

Argonne NATIONAL LABORATORY

LAPPD

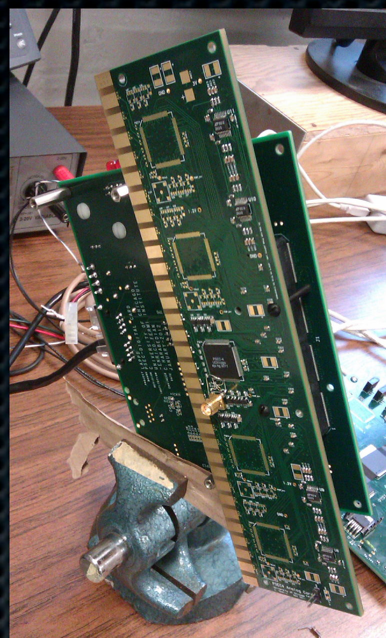
Fine-grained optical tracking with *imaging* photodetectors

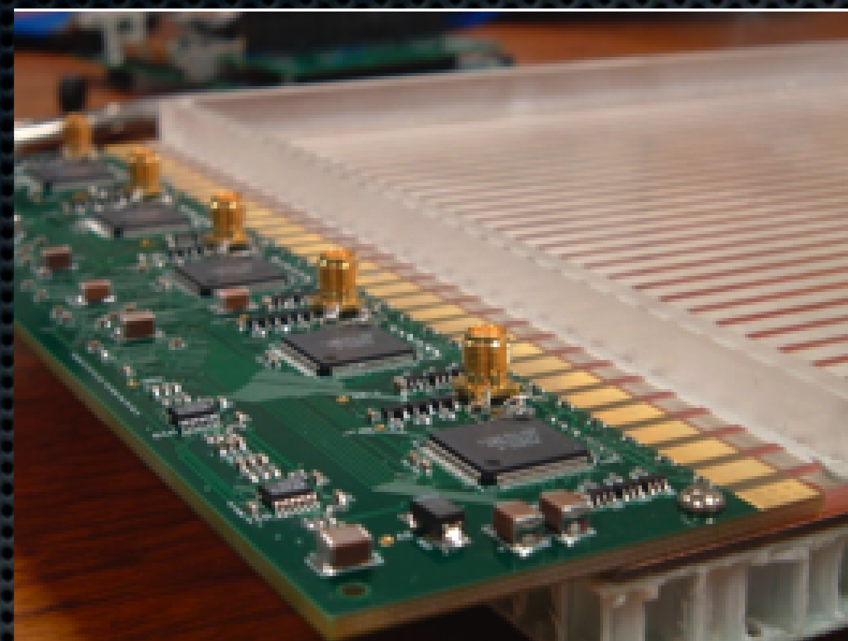
M. Wetstein
U Chicago

LAPPD Project in pictures...

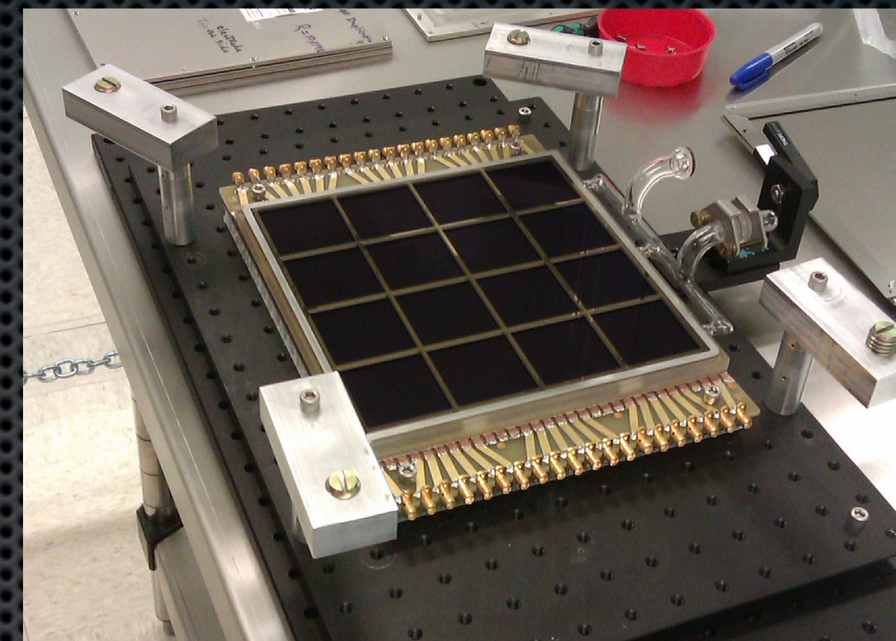
LAPPD Project in pictures...and plots

PSEC 4 readout system

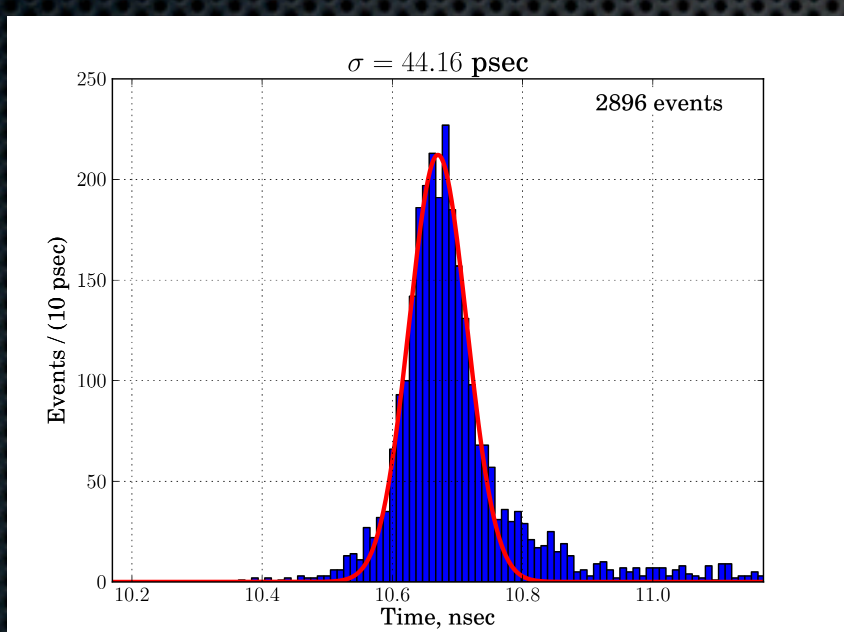




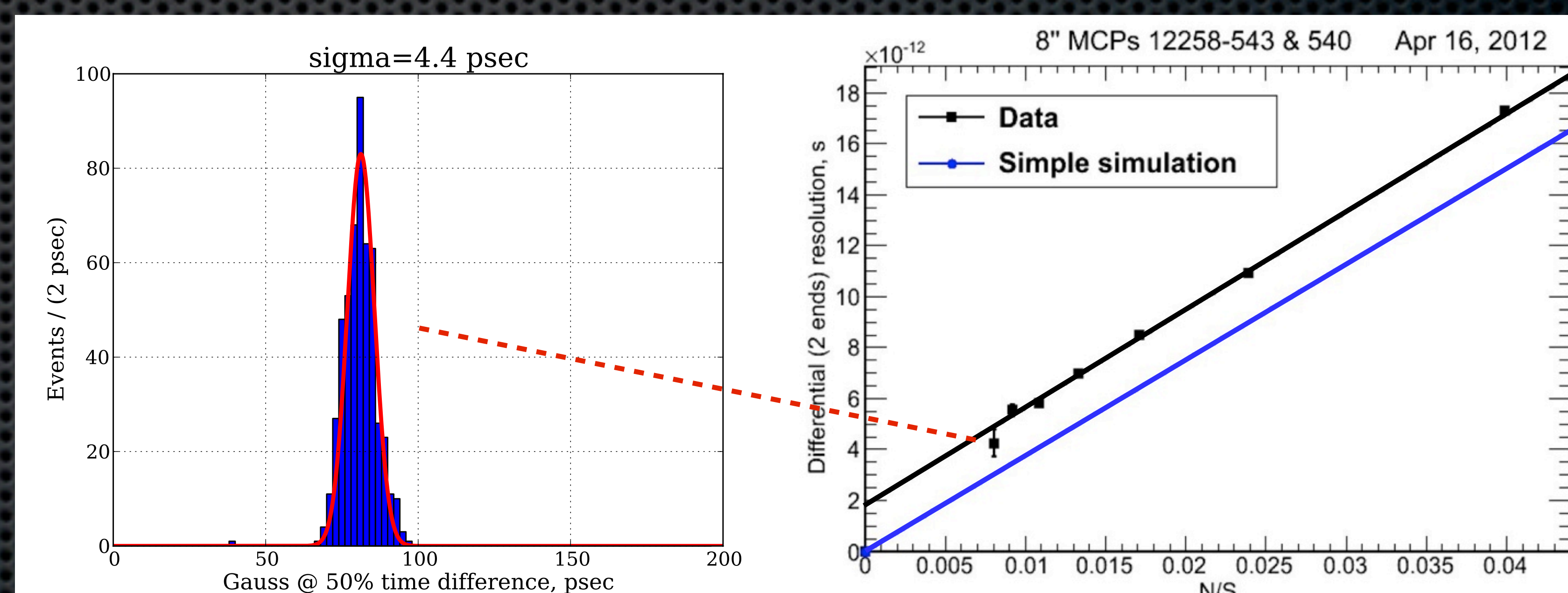
8” Demountable Detector



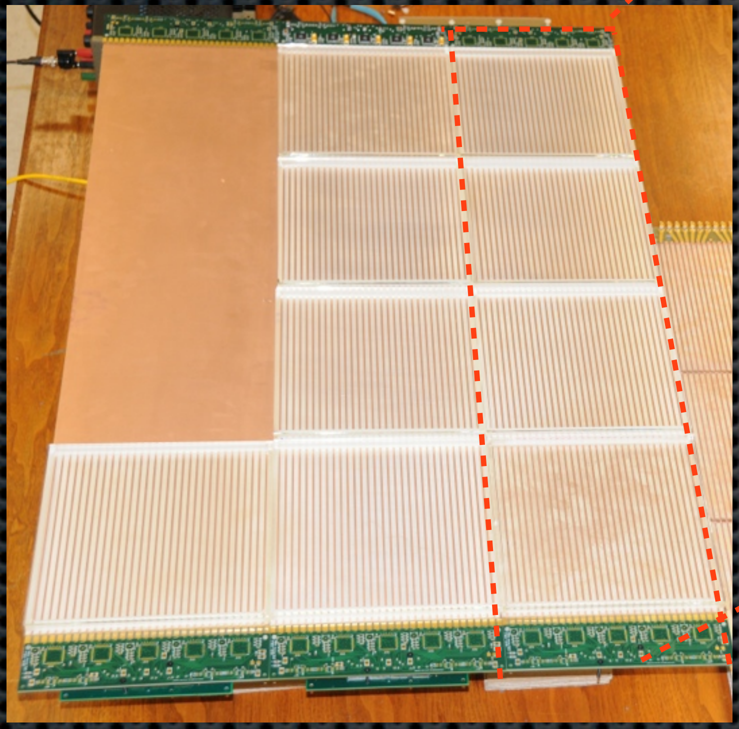
single PE timing



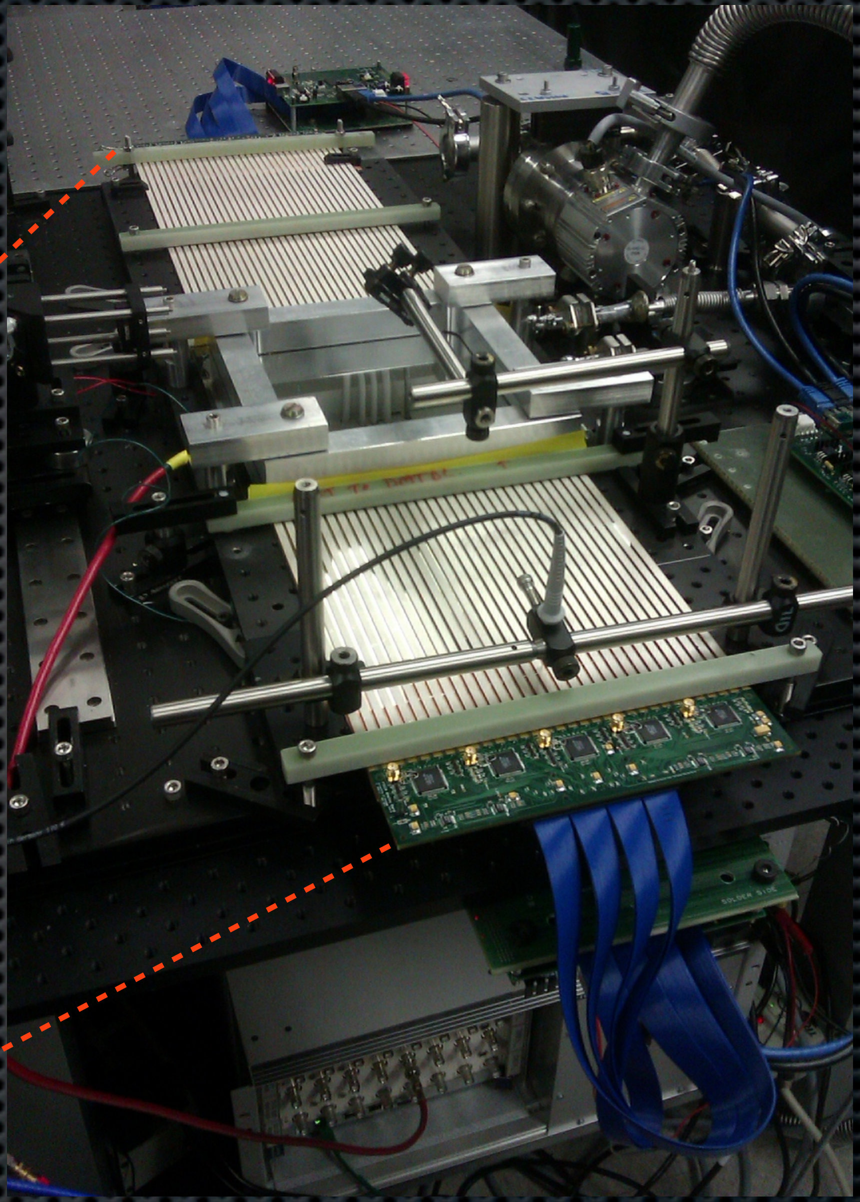
Large signal timing



LAPPD Project in pictures...



mock-up of a “Super Module (SuMo)



Testing a working SuMo slice with 90cm anode

Some reconstruction challenges using optical light

1. Signal per unit length (before attenuation)

~20 photons/mm

Acceptance and coverage are important, especially at Low E. Is there any way we can boost this number? Scintillation?

2. Drift time

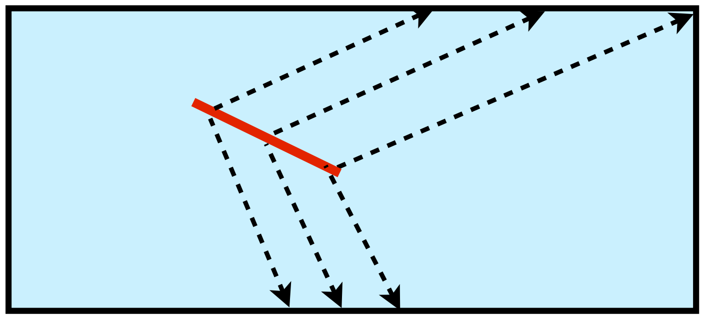
~225,000mm/microsecond

This necessitates **fast** photodetection. It also requires **spatial resolution commensurate with the time resolution.**

3. Topology

drift distances depend on track parameters

This presents some reconstruction challenges, but not unconquerable.



Also: scattering and dispersion

3 approaches to generic reconstruction

Fast/parametric

(simple track fits)

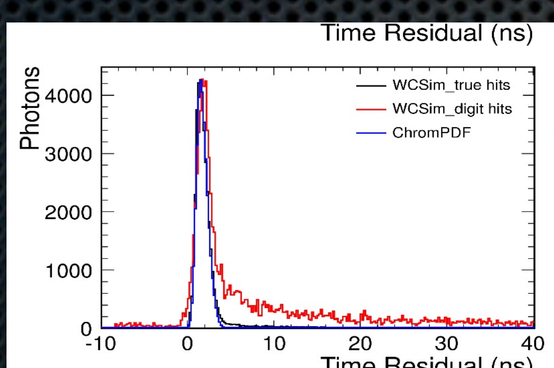
Useful for seed fits and helpful for pedagogical understanding of detector tradeoffs

Limited in Possible Complexity

Work with timing-residual based muon fits to study

- the relationship between vertex resolution and detector parameters
- improvements to track reconstruction with chromatic corrections

T. Xin, I. Anghel (Iowa State)



Working Backward

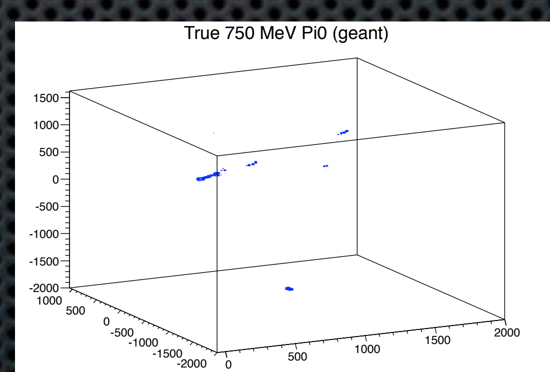
(Generalized Hough Transforms)

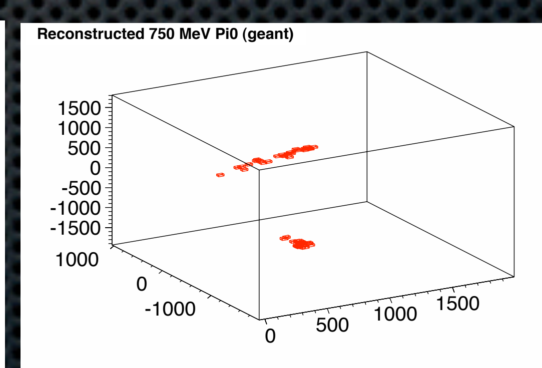
Requires no initial assumptions about event topology

Only makes use of direct light

- Isochron Transform: Causality-based Hough transform for building trakc segments from photon hit parameters
- exploring more detailed reconstruction of EM shower structure

M. Wetstein (U Chicago)





Working forward

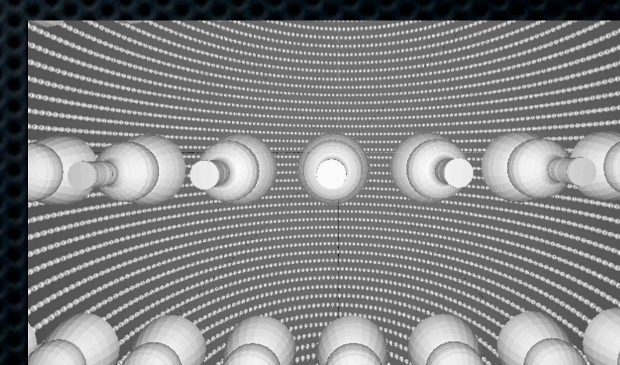
(pattern of light)

Makes fullest use of all photon information, both direct and indirect light

Becomes computationally prohibitive as one tries to resolve finer structure in the event topology

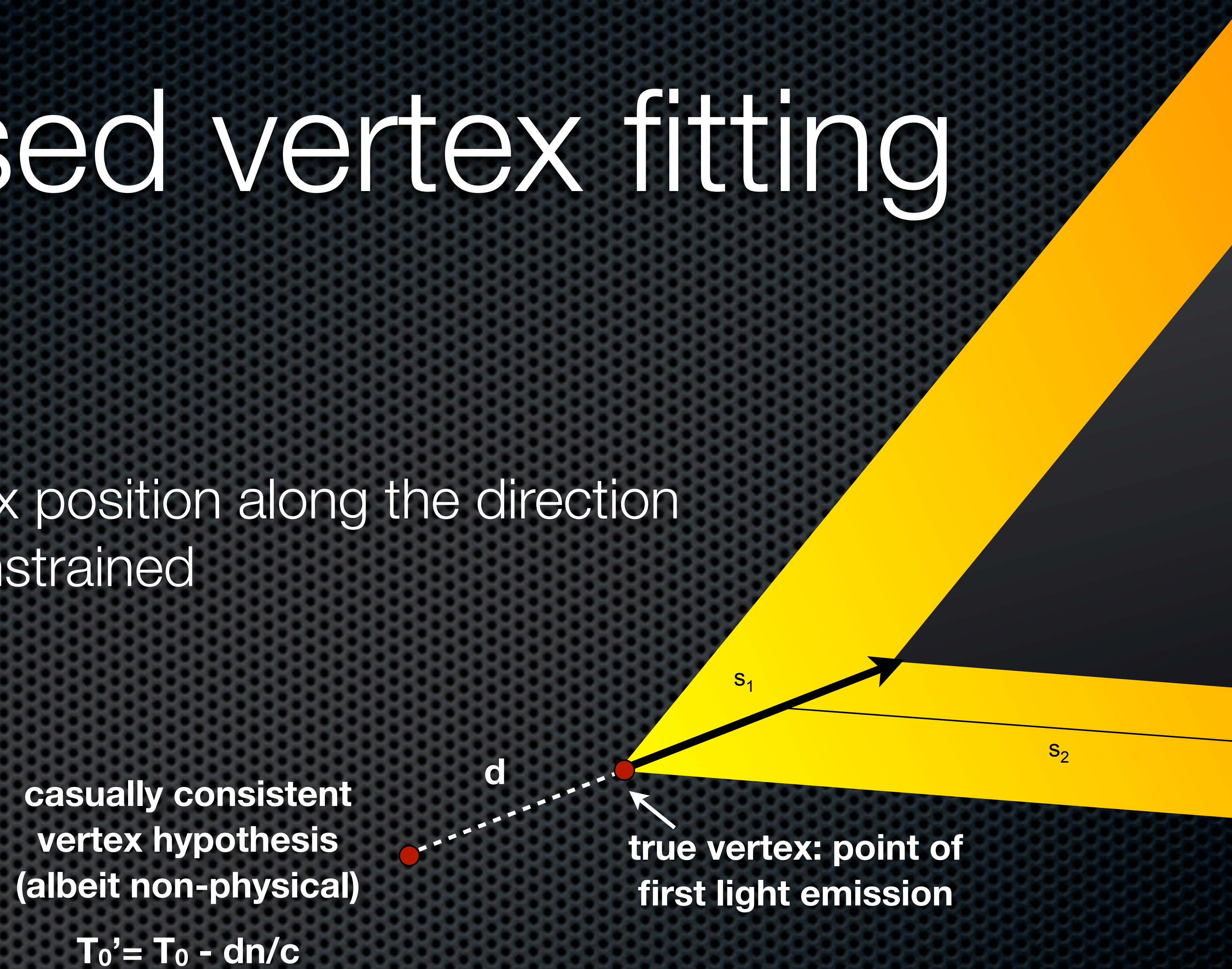
- Chroma: Geant-based, fast photon-tracking MC.
- Capable of rapidly generating large sample MC for a wide variety of detector designs
- Also capable of pattern-of-light fits, where the light pattern for each track hypothesis is generated in real-time.

S. Seibert, A. La Torre (U. Penn)



Timing-based vertex fitting

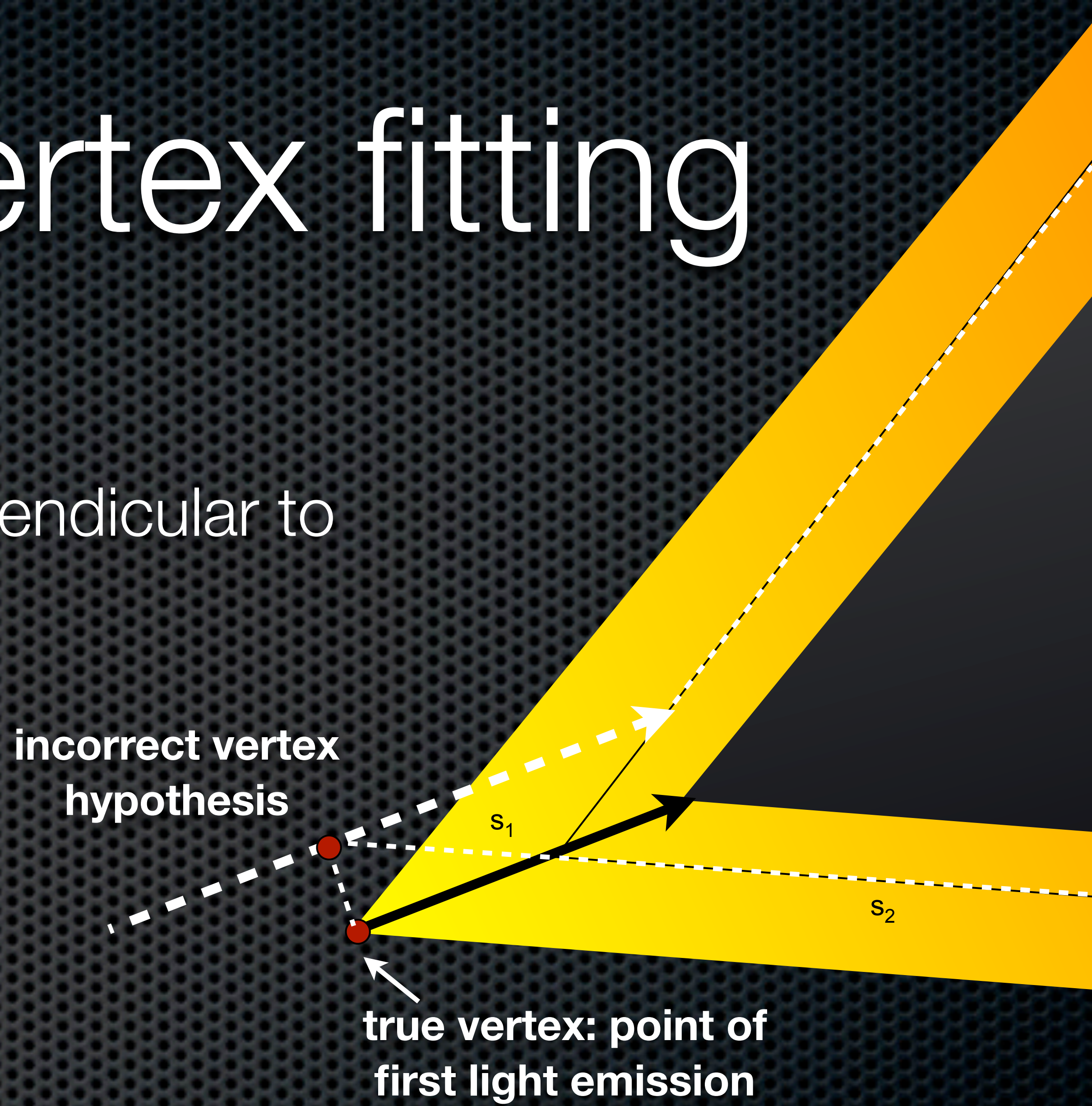
Based on pure timing, vertex position along the direction parallel to the track is unconstrained



Must used additional constraint: fit the “edge of the cone” (first light). A pattern of light approach to the rising edge of the first light, would be the best.

Timing-based vertex fitting

Position of the vertex in the direction perpendicular to the track *is* fully constrained by causality

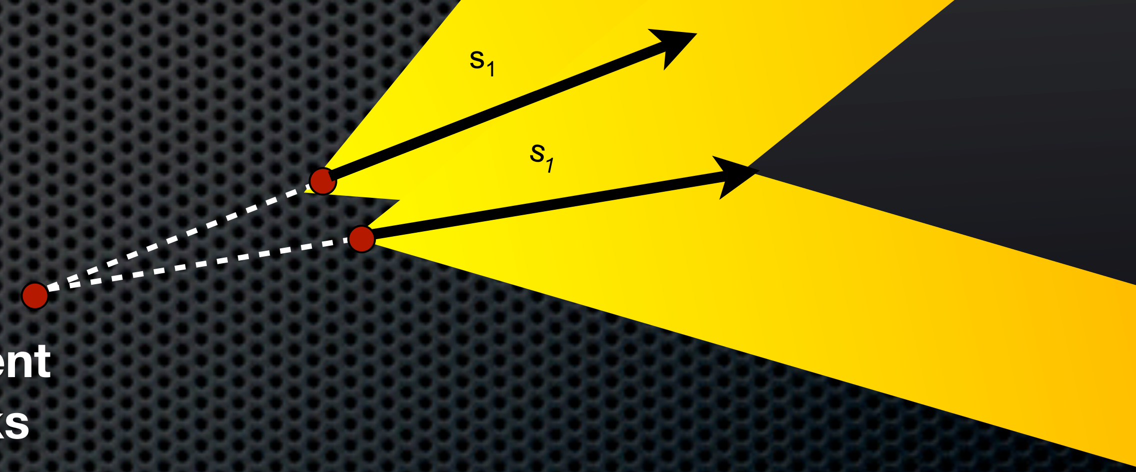


For single vertex fitting, we expect the transverse resolution to improve significantly with photosensor time-resolution!

Timing-based vertex fitting

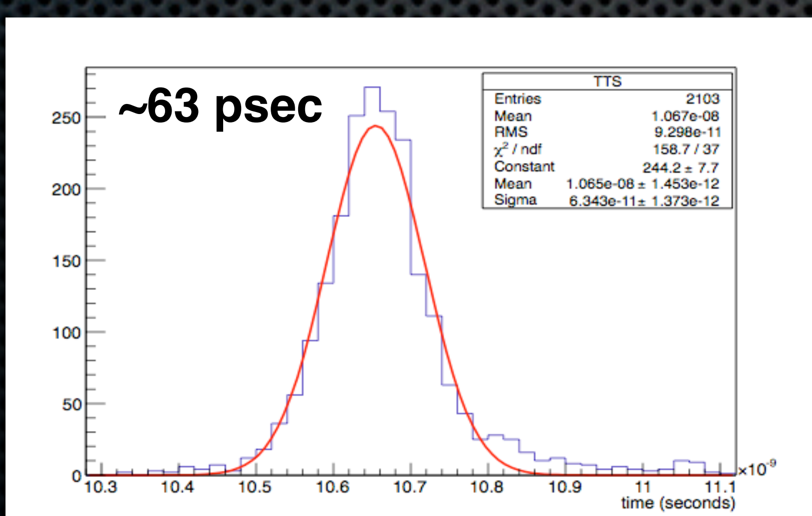
Fortunately, multi-vertex separation is a differential measurement.

Causality arguments are fully sufficient to distinguish between one and two vertices.



Only one unique solution that can satisfy the subsequent timing of both tracks

actual single PE time resolution for 8” detector (M. Wetstein, A. Elagin, S. Vostrikov)

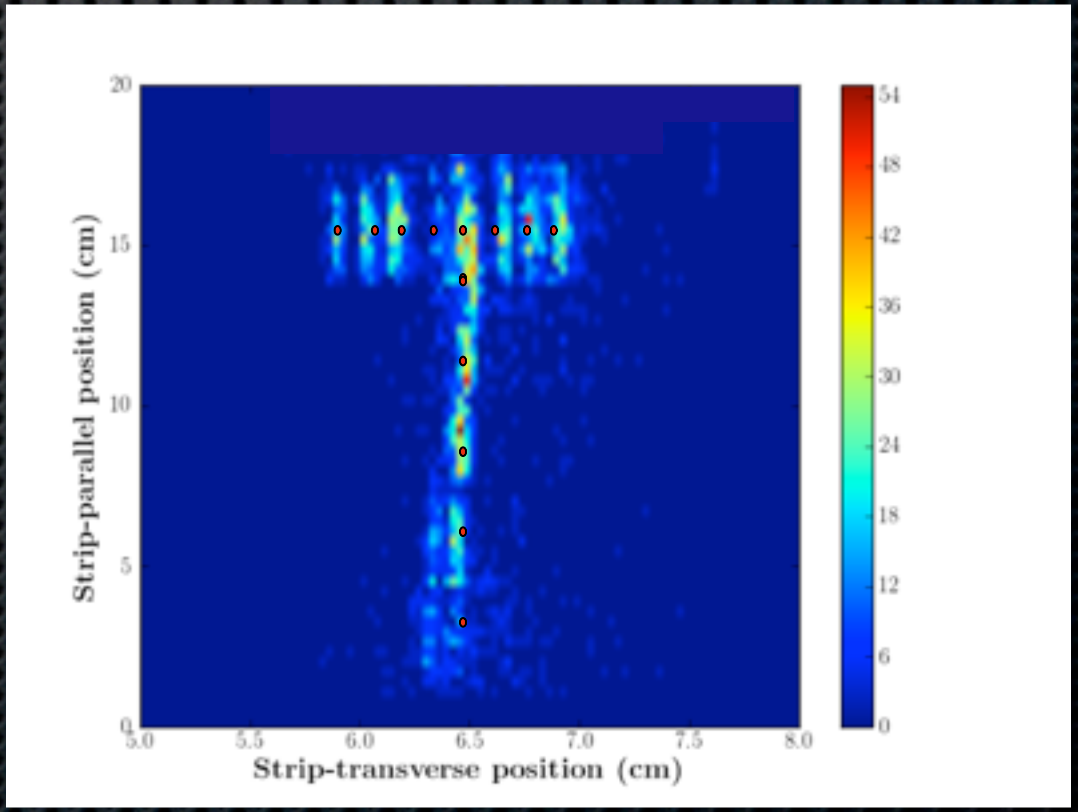


100 picoseconds ~ 2.25 centimeters

Imaging phototubes

- LAPPDs are imaging phototubes (each photon has a unique position (cm-resolution), time (100 psec resolution), *and* charge
- Which gives us *digital* photon counting capabilities.
- This means
  - better fits to the cone edge (better direction)
  - better energy resolution for charged leptons
- It also means the ability to use causality to cleanly separate between
  - scattered light and direct light better signal to noise
  - between overlapping light from multiple tracks and multiple shower constituents
  - for trajectories that differ by only a few centimeters

Reconstruction of a 'T' on the "demountble" LAPPD prototype (20 x 8 cm region)



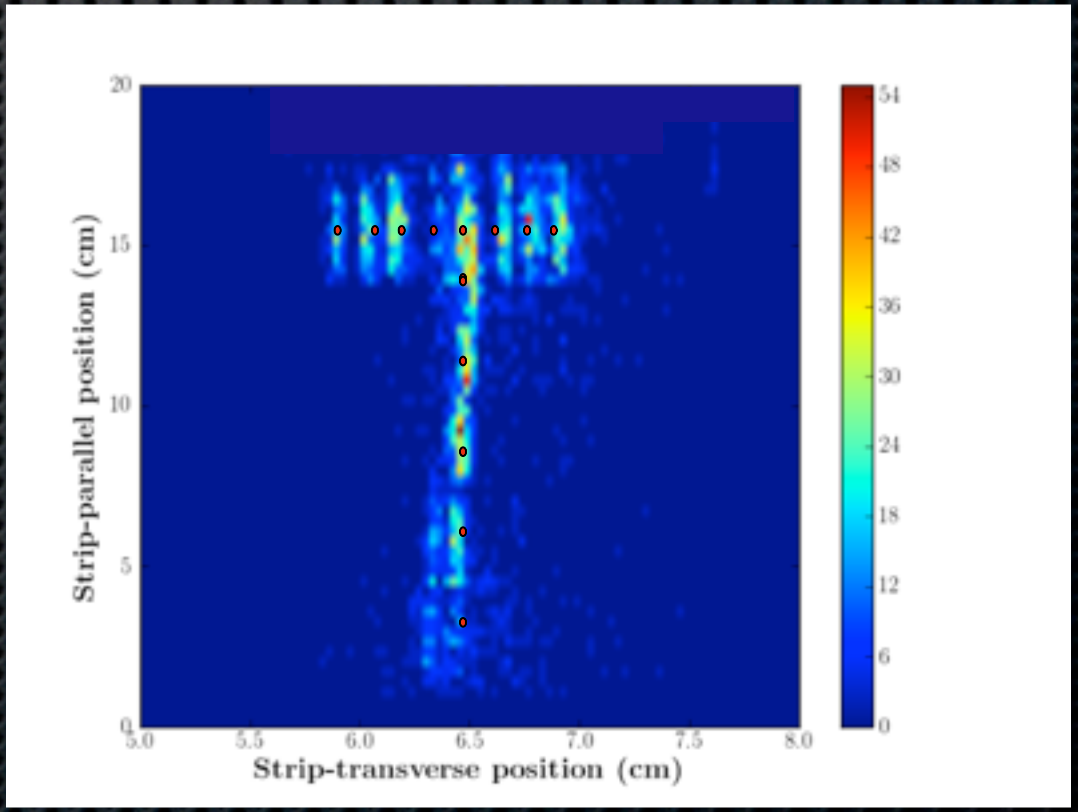
Imaging phototubes

The ability to sort and measure light on a photon-by-photon basis (not just charge and time) has the potential to fundamentally change reconstruction strategy:

Reconstruction of a 'T' on the "demountble" LAPPD prototype (20 x 8 cm region)

One can potentially isolate and independently separate those clusters of photons with the most useful information rather than averaging over the whole pattern of light (which washes out some information).

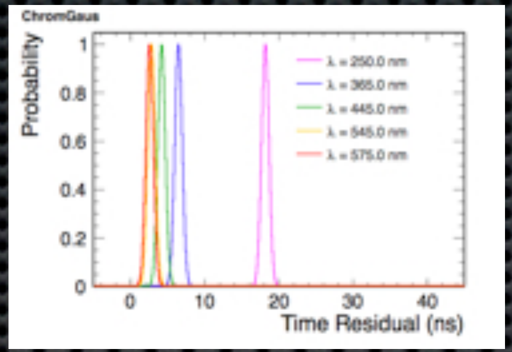
For speed sake, it may be possible reconstruct the first few stages of an EM shower, where most of the information is contained



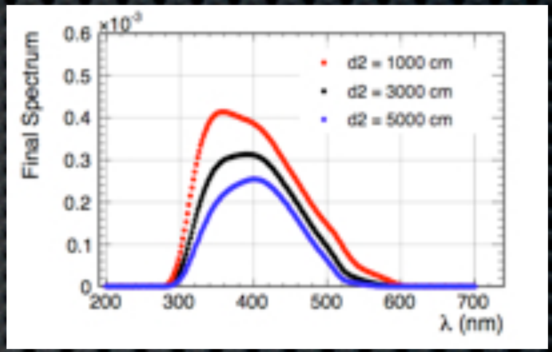
T. Xin, I. Anghel, M. Wetstein

Vertex fit method

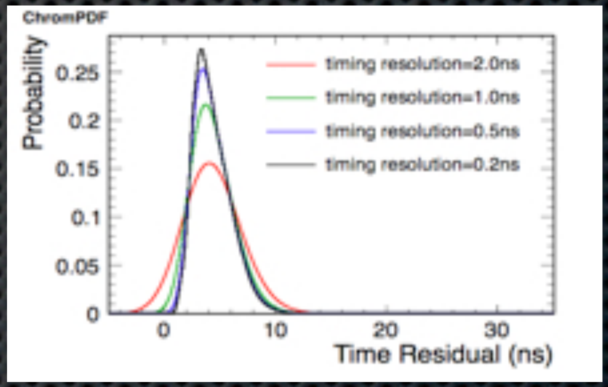
- A timing residual-based fit, assuming an extended track.
- Model accounts for effects of chromatic dispersion and scattering.
    - separately fit each photon hit with each color hypothesis, weighted by the relative probability of that color.
- For MCP-like photon detectors, we fit each photon rather than fitting (Q,t) for each PMT.
- Likelihood captures the full correlations between space and time of hits (not factorized in the likelihood).
- A simple window excludes any light that projects back to points far away from the vertex hypothesis
- Not as sophisticated as full pattern-of-light fitting, but in local fits, all tracks and showers can be well-represented by simple line segments on a small enough scale.

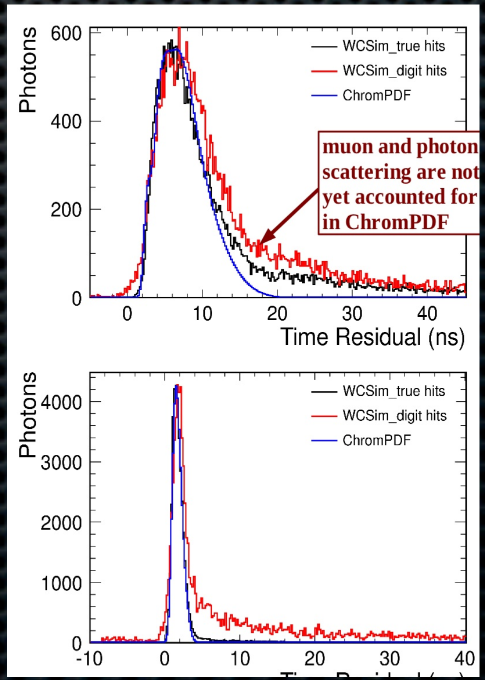


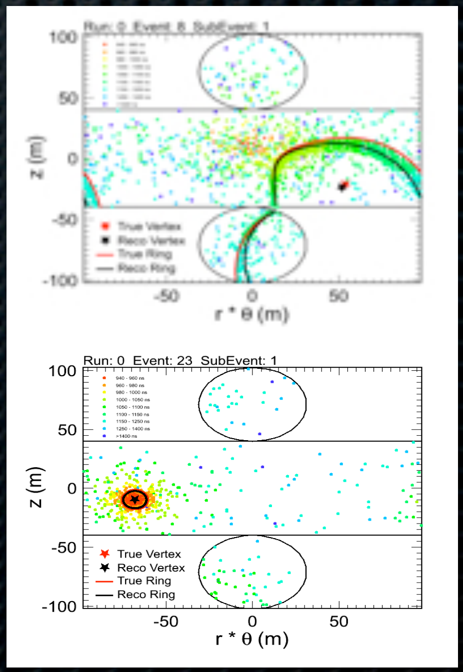
X



$$\mathrm{ChromPDF}(\lambda, \mathrm{d}) = \frac{\sum_\lambda \mathrm{ChromGaus}(\delta t(\lambda), \mathrm{d}) \times \mathrm{FinalSpectrum}(\lambda, \mathrm{d})}{\sum_\lambda \mathrm{FinalSpectrum}(\lambda, \mathrm{d})}$$







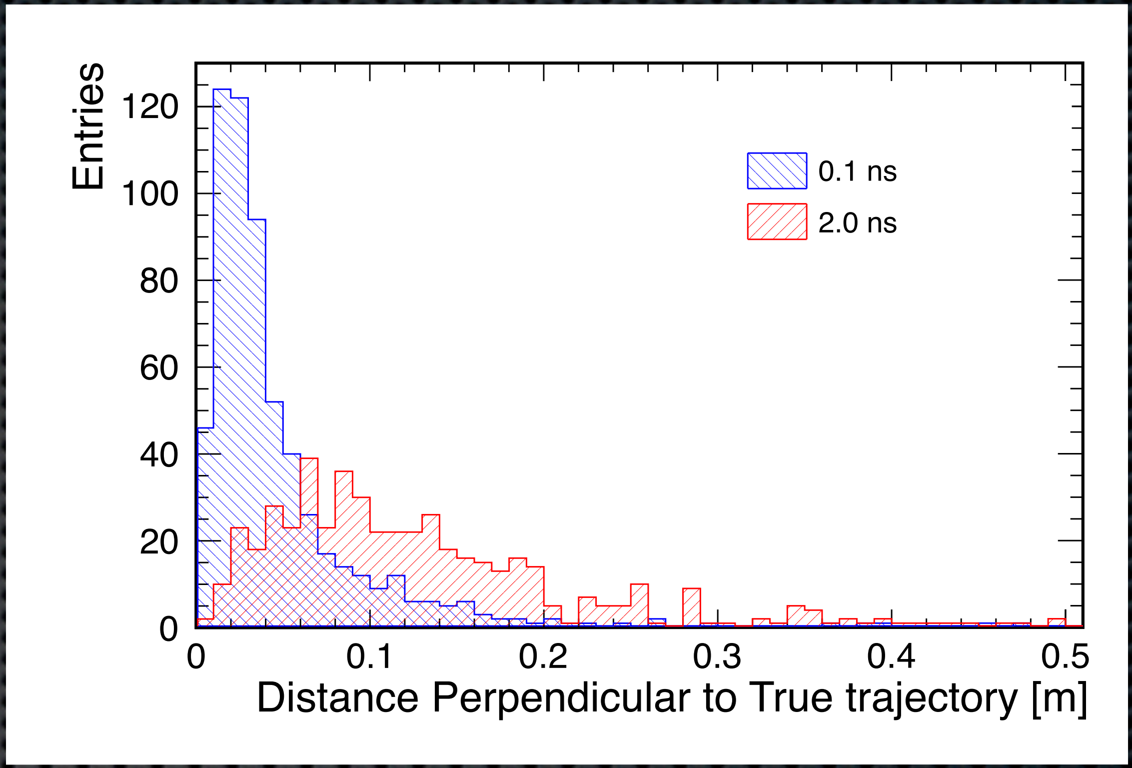
Fit results

T. Xin, I. Anghel, M. Wetstein

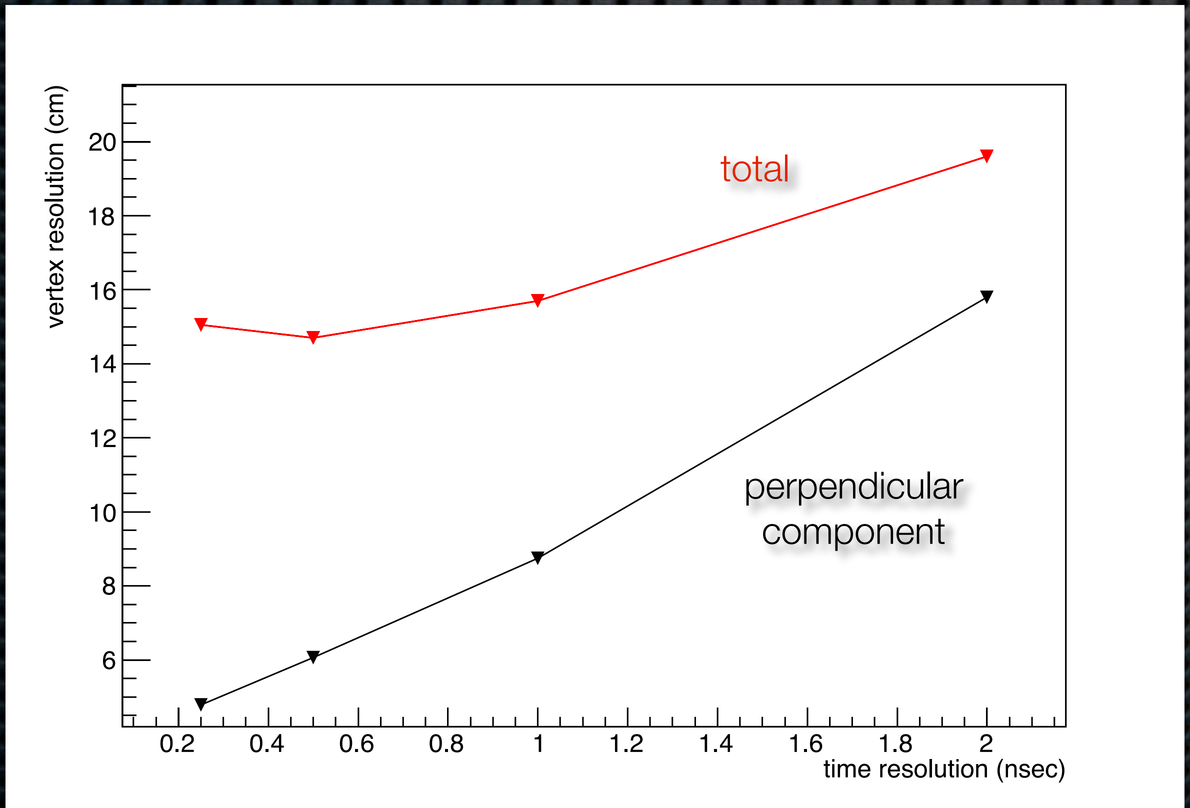
- With digital photon separation and imaging capabilities, we get excellent vertex resolutions.
- Transverse resolution (wrt to track direction) rapidly improves with timing and approaches a few cm. This is a good proxy for vertex separation.
- As expected total resolution plateaus because of the insensitivity of parallel vertexing to time resolution.
- Nonetheless, we thing we can significantly improve this by using more sophisticated fits to the first light (even with some help from timing)

perpendicular resolution:

As expected, we see significant improvement with better timing

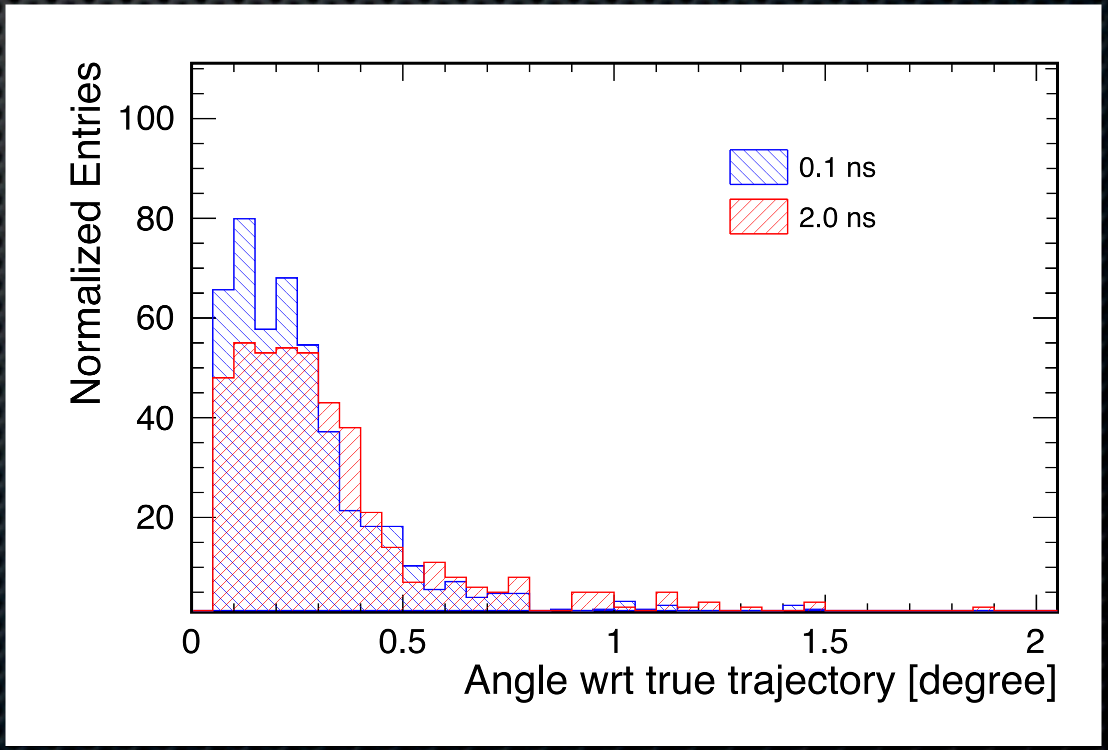


vertex resolution versus time resolution:



angular resolution:

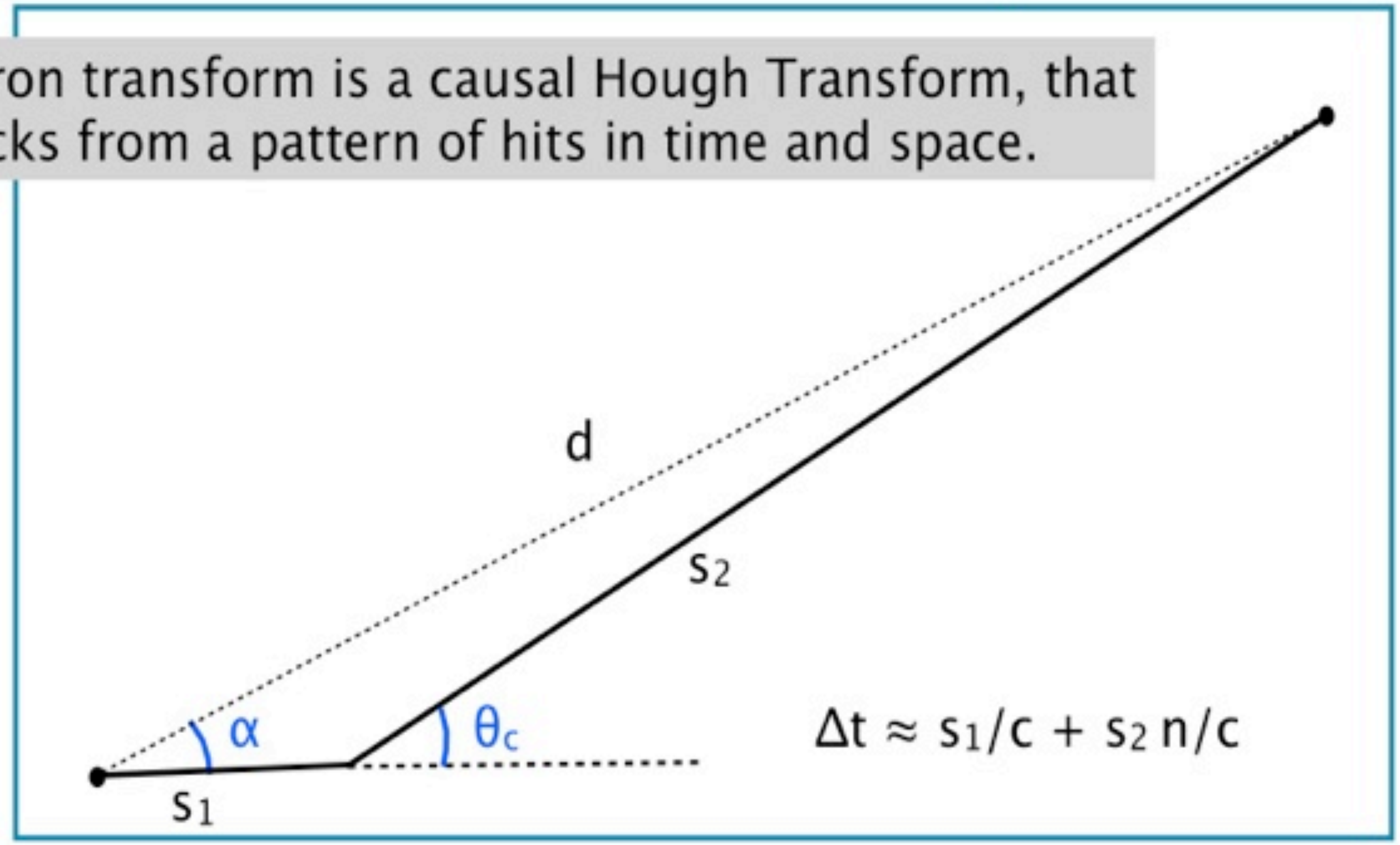
already excellent with imaging tubes, even at 2.0 ns



Isochron method

M. Wetstein

The isochron transform is a causal Hough Transform, that builds tracks from a pattern of hits in time and space.



Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns:

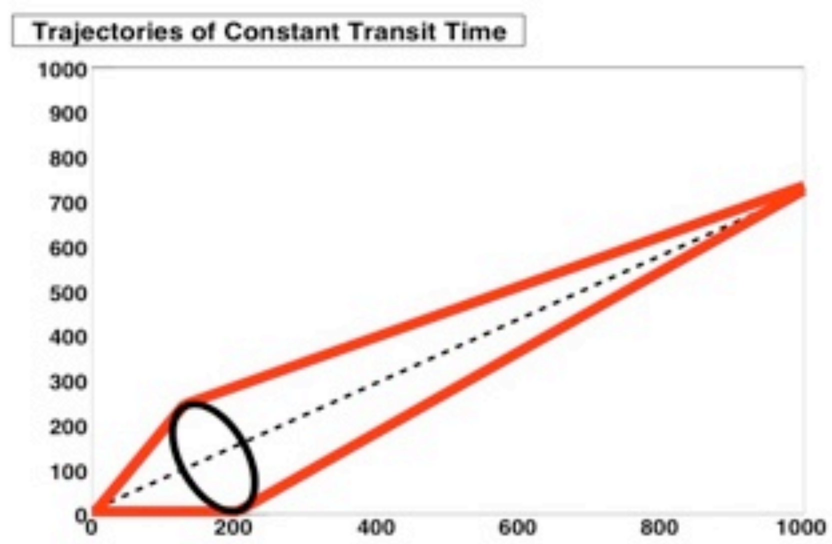
s_1 and α

but there are two constraints:

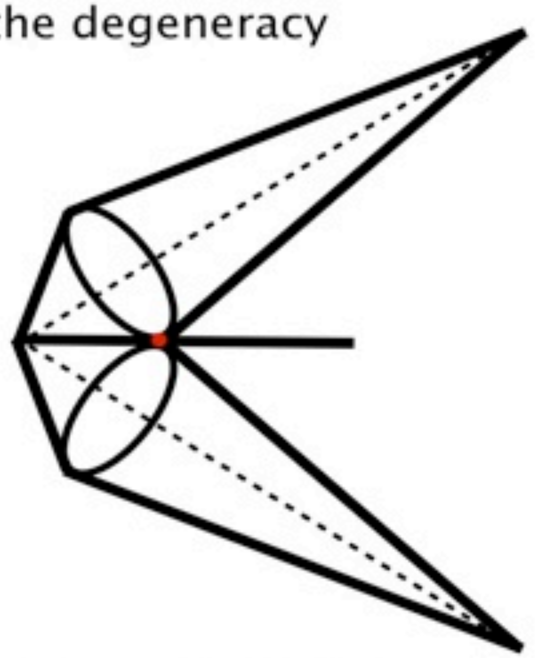
$s_1 + s_1 = d$ and $\Delta t_{measured} = s_1/c + s_2\, n/c$

M. Wetstein

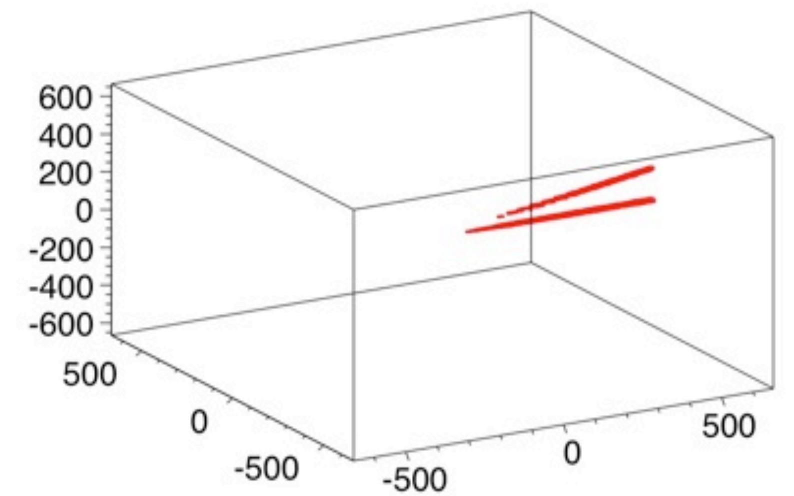
Isochron method



But, multiple hits from the same track will intersect maximally around their common emission point, resolving the degeneracy



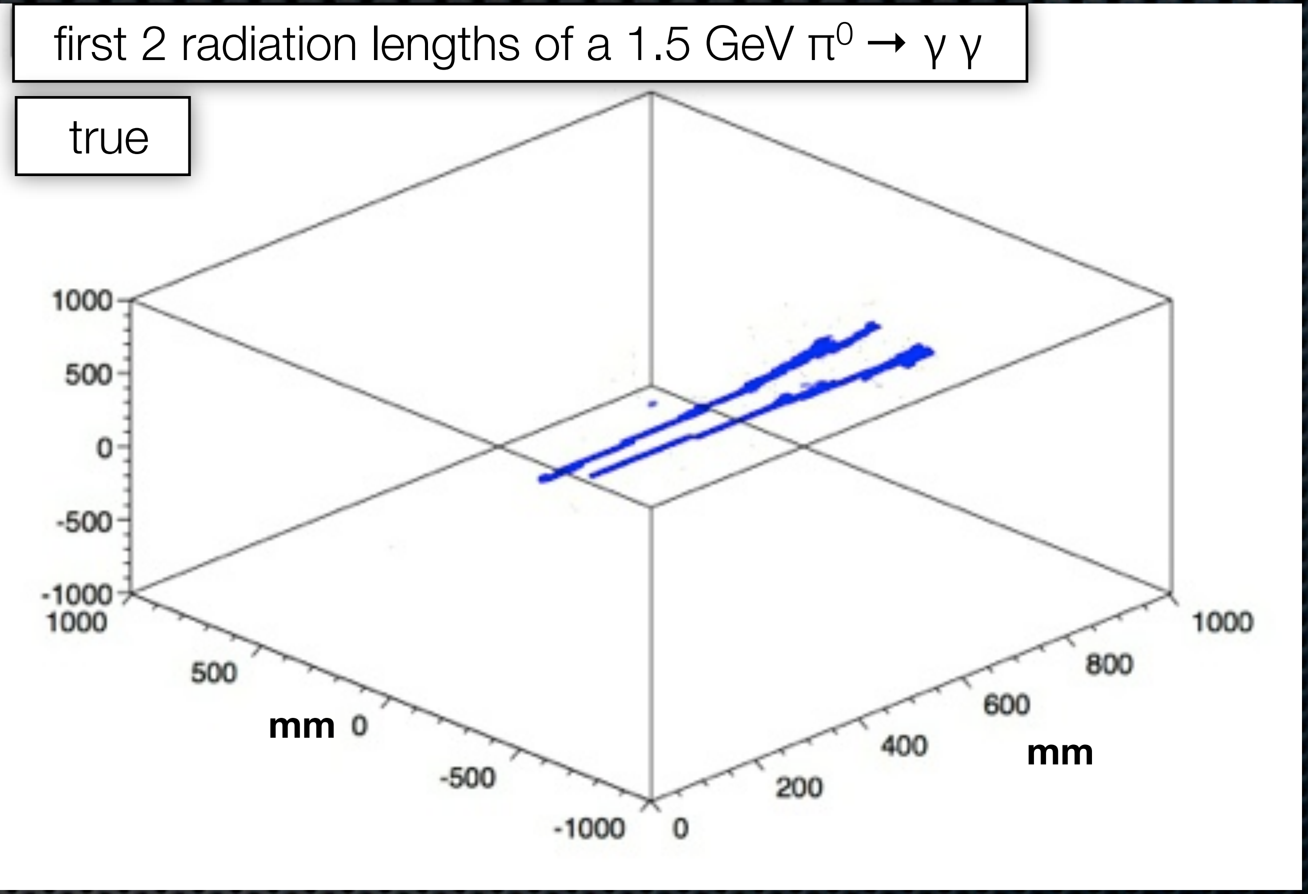
When integrated over all hits, these regions of dense intersection points form clusters around those tracks that share a common vertex. Here we demonstrate closure on a simple two-track toy with light no scattering or dispersion



M. Wetstein

Isochron method

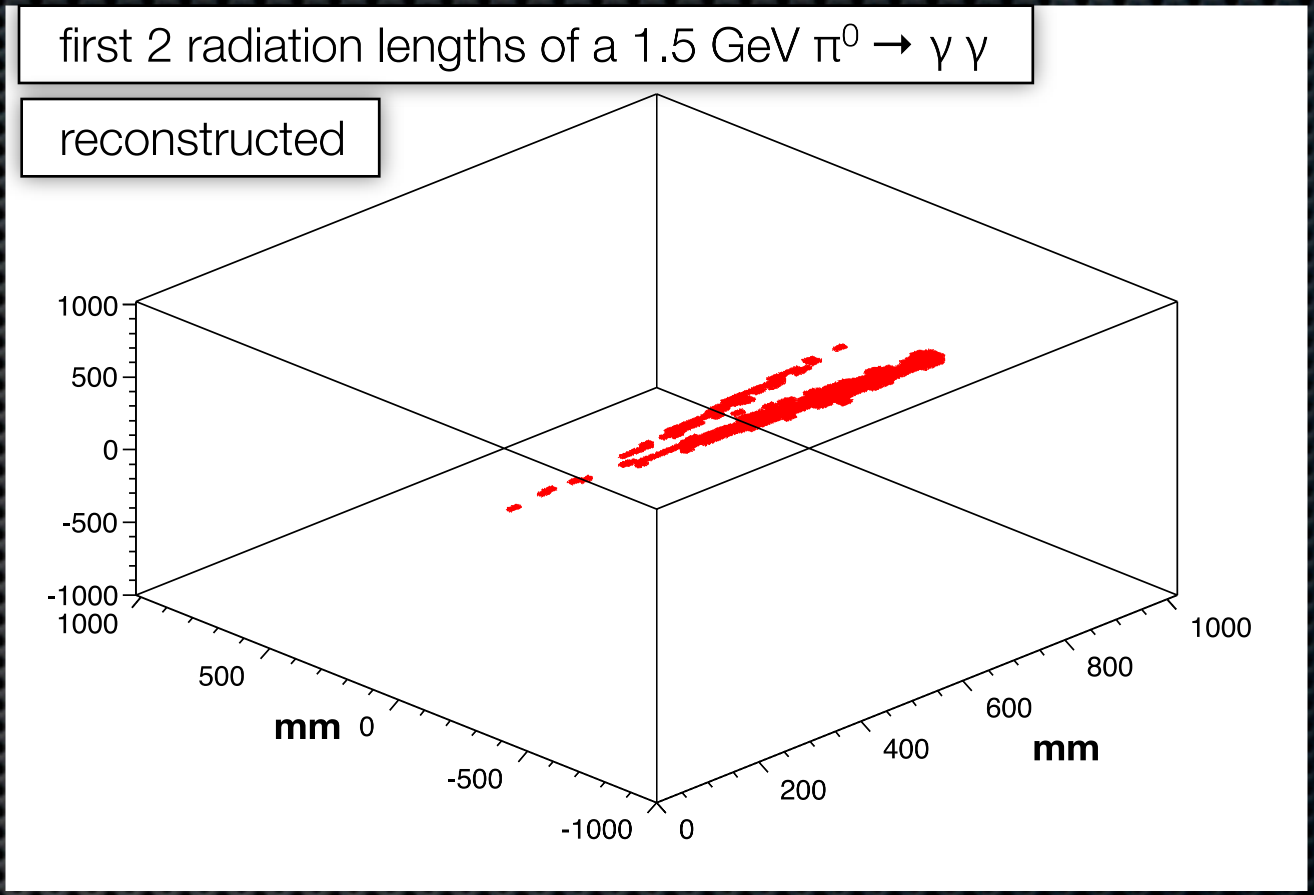
- Current implementation tested on a 6m spherical detector with 100% coverage and perfect resolution
- However, full optical effects are applied
  - we are not yet correcting for chromatic dispersion (use a fixed n_{water})
  - not using any timing-based quality cuts to clean up the “signal-to-noise” (scattering-to-direct light)
- Particular challenges for realistic implementation: optimization for larger detectors, sparser coverage, less resolution (work in progress)



Isochron method

M. Wetstein

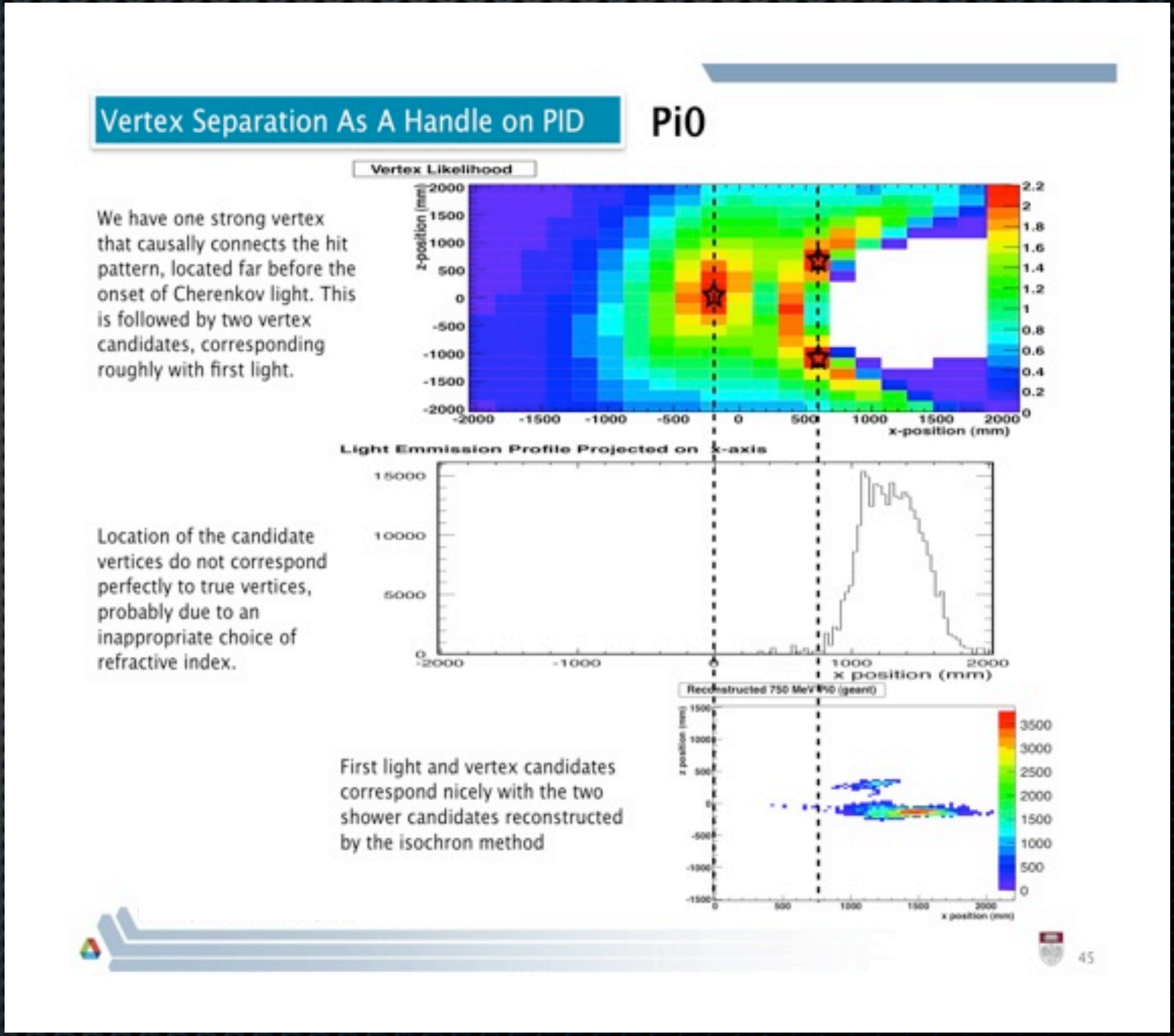
- This approach requires a seed vertex, but no prior assumption about number of tracks or event topology
- track-like clusters “emerge” from density of intersections
- Quality of the image depends on how close the reconstructed vertex is to the true vertex



M. Wetstein

Isochron method

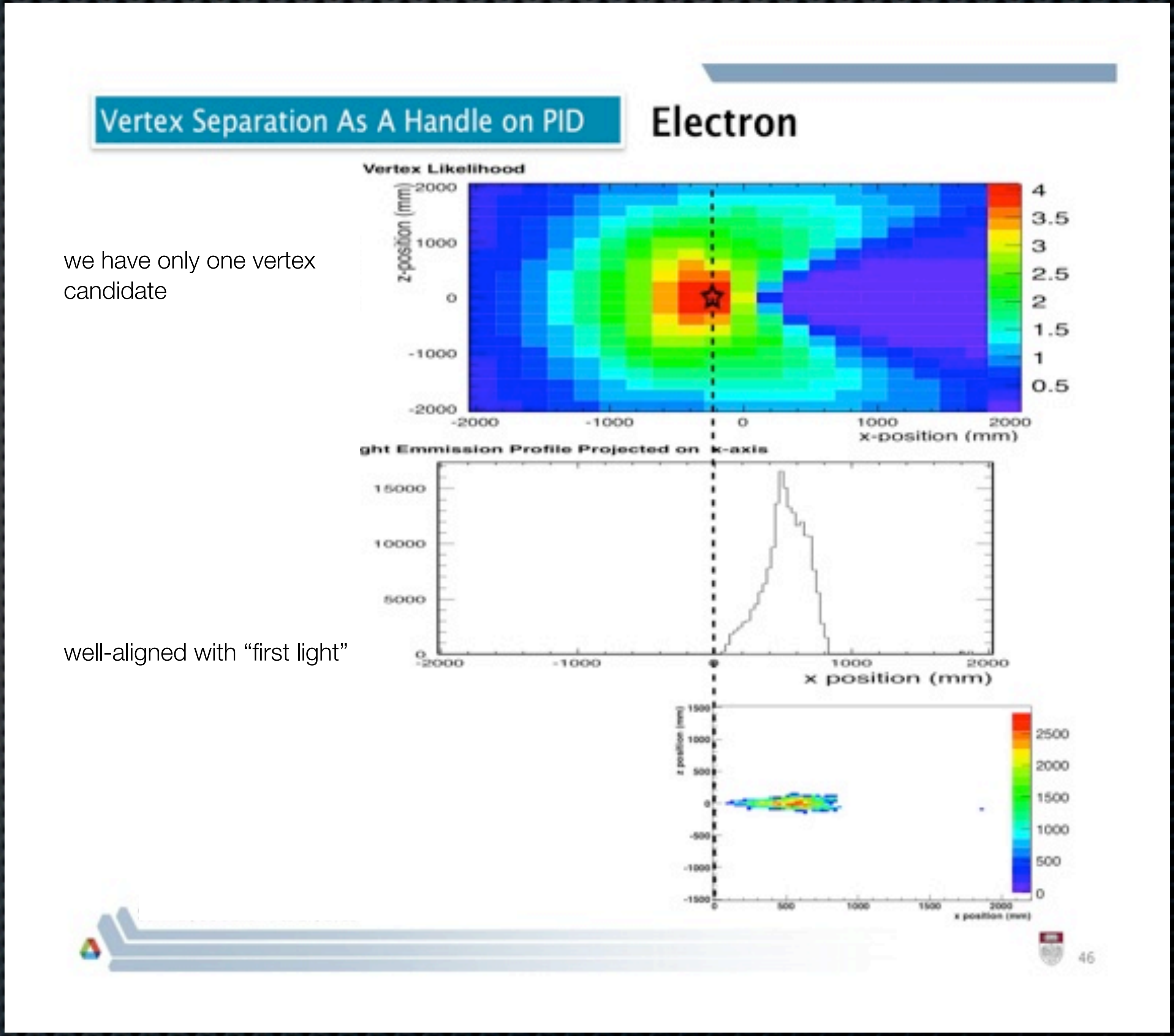
- But, one can use the density of intersections as a figure of merit to optimize the four-vertex
- One can plot density of intersections as a function of position in this vertex-likelihood space and try to discriminate between multiple vertices and single vertices



M. Wetstein

Isochron method

- But, one can use the density of intersections as a figure of merit to optimize the four-vertex
- One can plot density of intersections as a function of position in this vertex-likelihood space and try to discriminate between multiple vertices and single vertices.
- New results coming very soon. Stay tuned.



A potential Recipe

M. Wetstein

- Extended time-residual based track fits for seed vertexes and directions
- Isochron techniques to locate and constrain the key elements of a multi-track topology
- Complete pattern fitting (restricted to the much smaller neighborhood of the isochron clusters to optimize and give final likelihoods

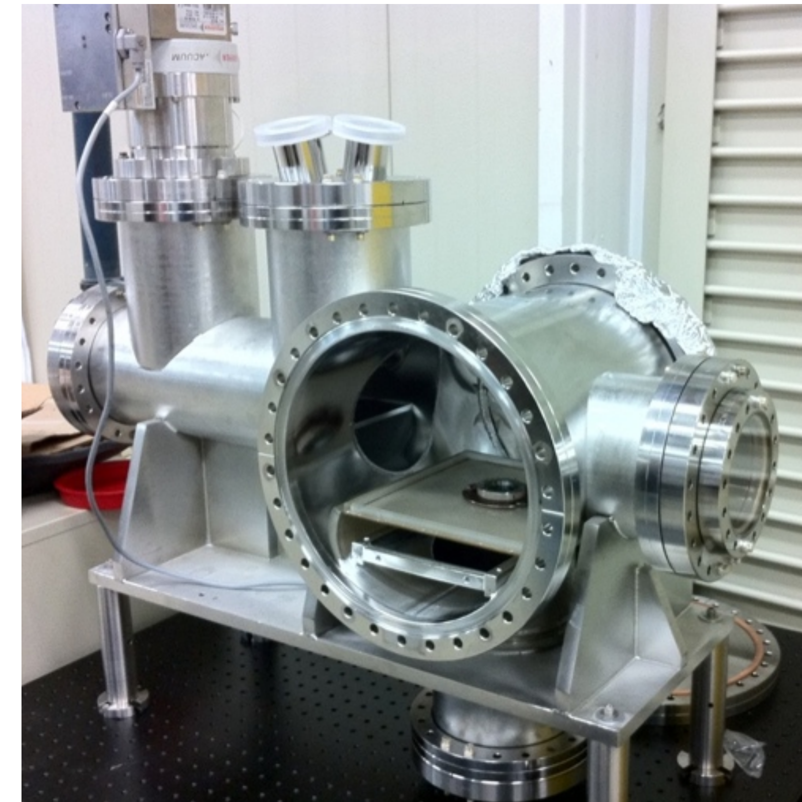
Uses in liquid nobles?

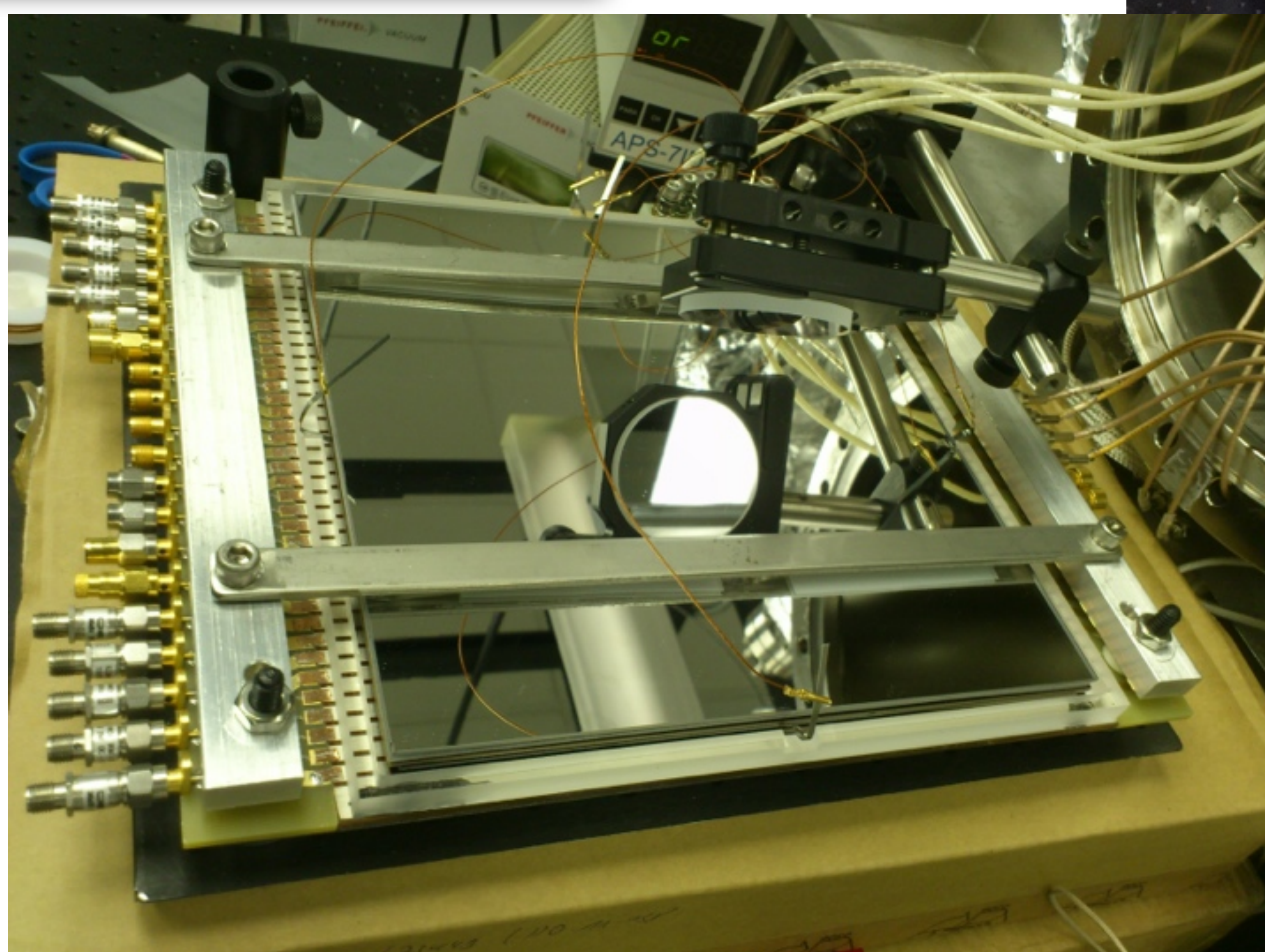
- Let's discuss

A random smattering of backup slides

8” Program

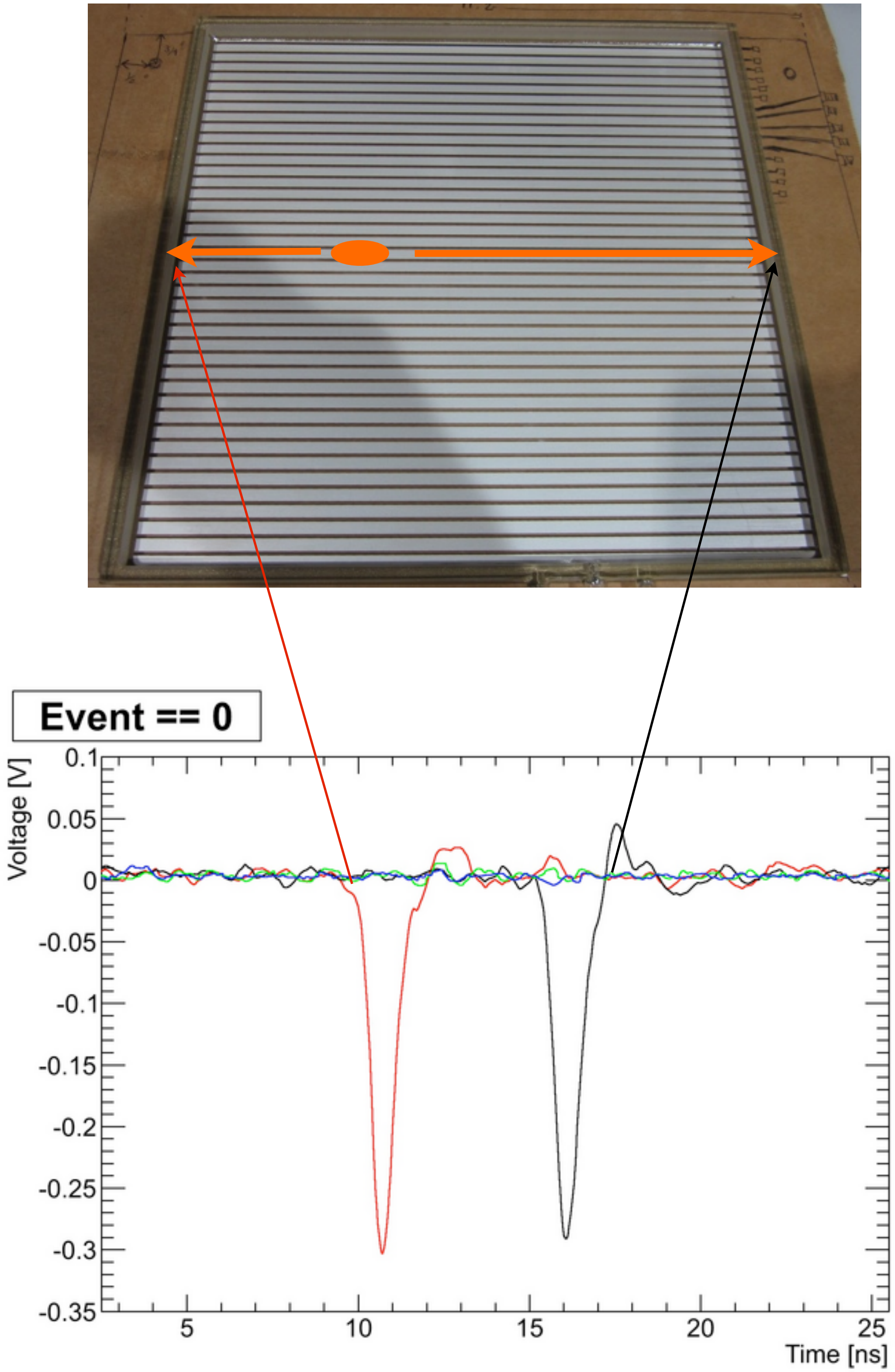
- To demonstrate full-sized detector systems.
- To study operation with the “frugal anode” design (silk-screened silver microstrip delay lines)
- To benchmark some of the key resolutions to be expected in sealed-glass LAPPDs



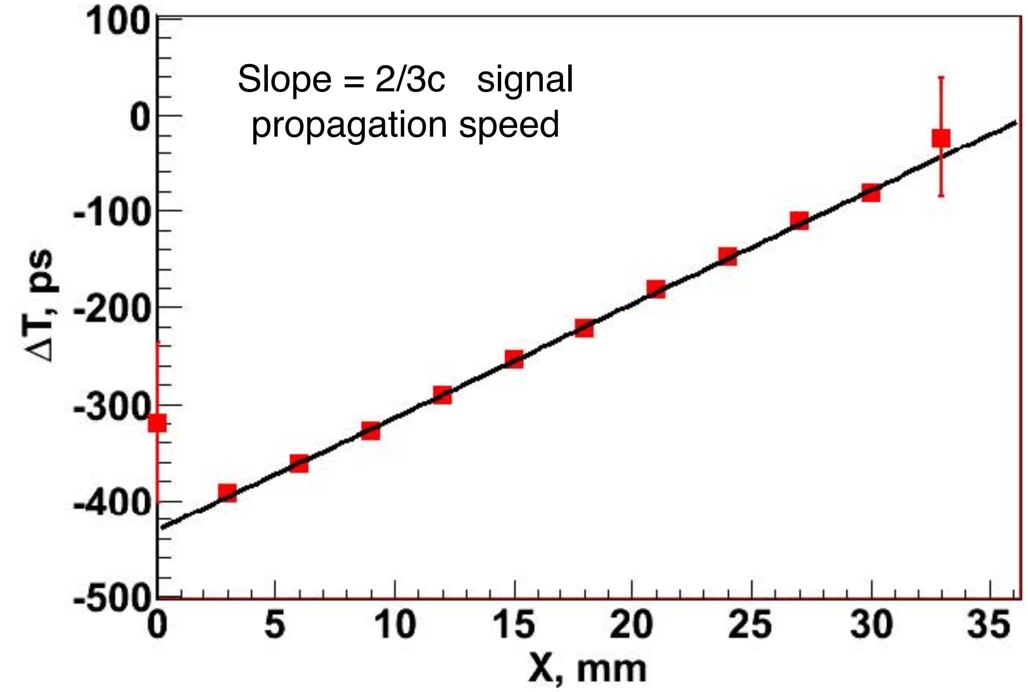


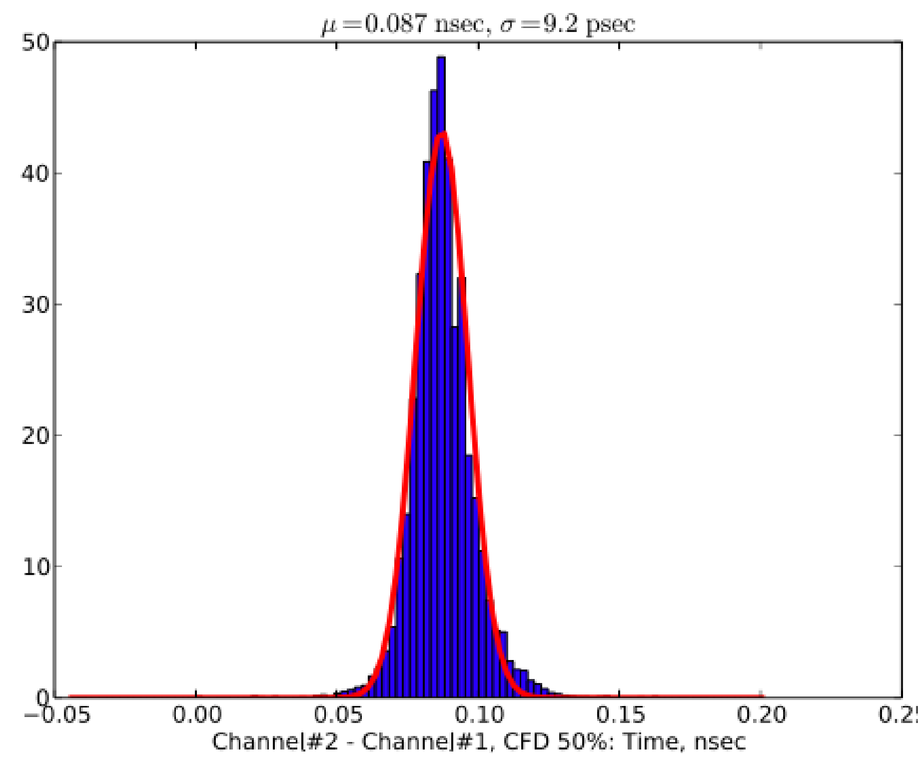
8" Program

Photon position is determined by signal centroid in the transverse direction and difference in signal arrival time in the parallel direction.



Difference in arrival time as a function of laser position

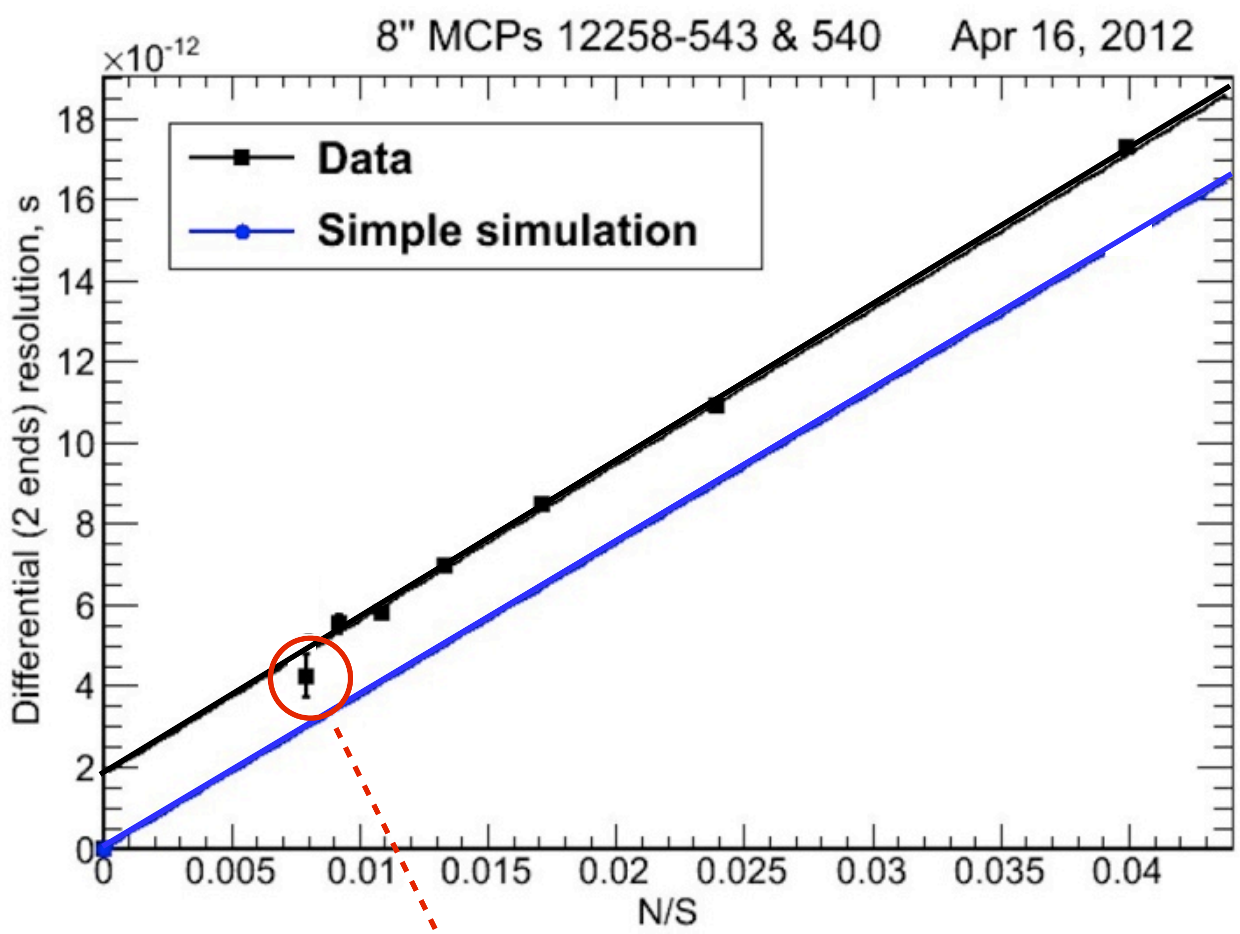


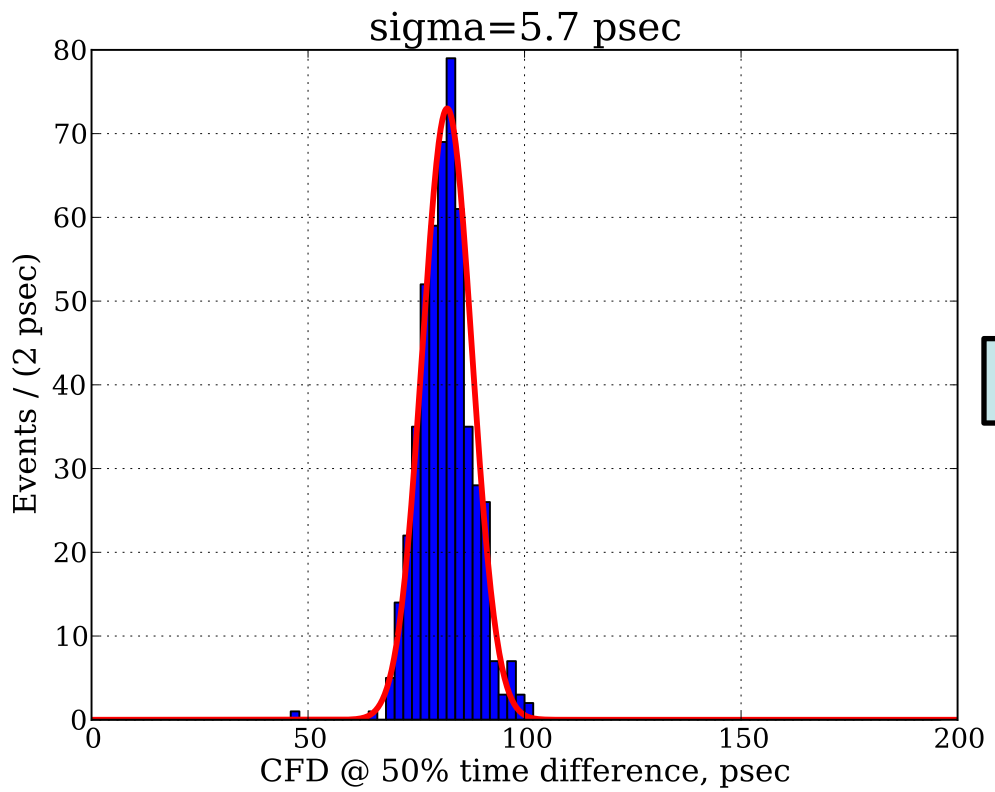


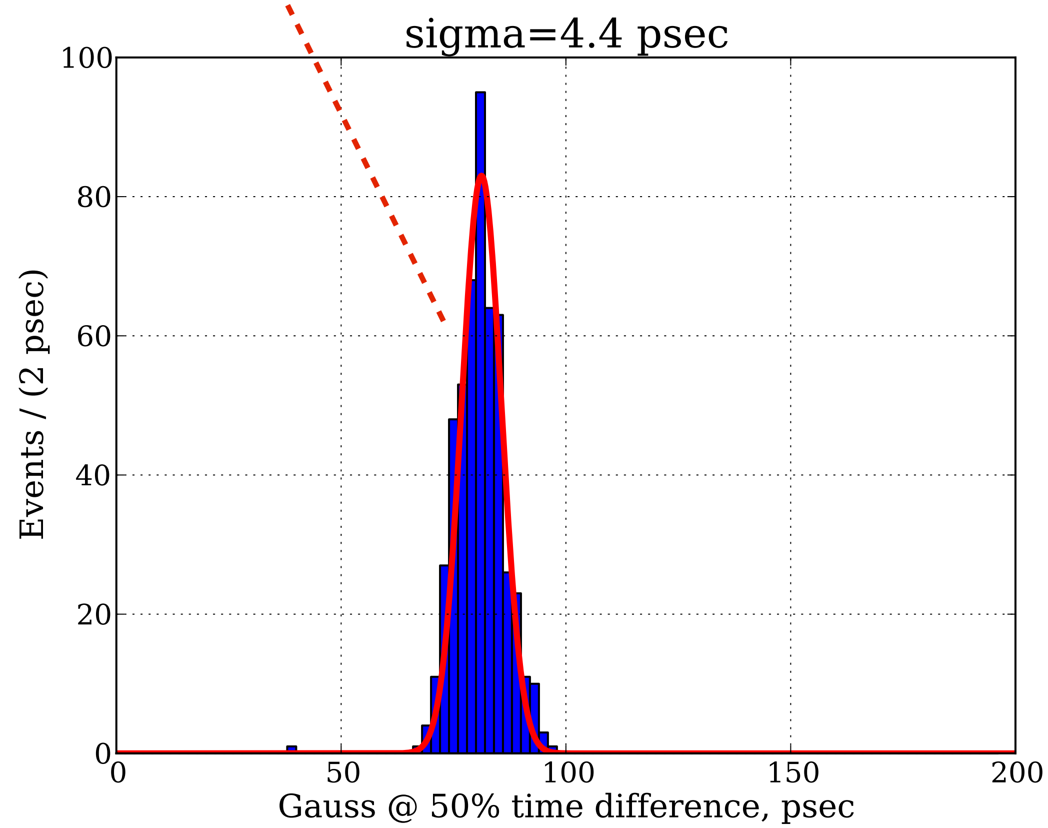
Differential time resolution between two ends of an optimized anode (~10 PE): ~9 psec (~1mm)

8” Program

With improved fitting to the rising edge of the MCP pulses, we reconstruct an even narrower TTS!



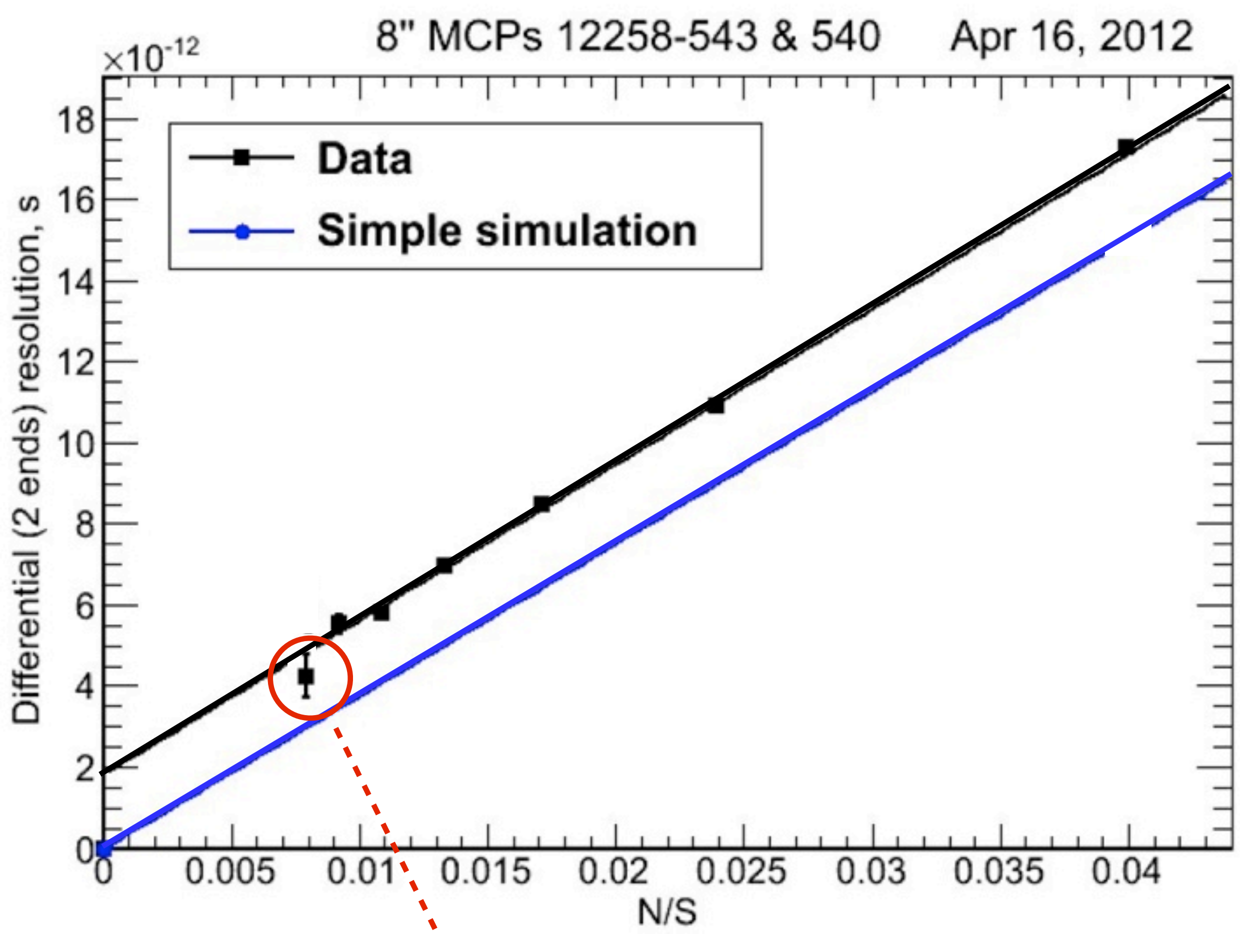


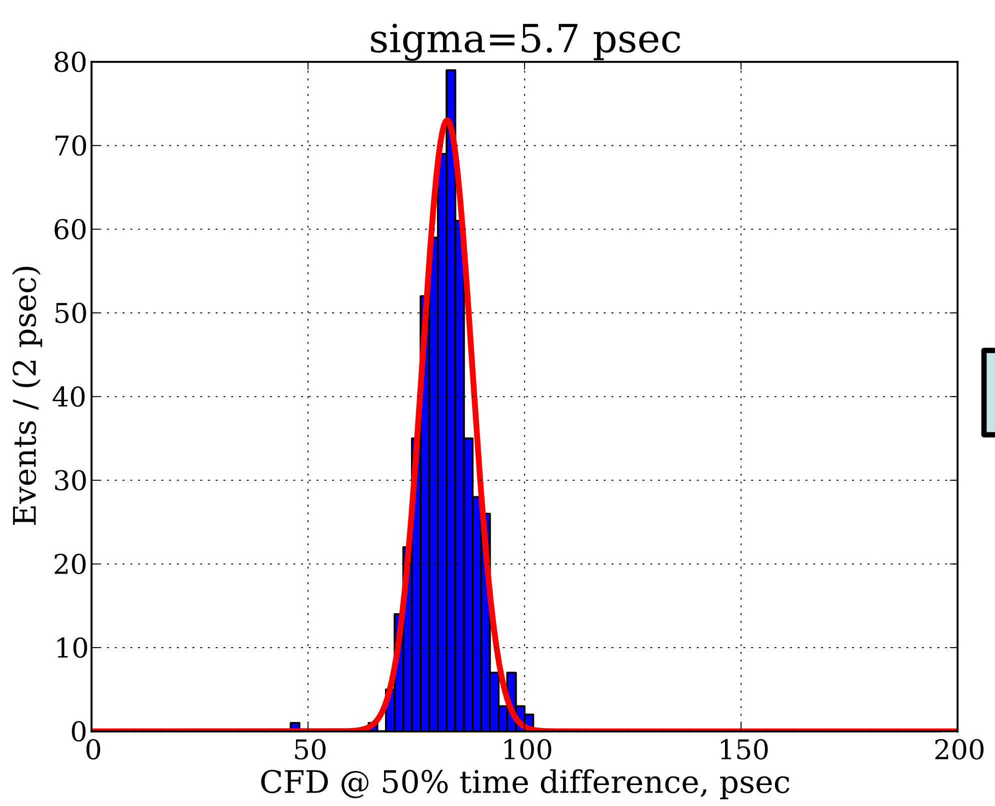


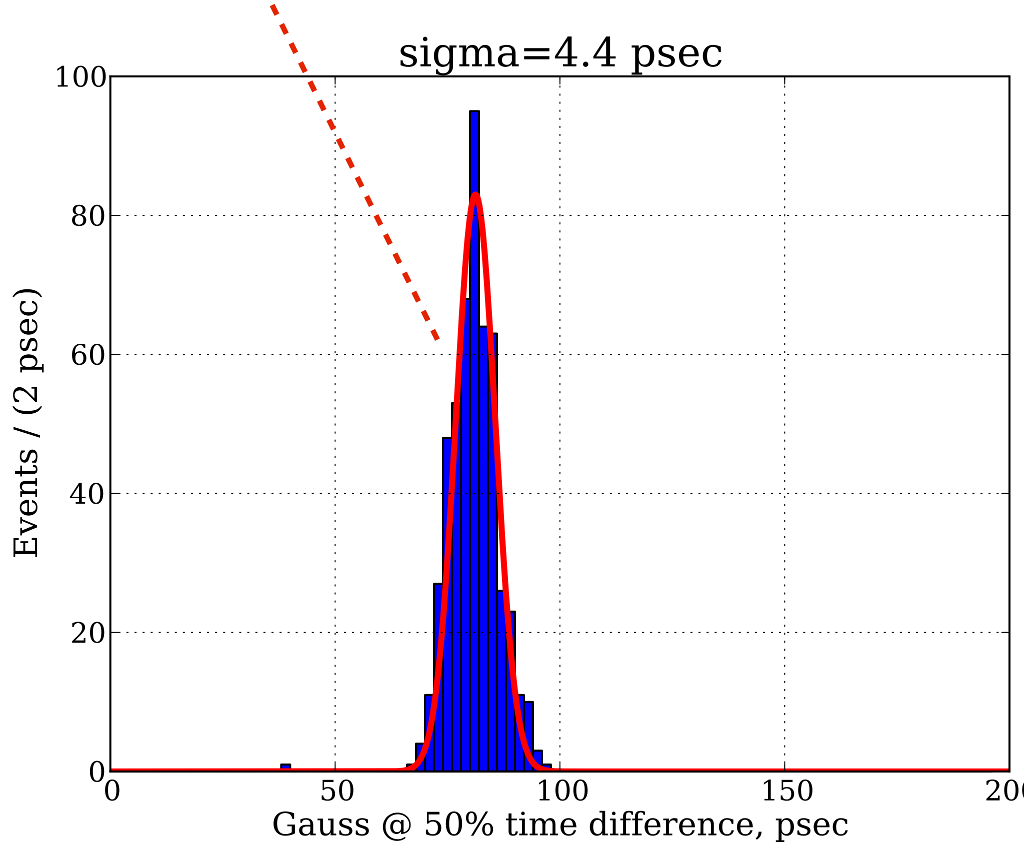
8” Program

With improved fitting to the rising edge of the MCP pulses, we reconstruct an even narrower TTS!

Currently editing the rough draft of a NIM paper on first 8”x8” results

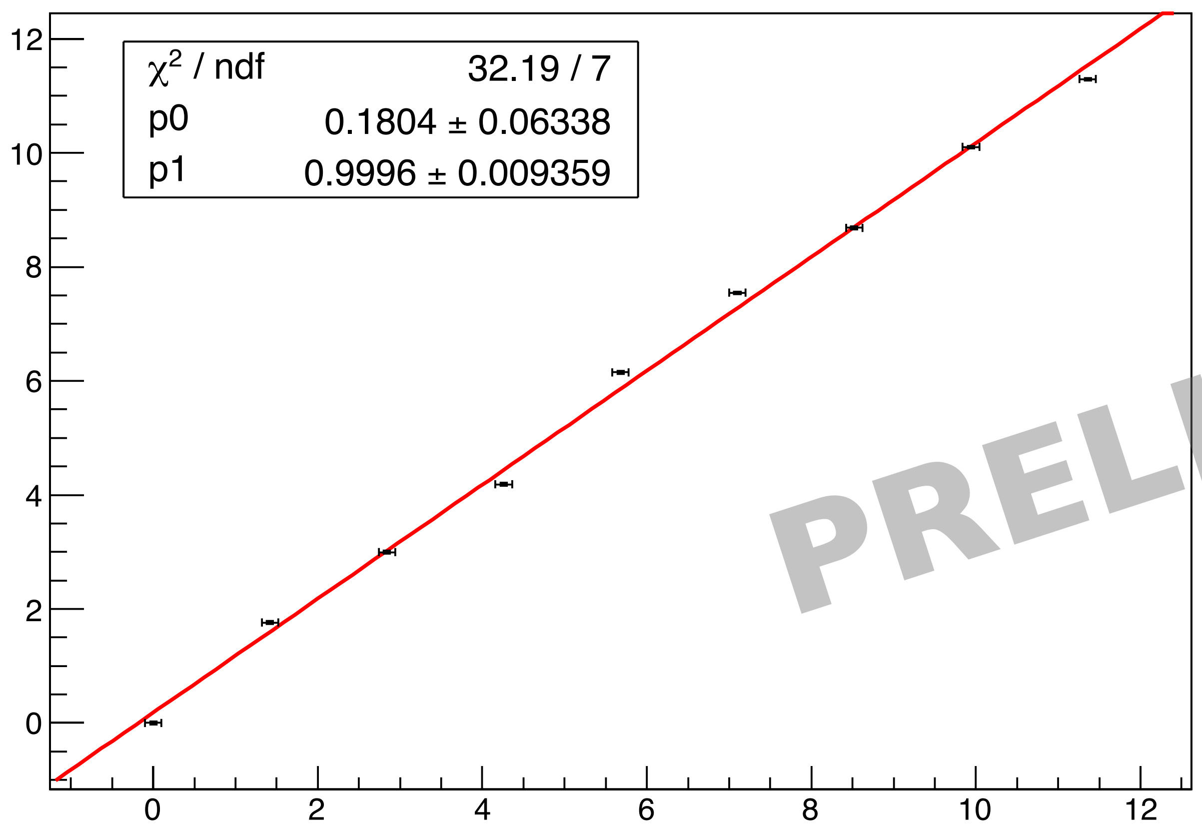


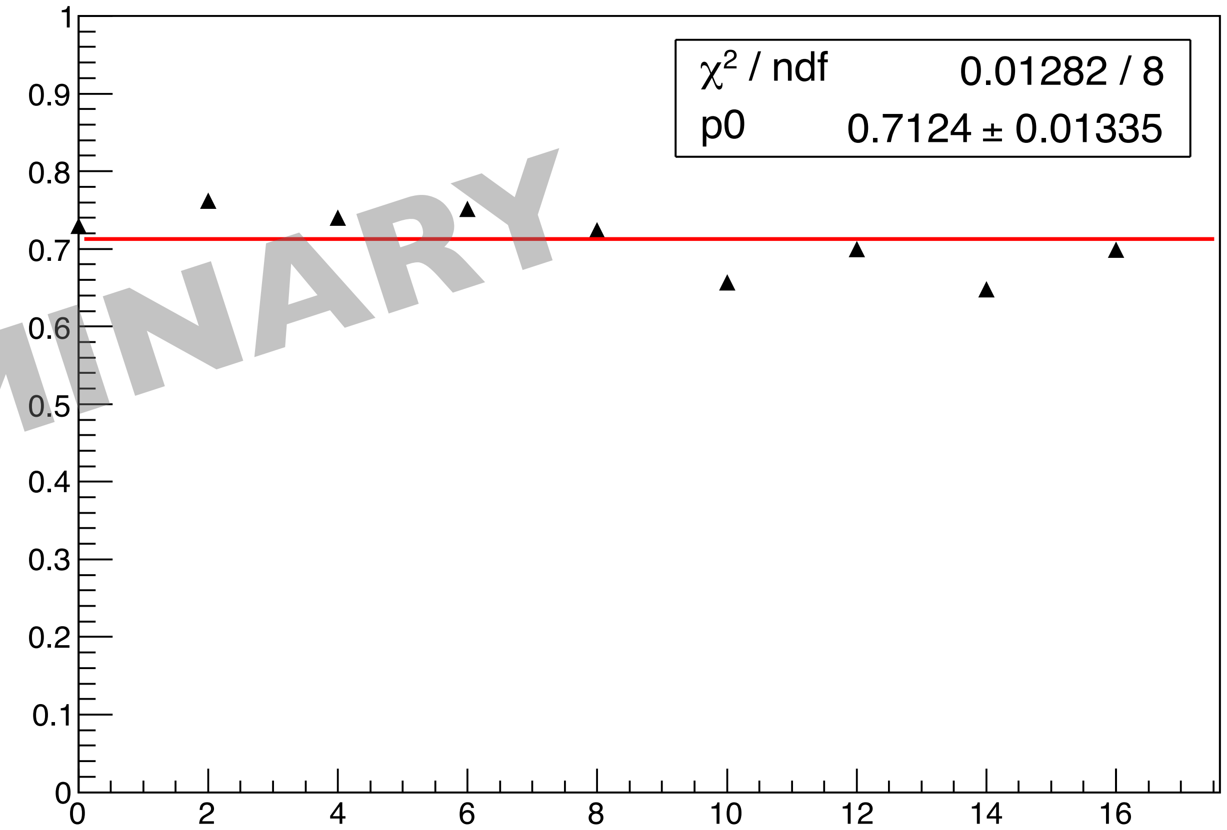




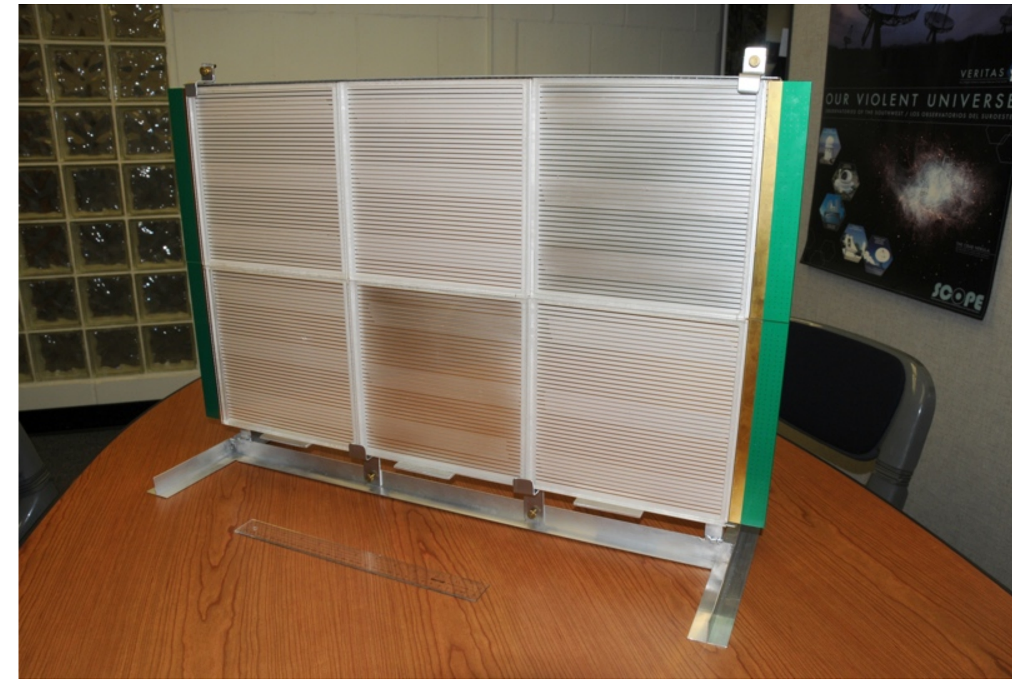
SuMo Slice – Full PSEC Readout

Position in the transverse direction, reconstructed even using a naive, out-of-the-box 5-strip centroid algorithm gives us resolutions consistently below 1 mm.





New Developments in Water-Based Detectors: Large Area, High Resolution MCP-PMTs

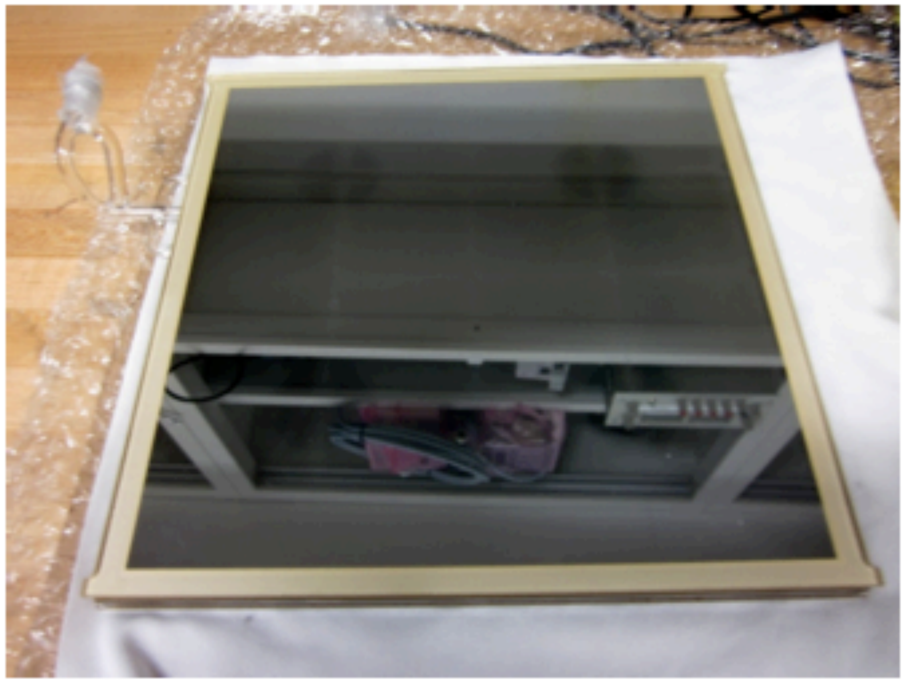


LAPPD (Large-Area Picosecond Photodetector) Project:

Make large-area MCPs with low-cost, bulk materials and batch industrial techniques

- We're attacking all aspects of this problem from the photocathode to the MCPs to vacuum sealing technology
- Goal is not just proof of principle...It's the development of a commercializable product.

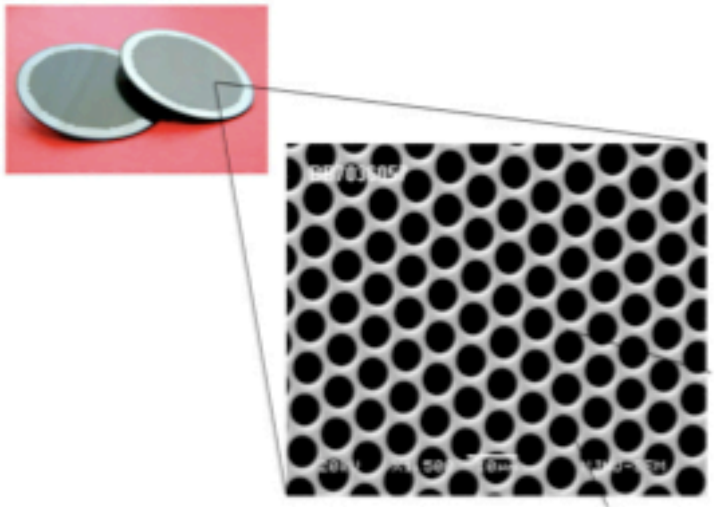
Reinventing the unit-cell of light-based neutrino detectors



- single pixel (poor spatial granularity)
- nanosecond time resolution
- bulky
- blown glass
- sensitive to magnetic fields

- millimeter-level spatial resolution
- <100 picosecond time resolution
- compact
- standard sheet glass
- operable in a magnetic field

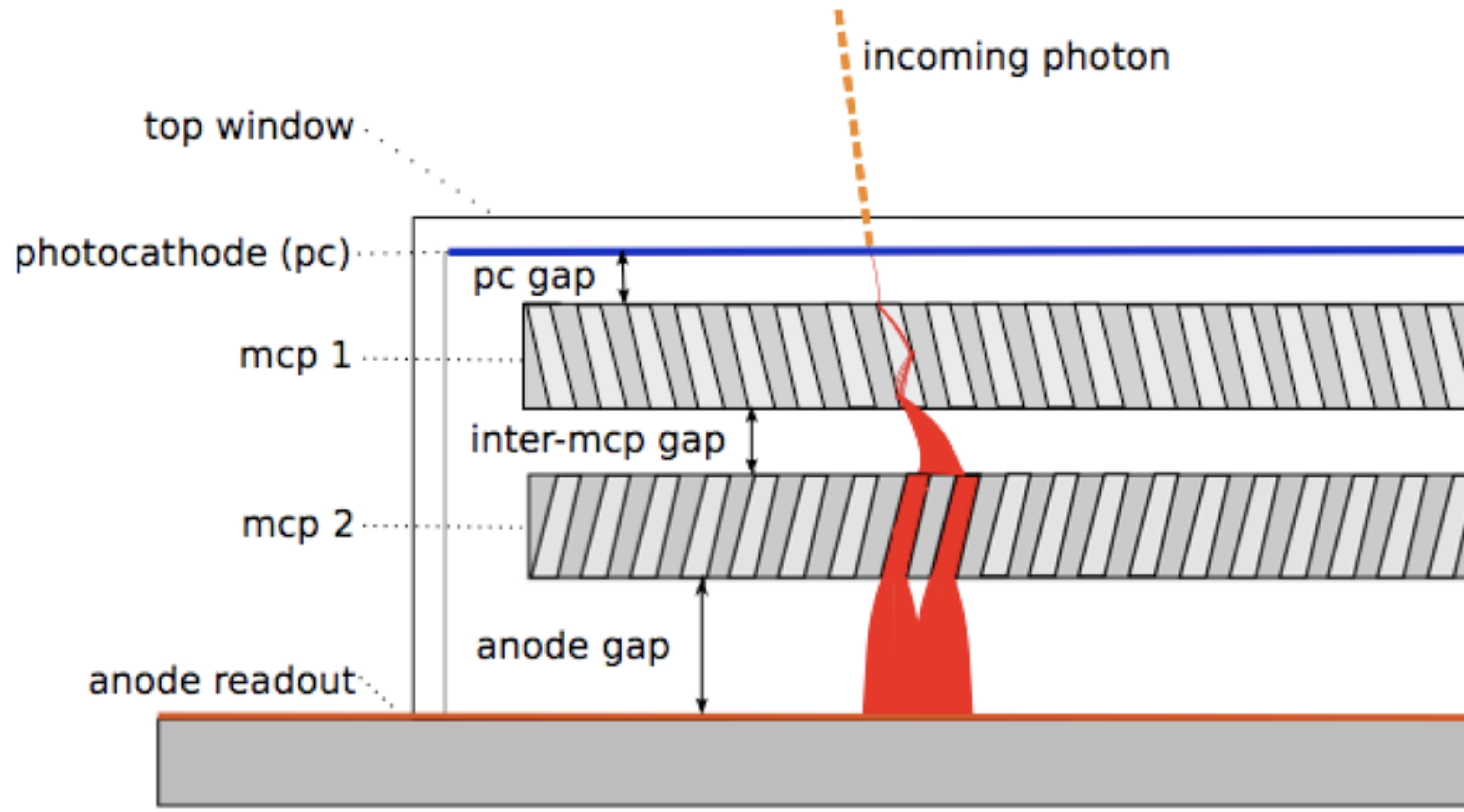
What is an MCP-PMT?



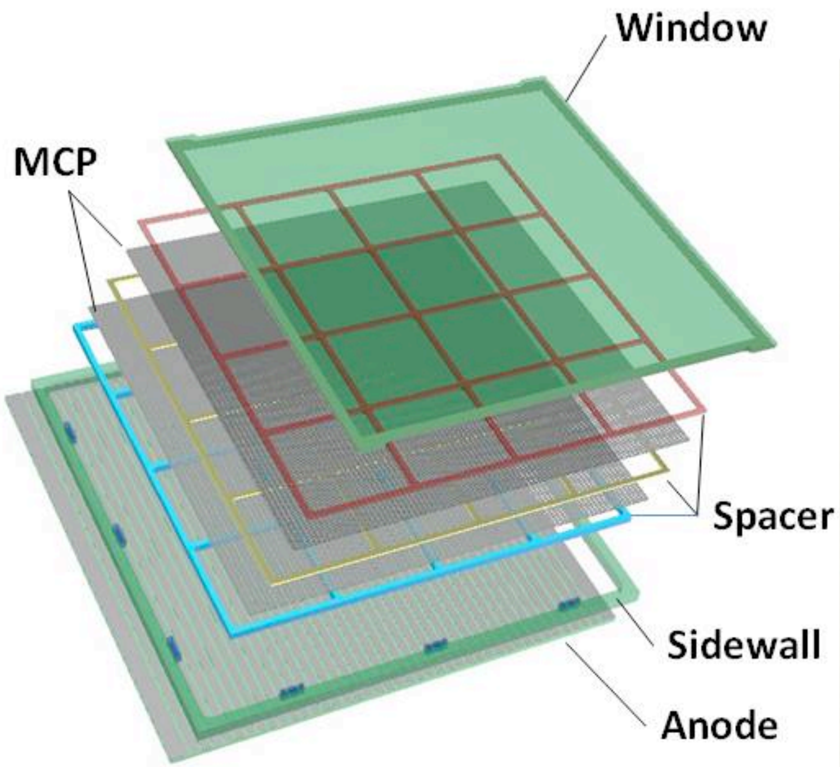
Microchannel Plate (MCP):

- a thin plate with microscopic (typically <50 μm) pores
- pores are optimized for secondary electron emission (SEE).
- Accelerating electrons accelerating across an electric potential strike the pore walls, initiating an avalanche of secondary electrons.

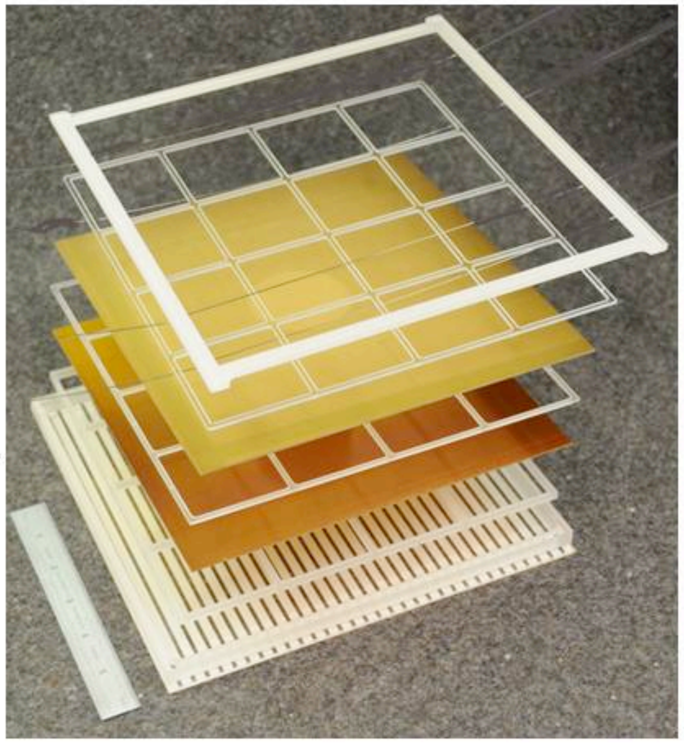
- An MCP-PMT is, sealed vacuum tube photodetector.
- Incoming light, incident on a photocathode can produce electrons by the photoelectric effect.
- Microchannel plates provide a gain stage, amplifying the electrical signal by a factor typically above 10^6.
- Signal is collected on the anode



What is the LAPPD Concept



Design Drawing - September 2010



Actual Glass Parts - April 2012

The Frugal Tile

LAPPD detectors:

- •Thin-films on borosilicate glass
- •Glass vacuum assembly
- •Simple, pure materials
- •Scalable electronics
- •Designed to cover large areas

Conventional MCPs:

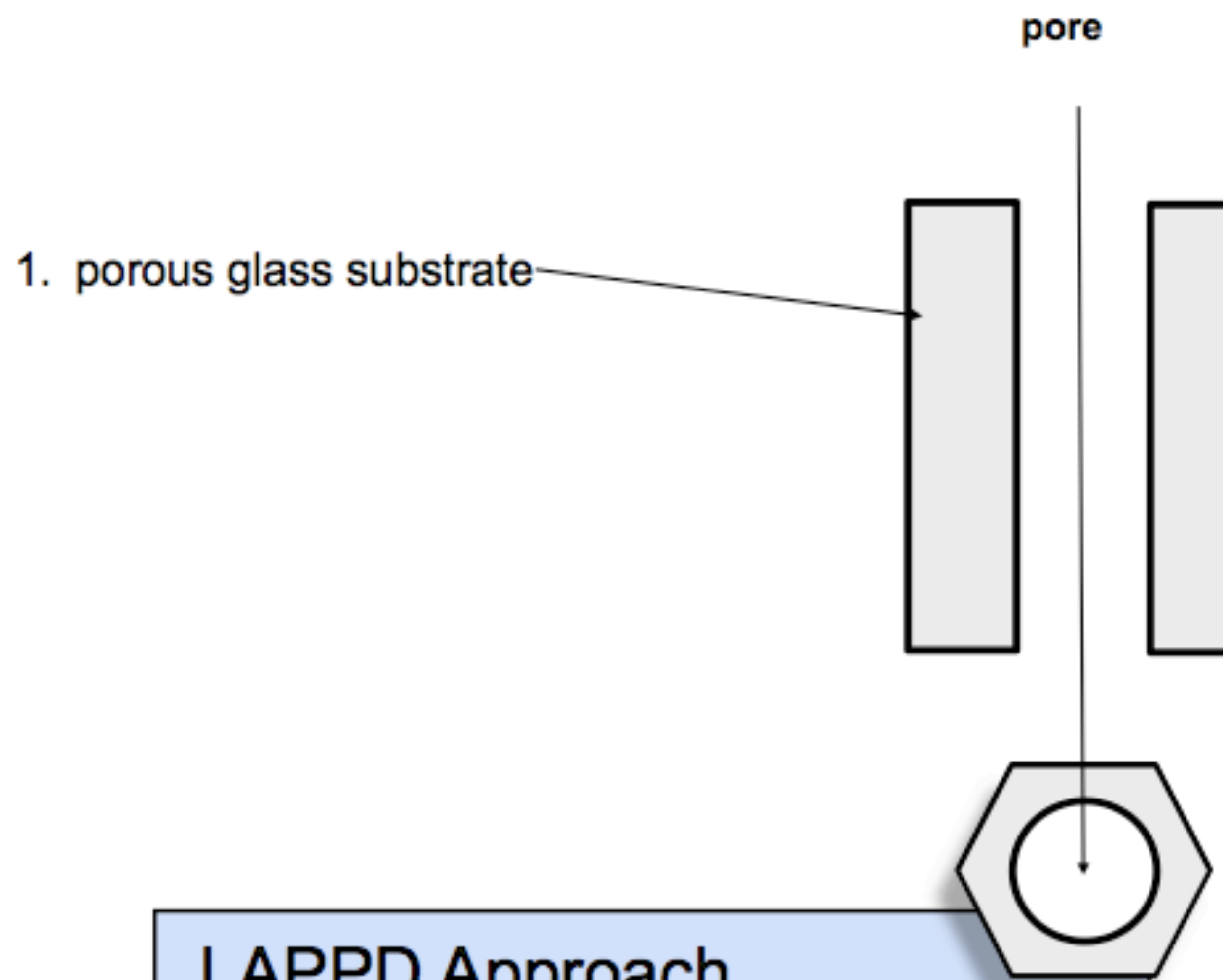
- •Conditioning of leaded glass (MCPs)
- •Ceramic body
- •Not designed for large area applications

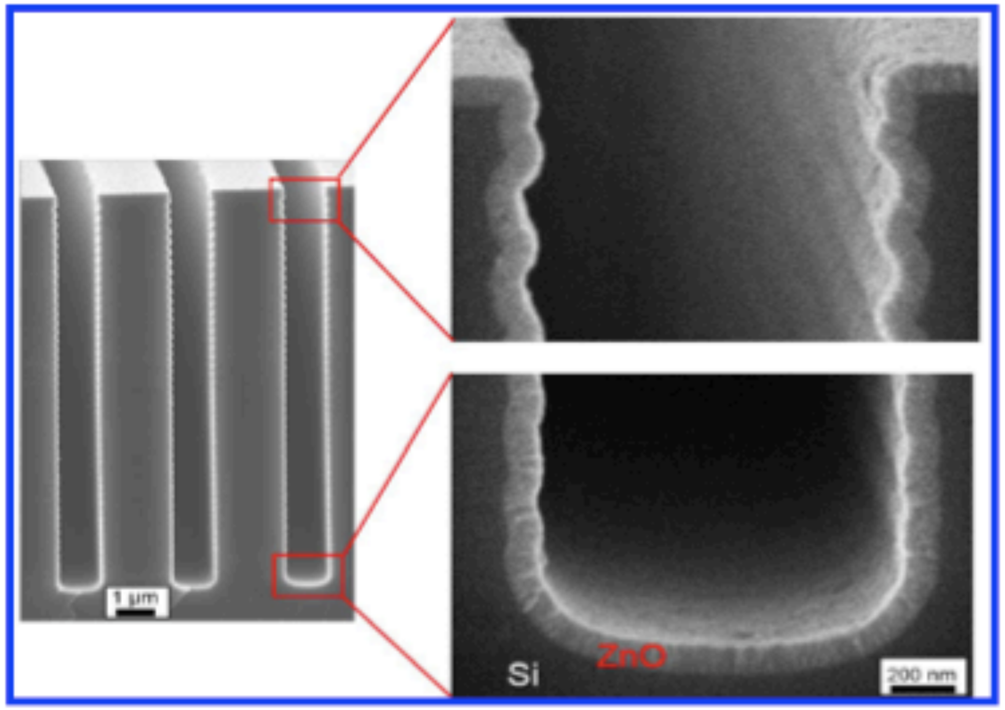
Our Approach

J. Elam, A. Mane, Q. Peng (ANL-ESD),
N. Sullivan (Arradiance), A. Tremsin (Arradiance, SSL)

Conventional MCP Fabrication

- Pore structure formed by drawing and slicing lead-glass fiber bundles. The glass also serves as the resistive material
- Chemical etching and heating in hydrogen to improve secondary emissive properties.
- Expensive, requires long conditioning, and uses the same material for resistive and secondary emissive properties. (Problems with thermal run-away).





LAPPD Approach

- Separate out the three functions
- Hand-pick materials to optimize performance.
- Use Atomic Layer Deposition (ALD): a cheap industrial batch method.
  - ALD is diffusive, conformal and allows application of material in single atomic monolayers

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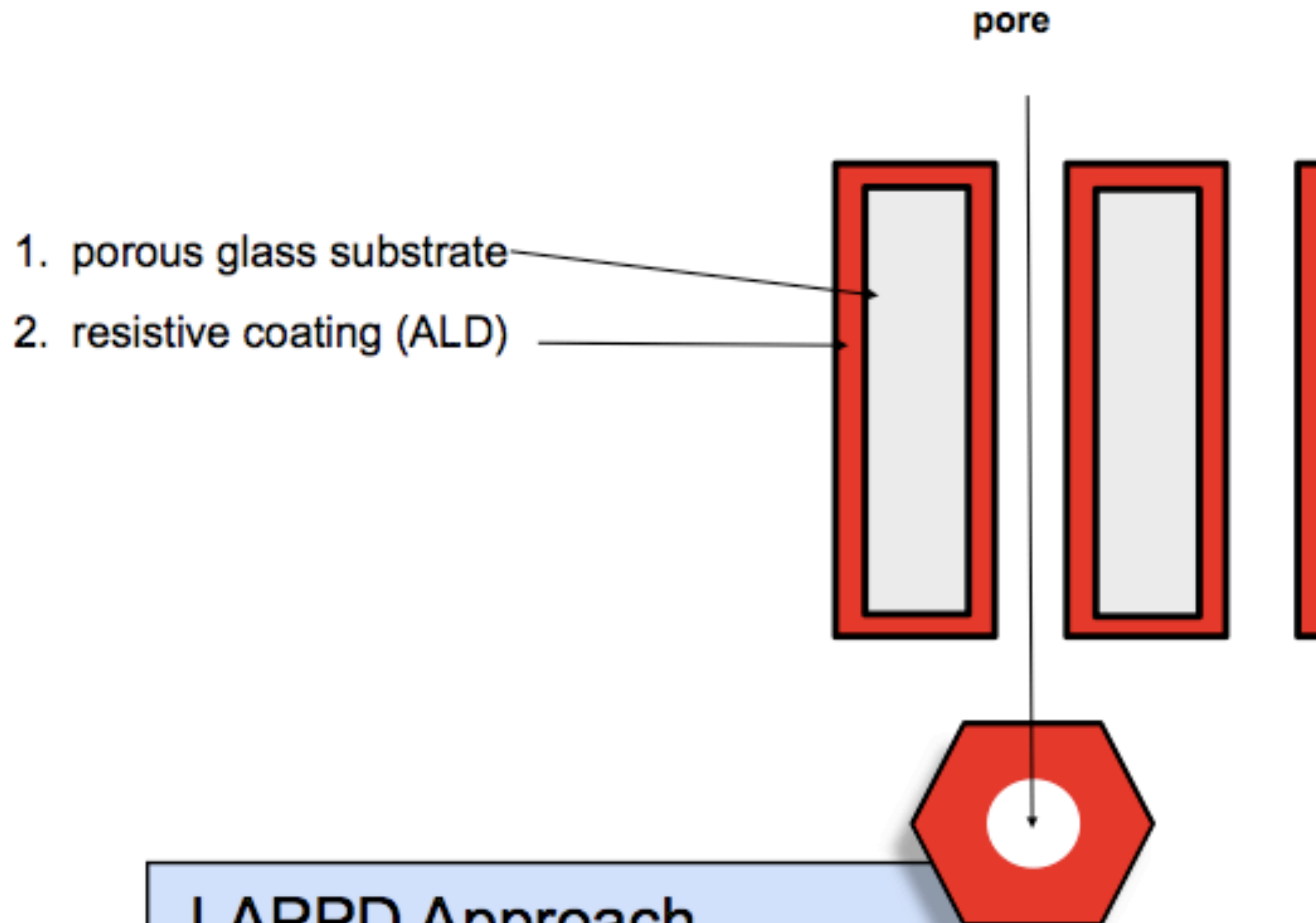

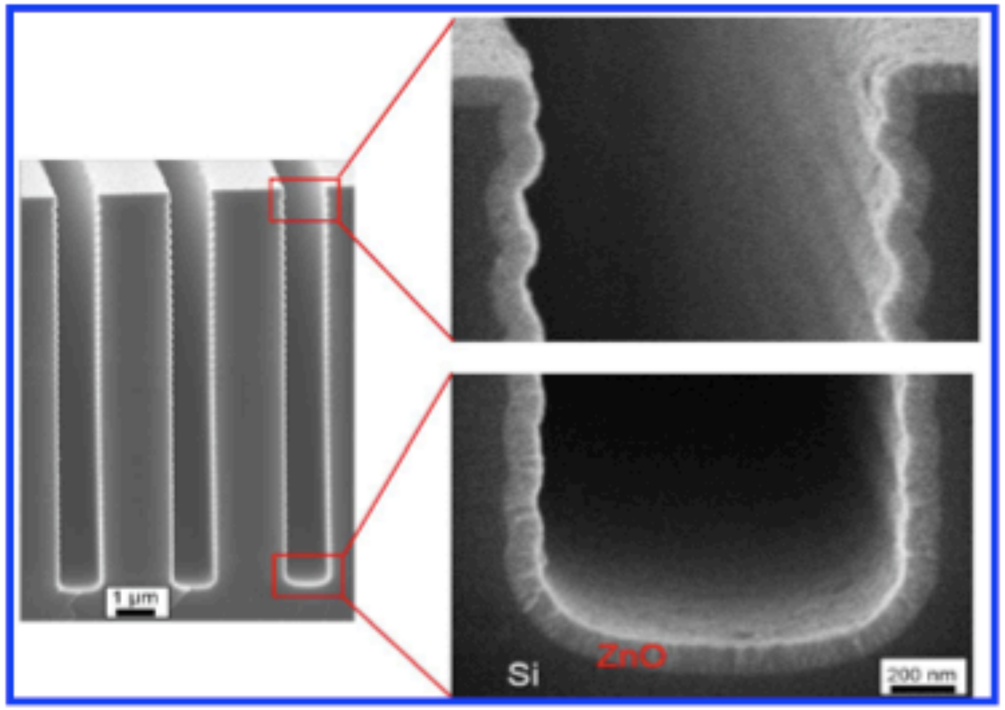

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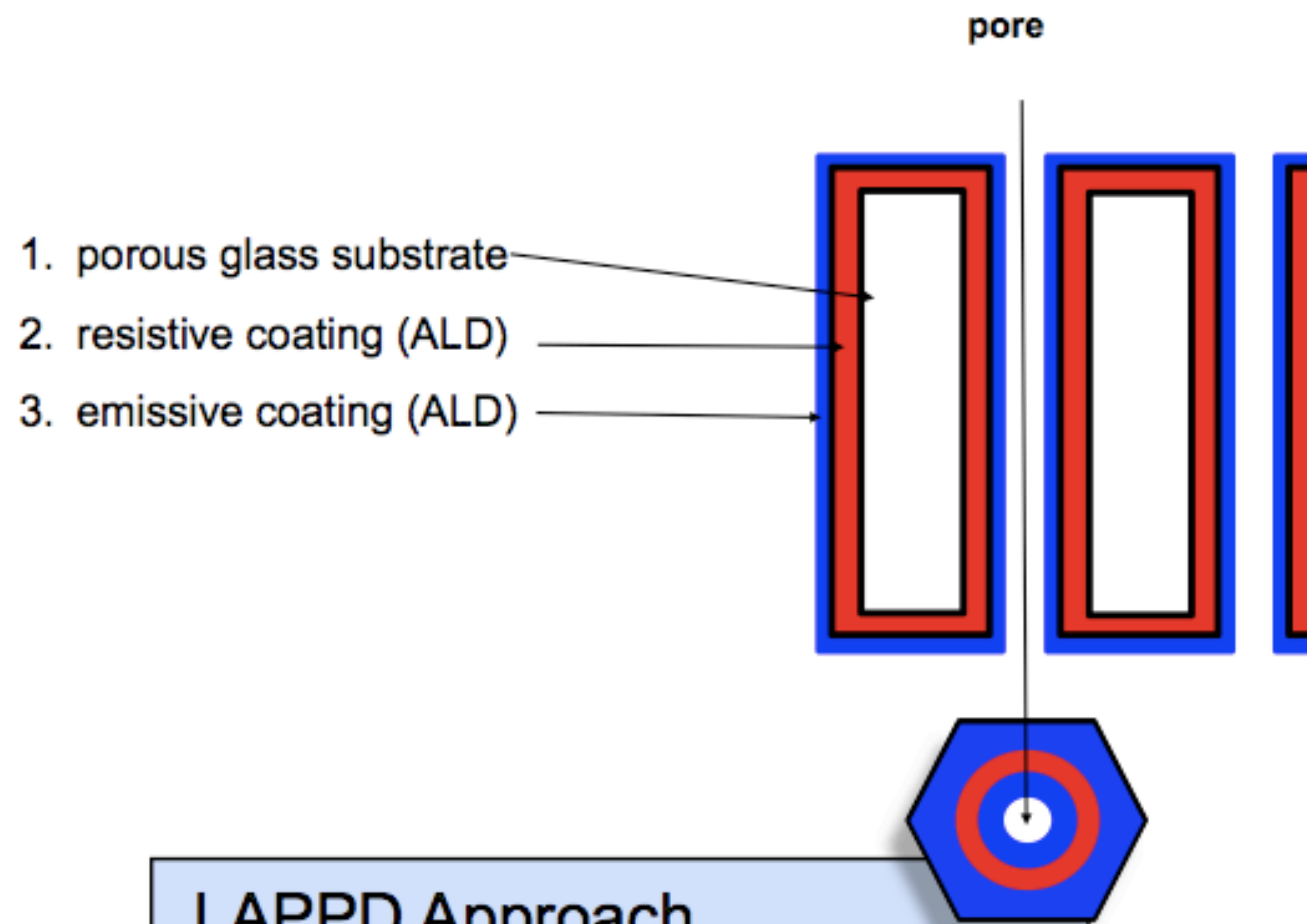

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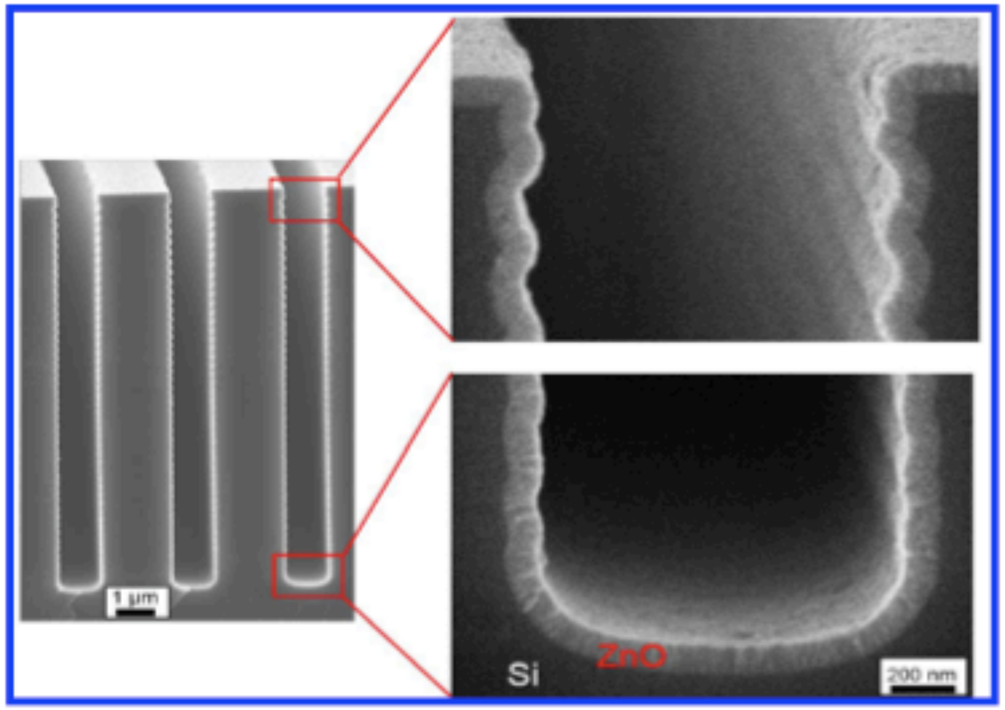

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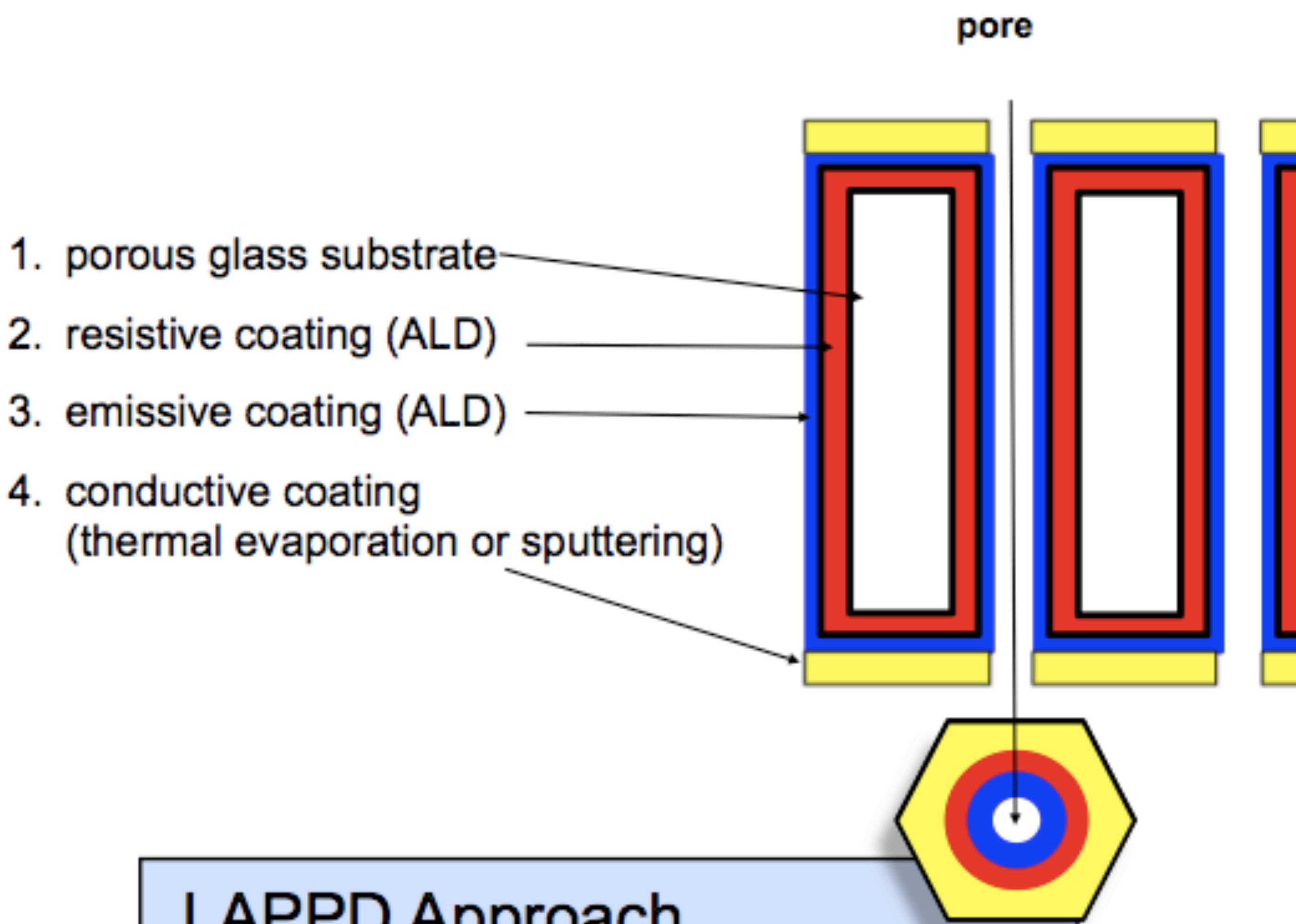

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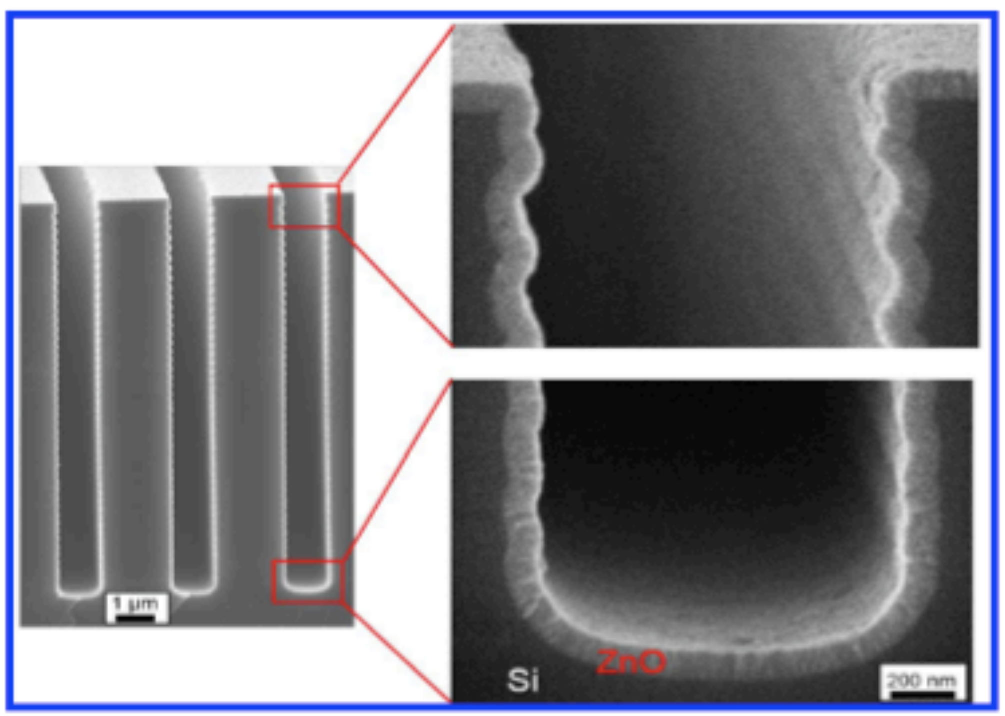
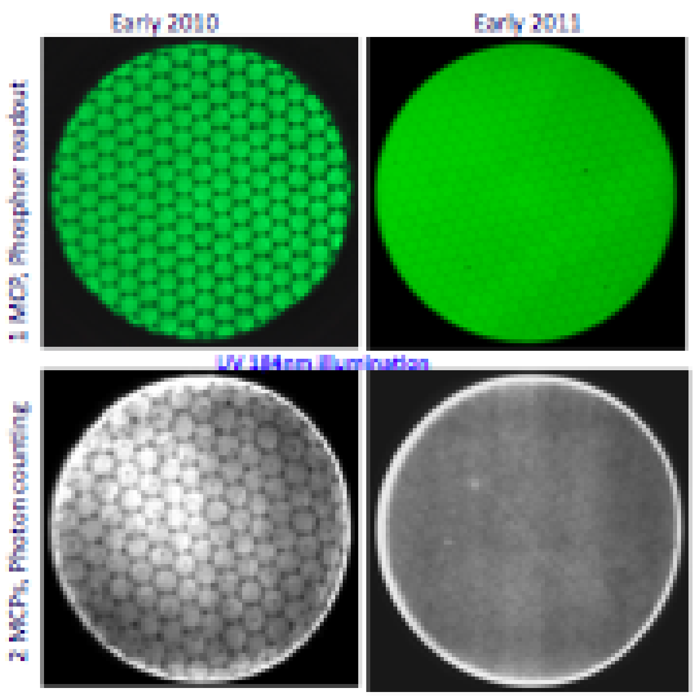


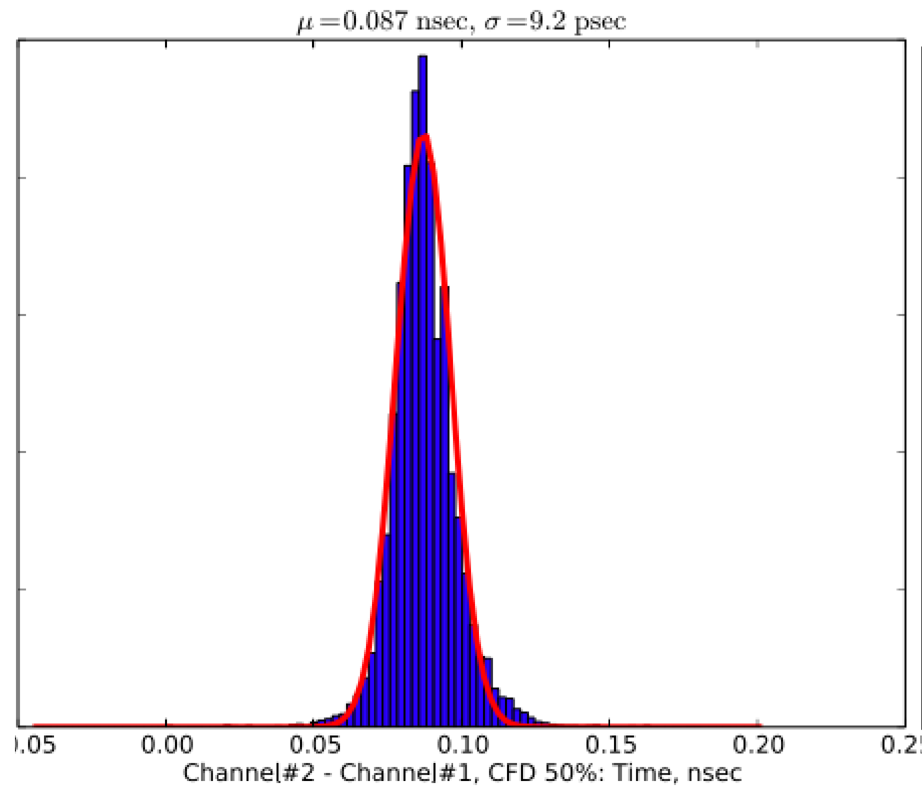
Microchannel Plates

Rapidly improving substrates (Arradiance)

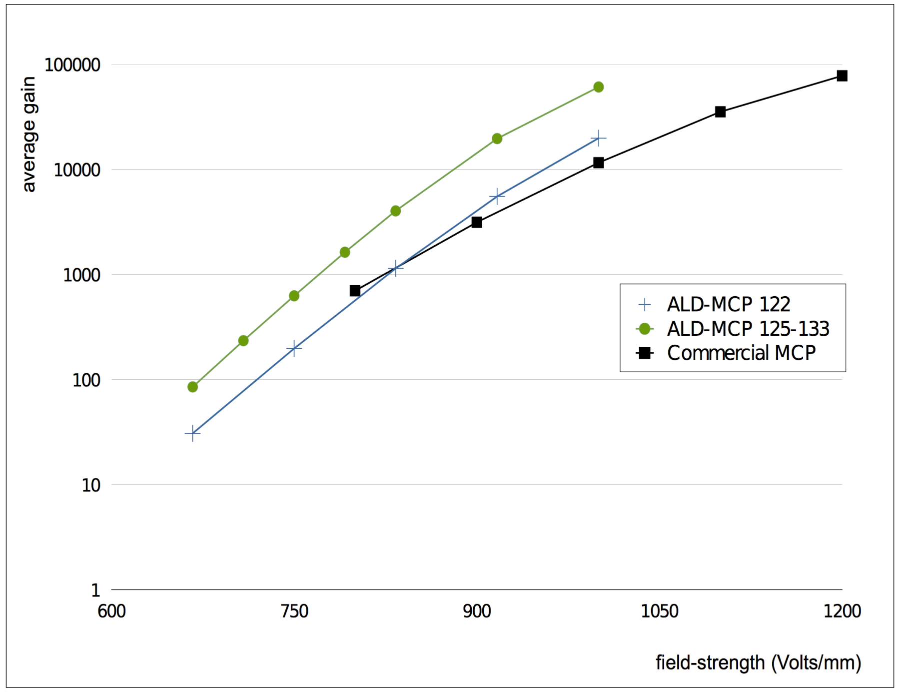


bkgd rate of 0.099 evts cm^{-2} sec^{-1} at 1.3 kV per plate

Differential Time Resolution ~9 psec



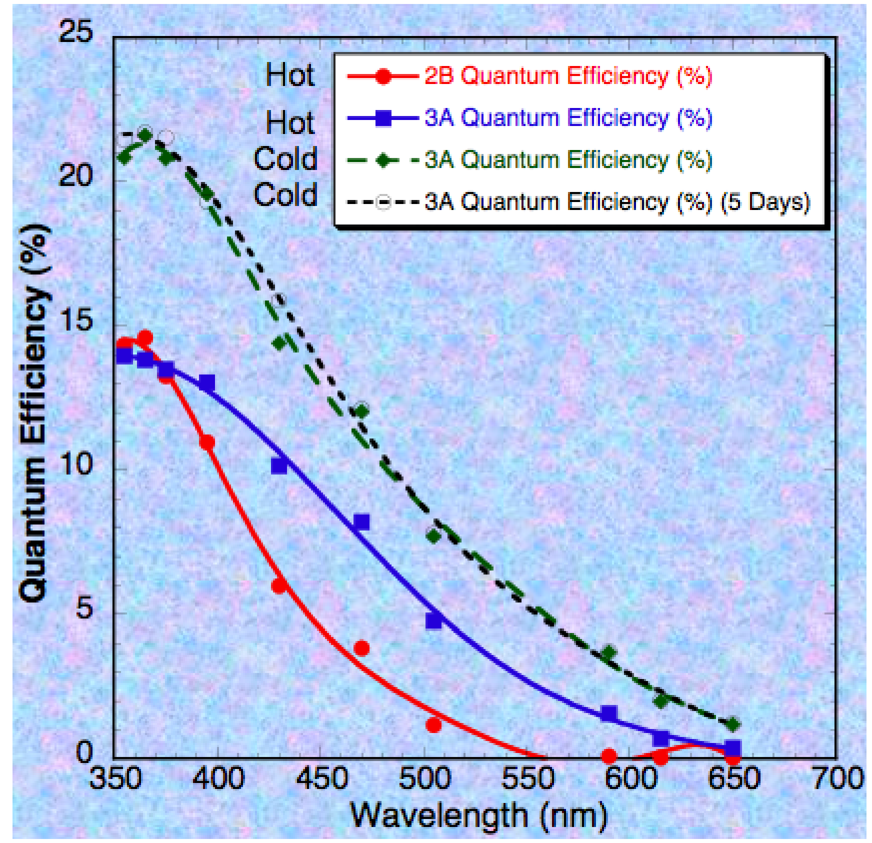
Gains better than high performance commercial plates (>10e5)



Photocathode

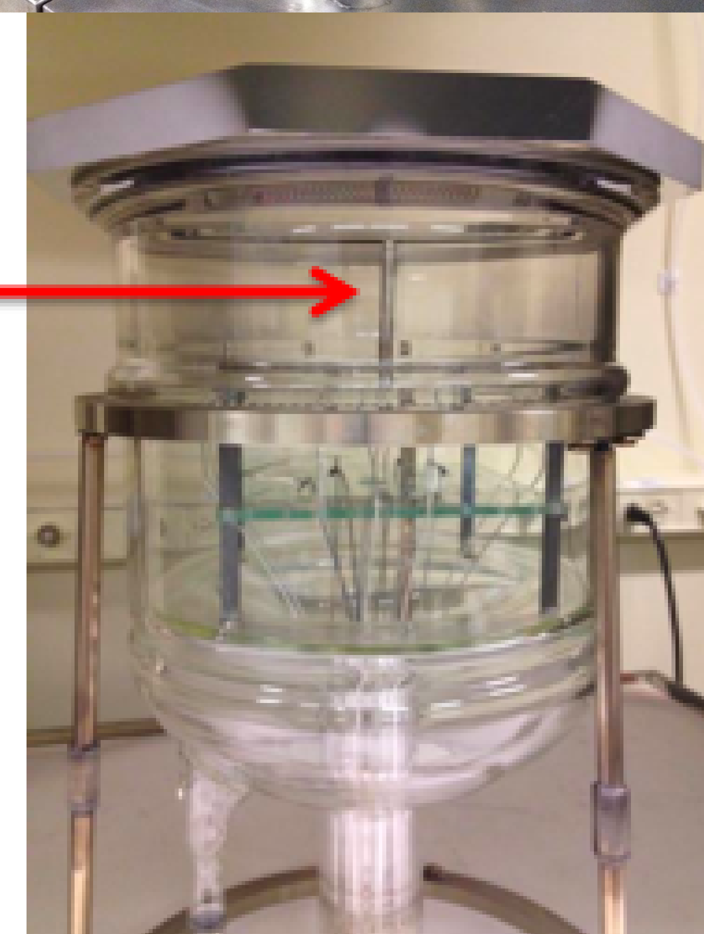
- Two main parallel paths:
  - scale traditional bi-alkali photocathodes to large area detectors. Decades of expertise at Berkeley SSL. Significant work at ANL to study new methods for mass production lines.
  - Also pursuing a deeper microscopic understanding of various conventional photocathode chemistries and robustness under conditions relevant to industrial batch processing. Could lead to a longer term photocathode program as part of the new ANL detector center
- Achievements:
  - Commissioning of 8" photocathode facility at UCB-SSL
  - Completion of ANL photocathode lab
  - Acquisition of a Burle-Photonis photocathode deposition system. Progress in adapting it to larger areas.
  - Successful development of a 24% QE photocathode in a small commercial

K. Attenkofer(ANL-APS), Z. Yusof, J. Xie, S. W. Lee (ANL-HEP),
S. Jelinsky, J. McPhate, O. Siegmund (SSL)
M. Pellin (ANL-MSD)



8” Tile-Assembly Chamber (UCB)

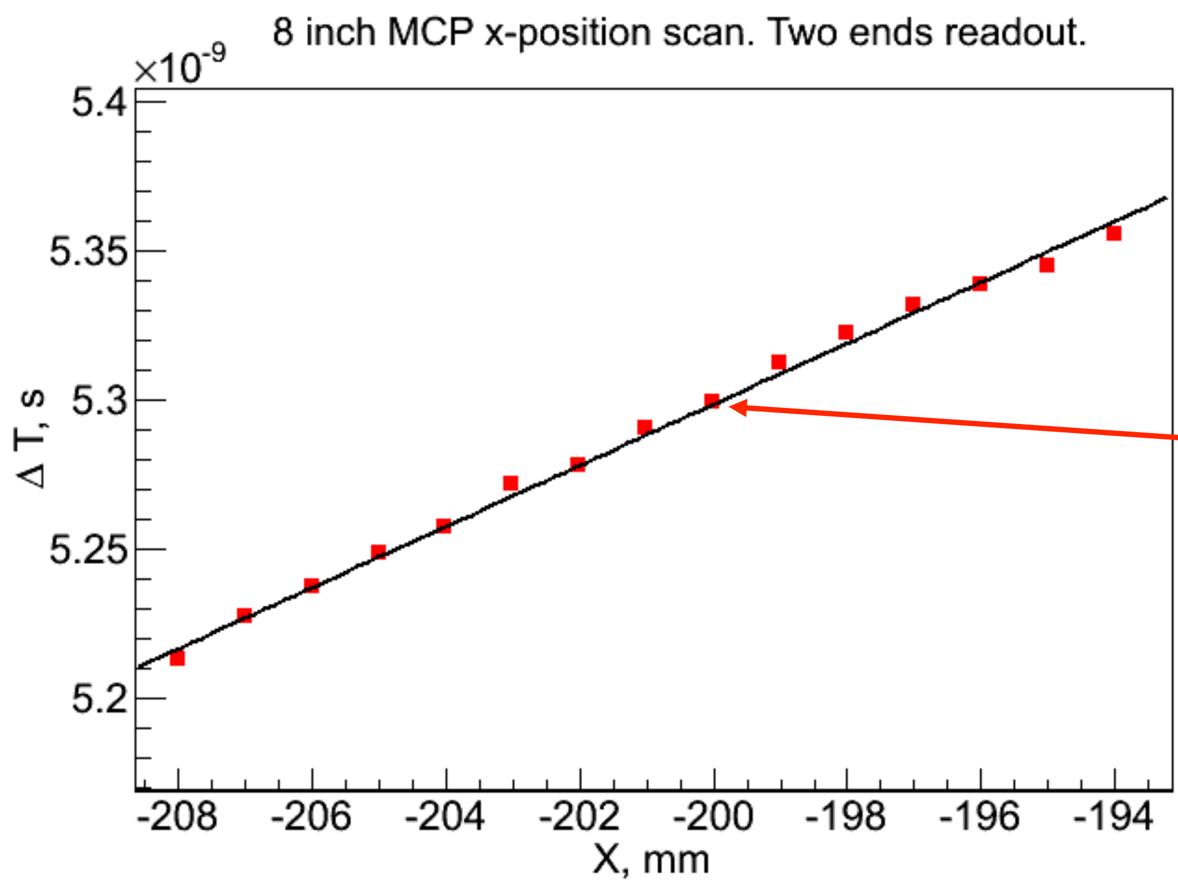
The “Chalice” (ANL)

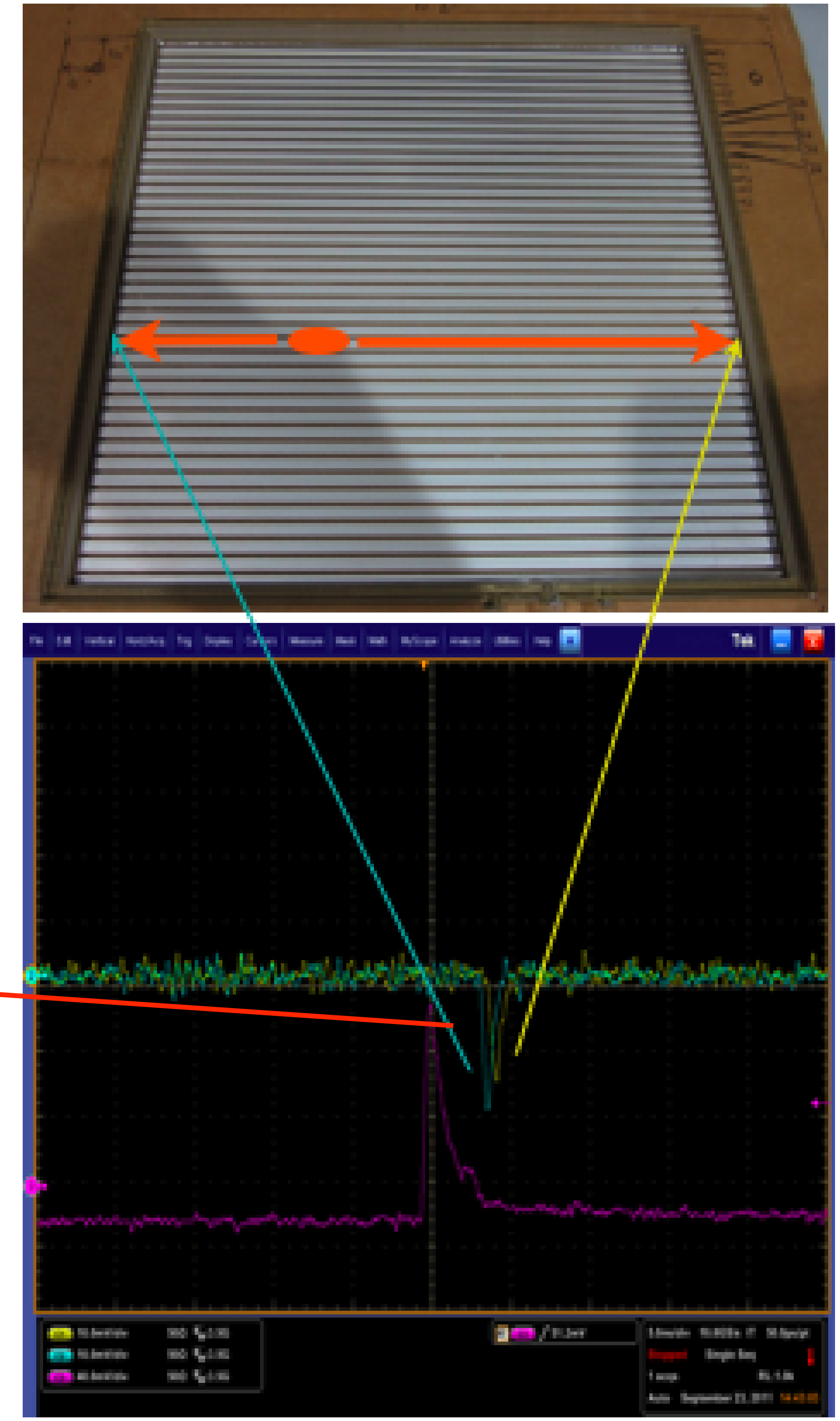


Anode Design: Delay Lines

Channel count (costs) scale with length, not area
Position is determined:

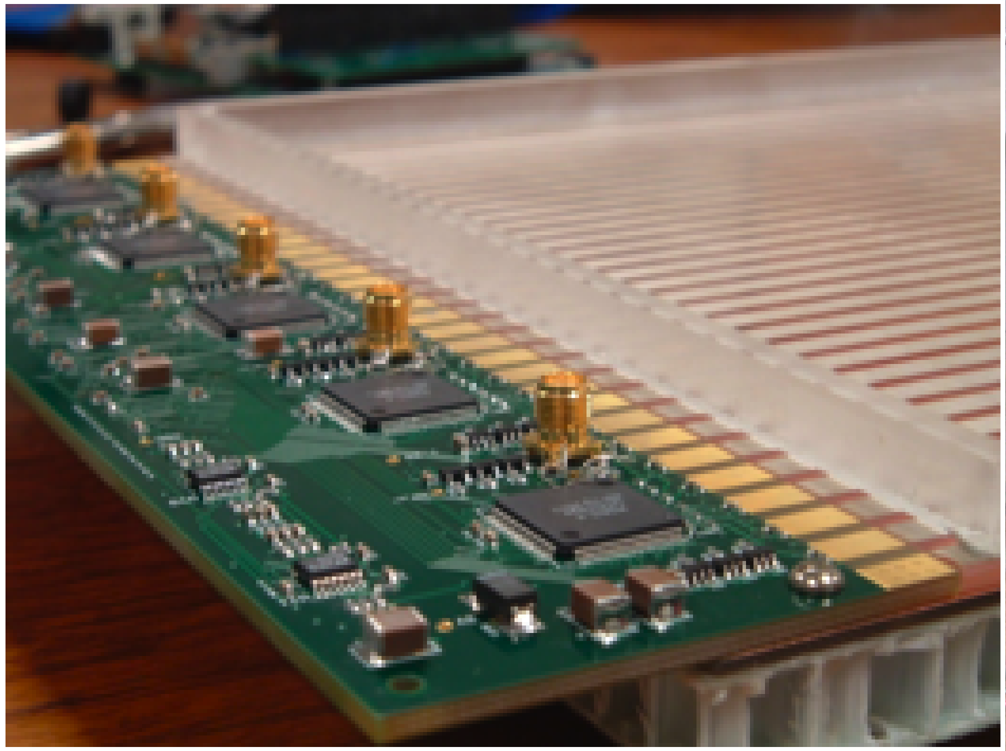
- **by charge centroid in the direction perpendicular to the striplines**
- **by differential transit time in the direction parallel to the strips**

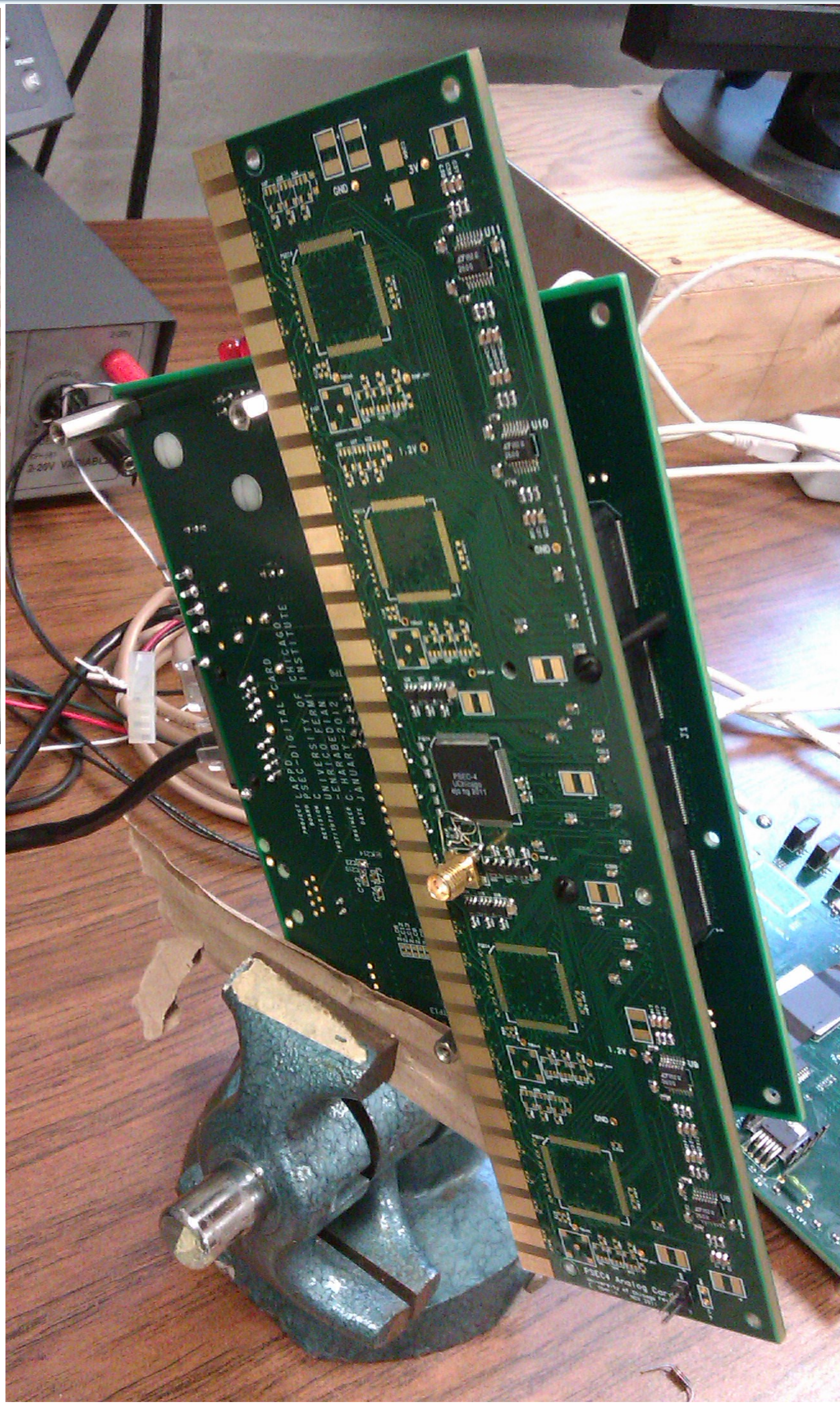




Slope corresponds to ~2/3 c propagations speed on the microstrip lines. RMS of 18 psec on the differential resolution between the two ends: equivalent to roughly 3 mm

Front-end Electronics





Psec4 chip:
- CMOS-based, waveform sampling chip
- 17 Gsamples/sec
- ~1 mV noise
- 6 channels/chip

Analog Card:
- Readout for one side of 30-strip anode
- 5 psec chips per board
- Optimized for high analog bandwidth (>1 GHz)

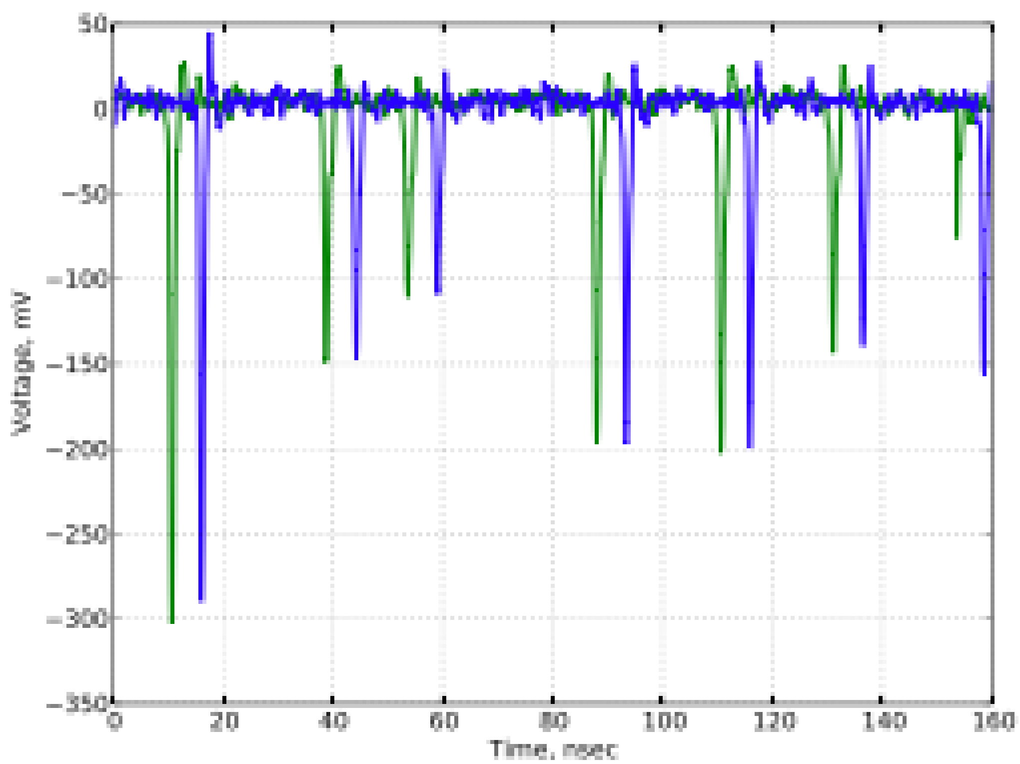
Digital Card:
- Analysis of the individual pulses (charges and times)

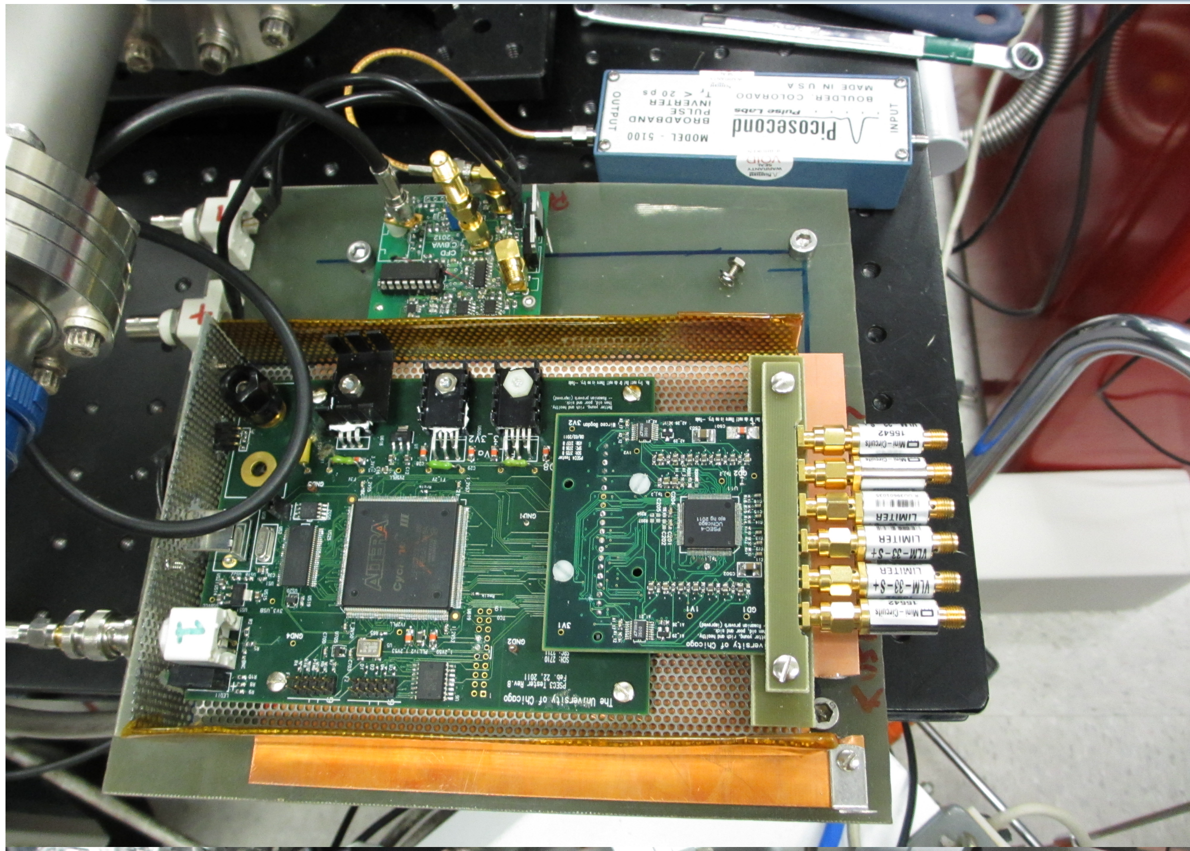
Central Card:
- Combines information from both ends of multiple striplines

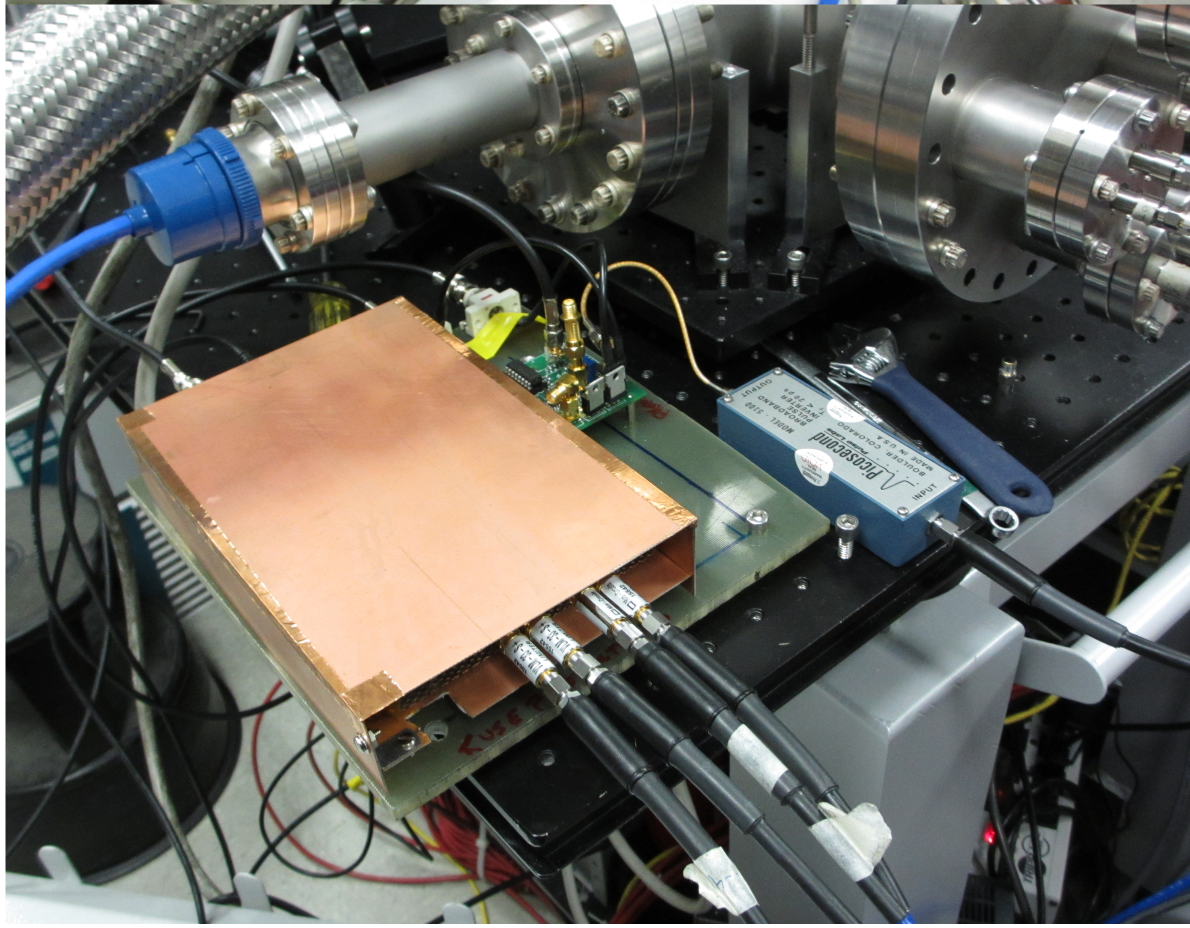
scope-in-a-box

We are now able to test the psec4 chip integrated with our detector system.

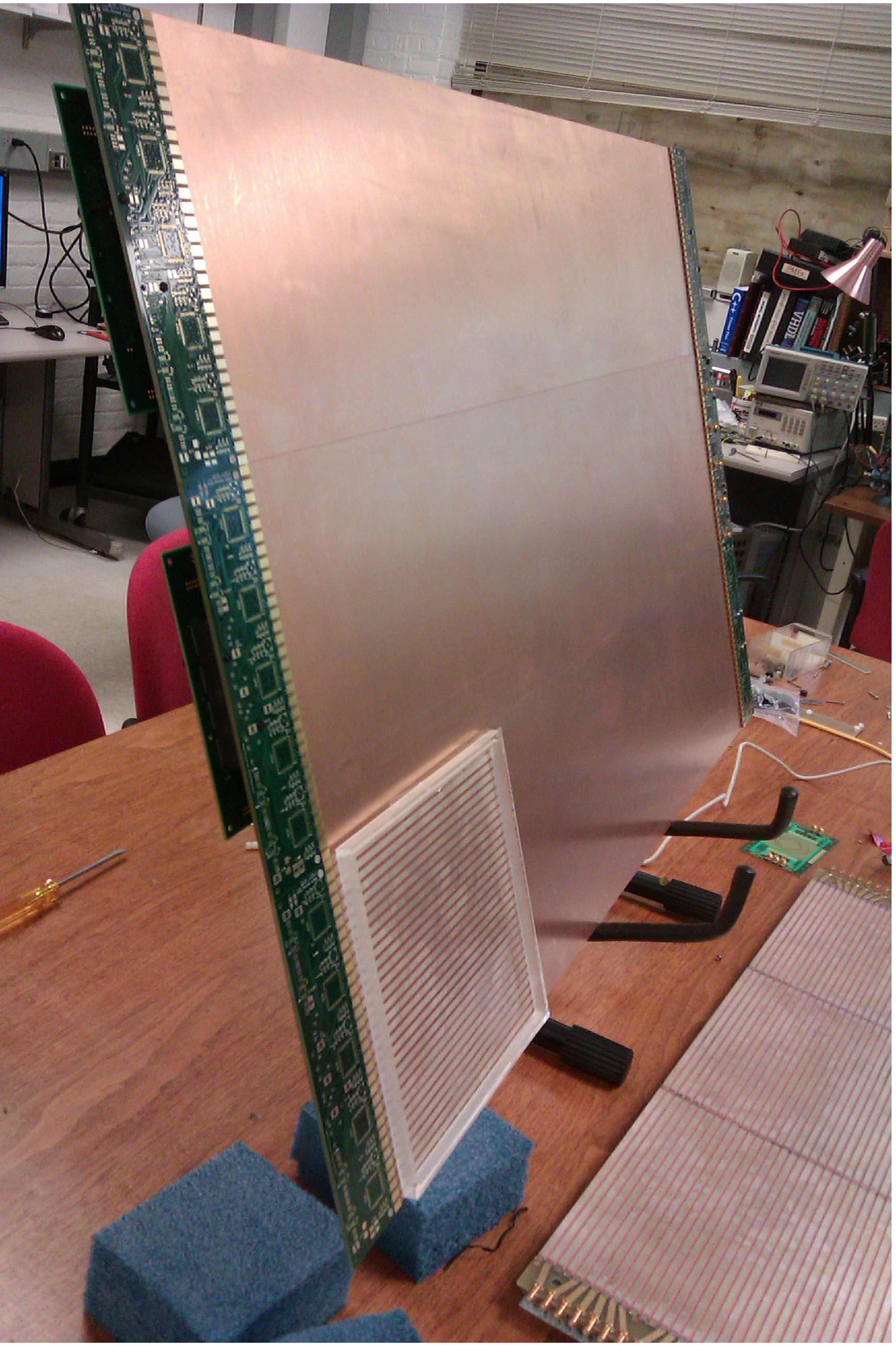
Scope-in-a-box is a six channel oscilloscope, built around our psec4 chip and digital electronics.

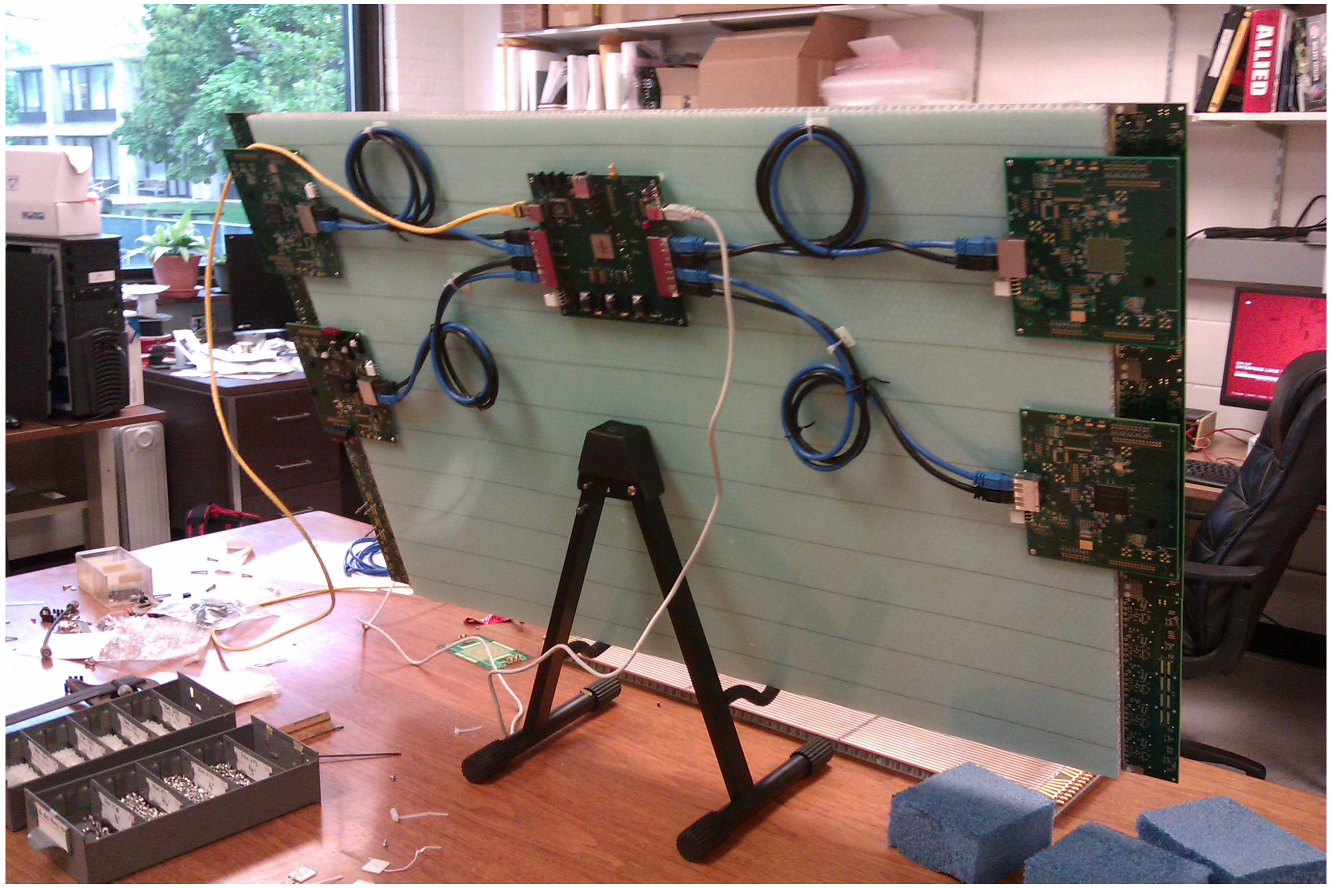






The Big Picture





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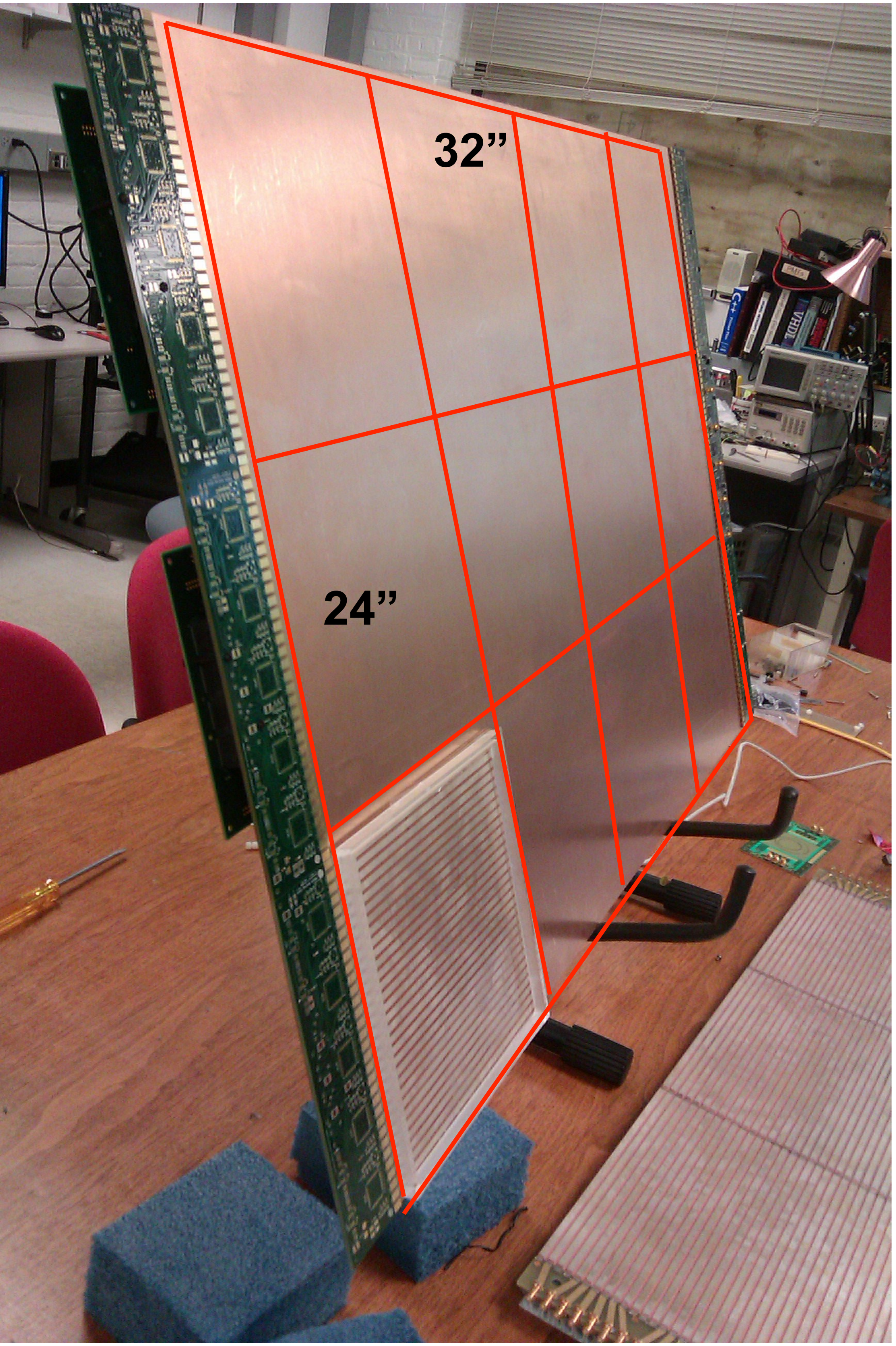
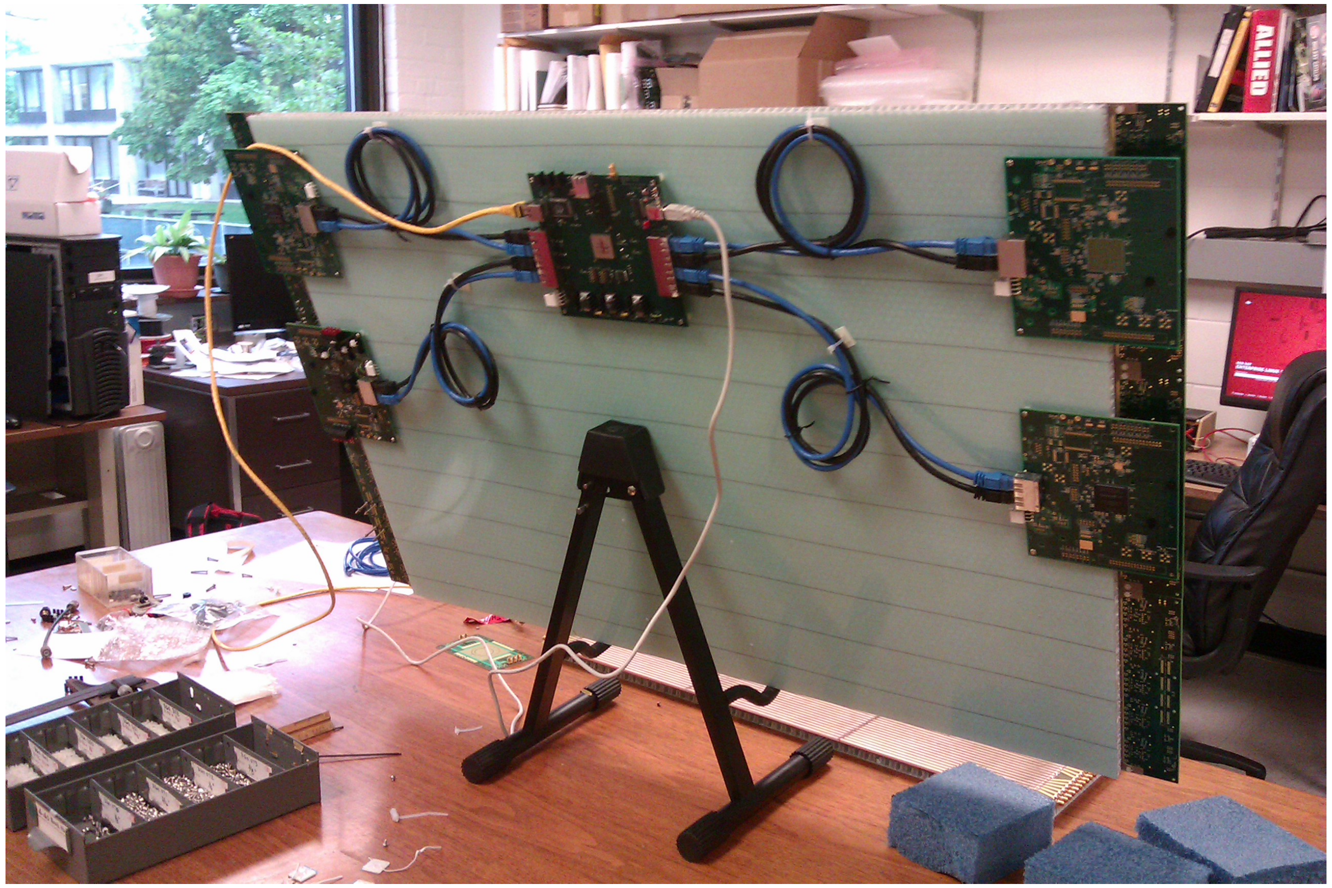


Supermodule:

- •Multiple MCP detectors share a single delay line anode.
- •Reduced channel count (slight loss of bandwidth)
- •Fully integrated electronics
- •Minimal cabling
- •Thin!



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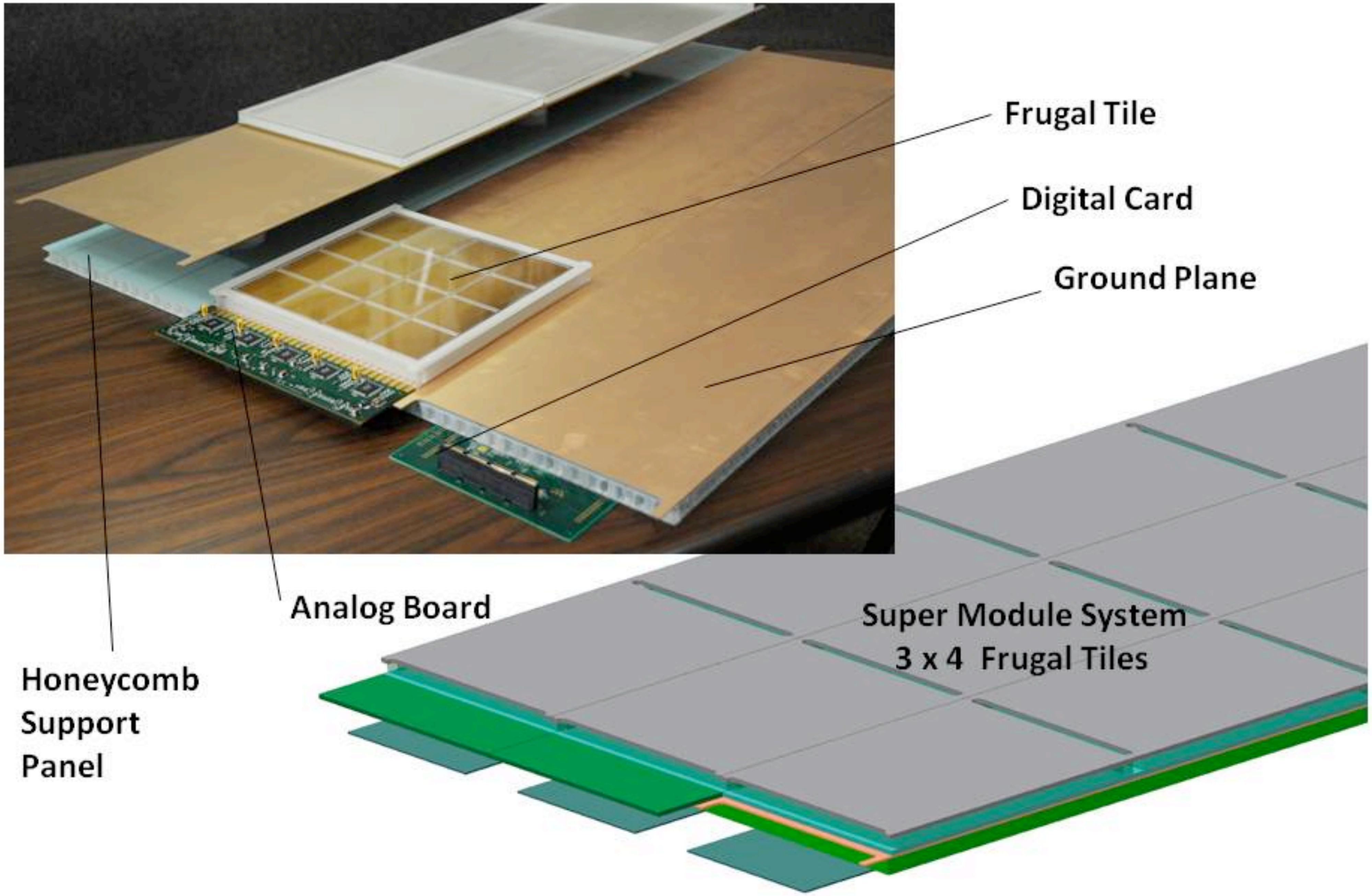
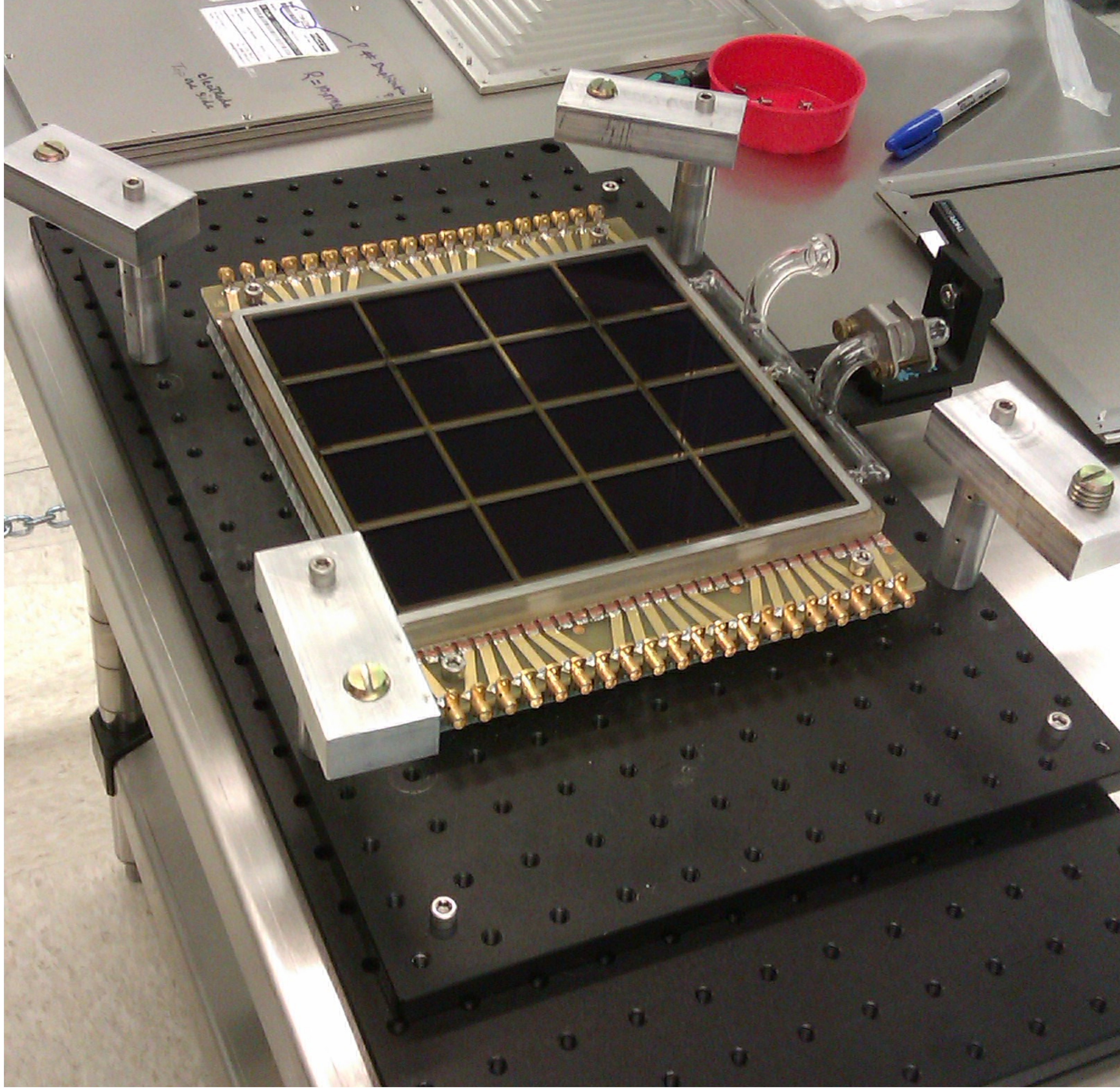


Tray and Tiles - The Super Module System

Status and Next Steps

- Many of the individual components are now working
- Next Challenges:
  - Integration
  - Commercialization

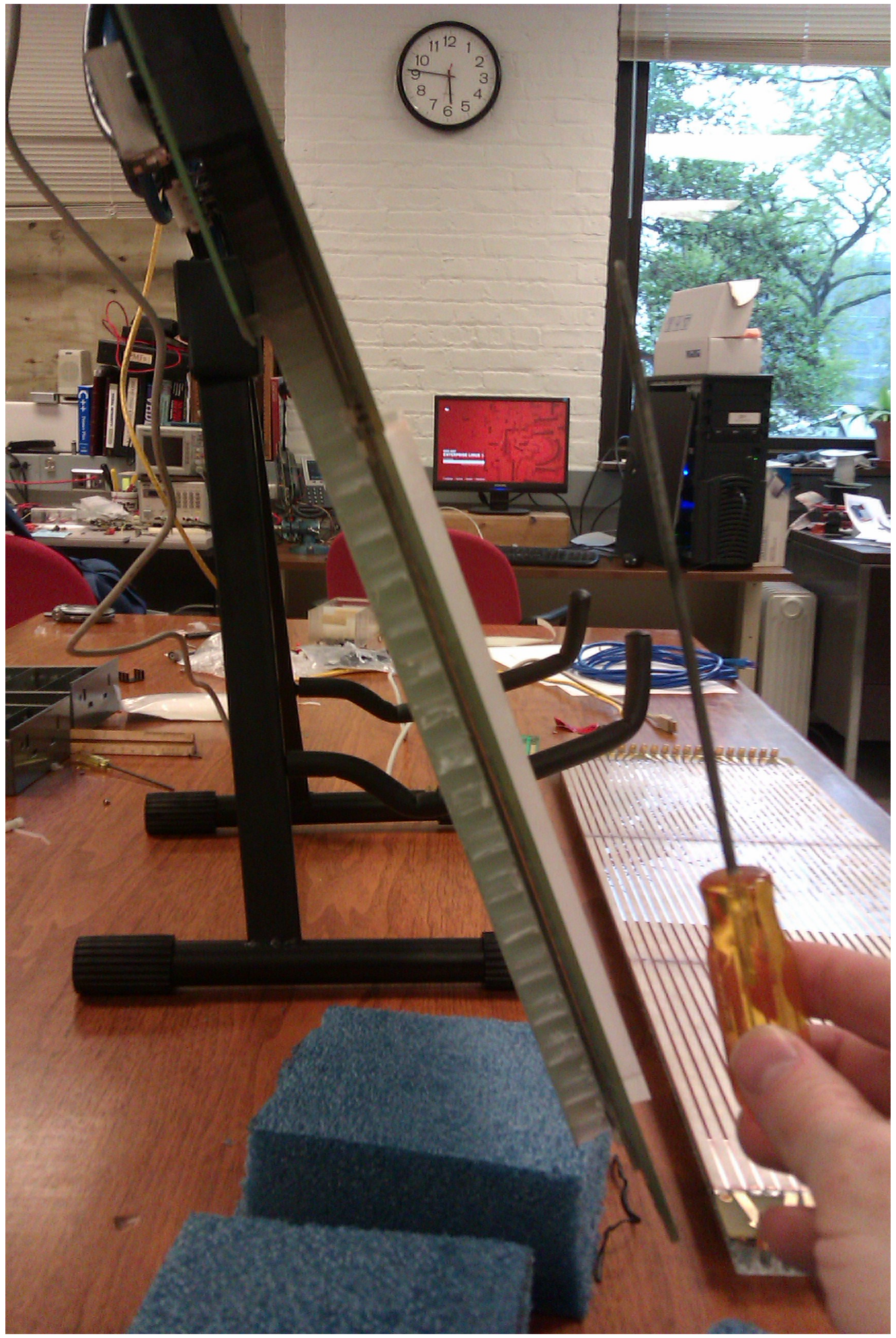


Now testing the "demountable tile":

- Test tile consisting entirely of LAPPD made parts
- Close to a final product except:
  - Aluminum PC
  - Top window sealed with an O-ring
  - Active Pumping
- Active components under vacuum as of this week.

Advantageous Characteristics for Neutrino Detection

Compactness



Excellent Photon Counting

Don't need to rely on charge only:

- **Can see individual photons based on where and when they hit.**
- **Could mean improved energy resolution.**

Operation in a Magnetic Field

MCPs can operate in a magnetic field. Bend magnets could be used to determine sign.

Geant4 simulations: Tracks at $1 \times 1 \times 4$ m

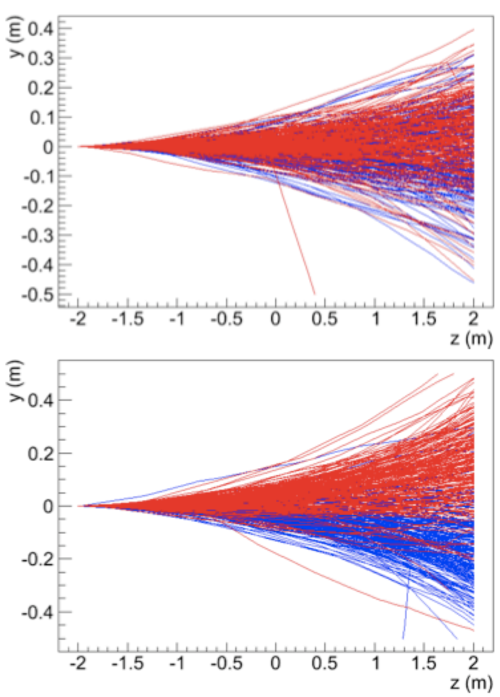


Figure: $B = 100$ gauss (top), $B = 500$ gauss (bottom).

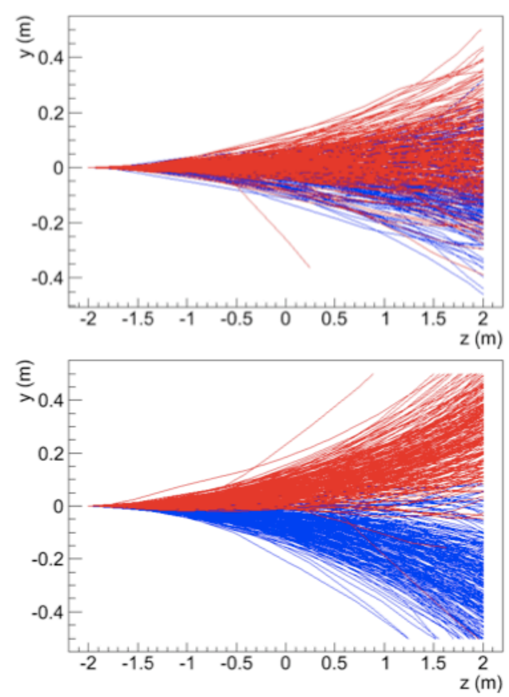
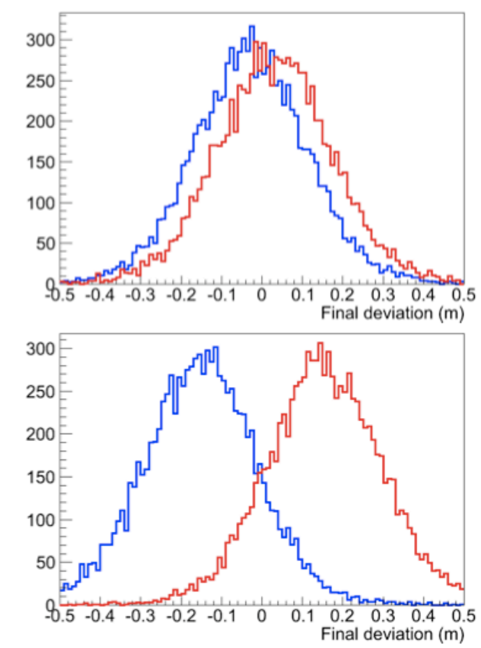


Figure: $B = 200$ gauss (top), $B = 1$ kgauss (bottom).

Geant4 simulations: Naive resolution at $1 \times 1 \times 4$ m



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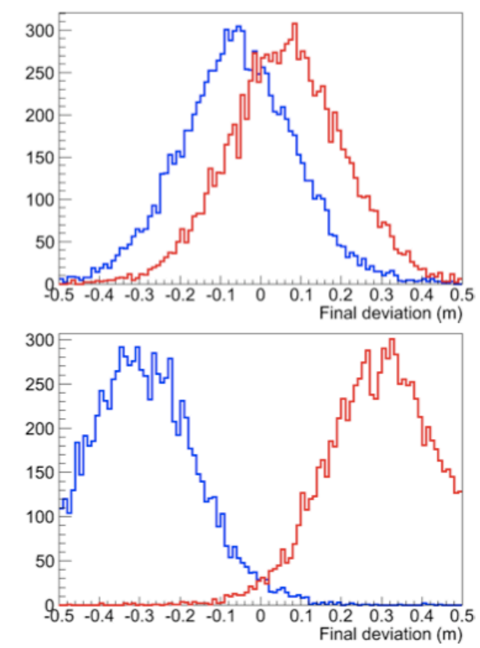
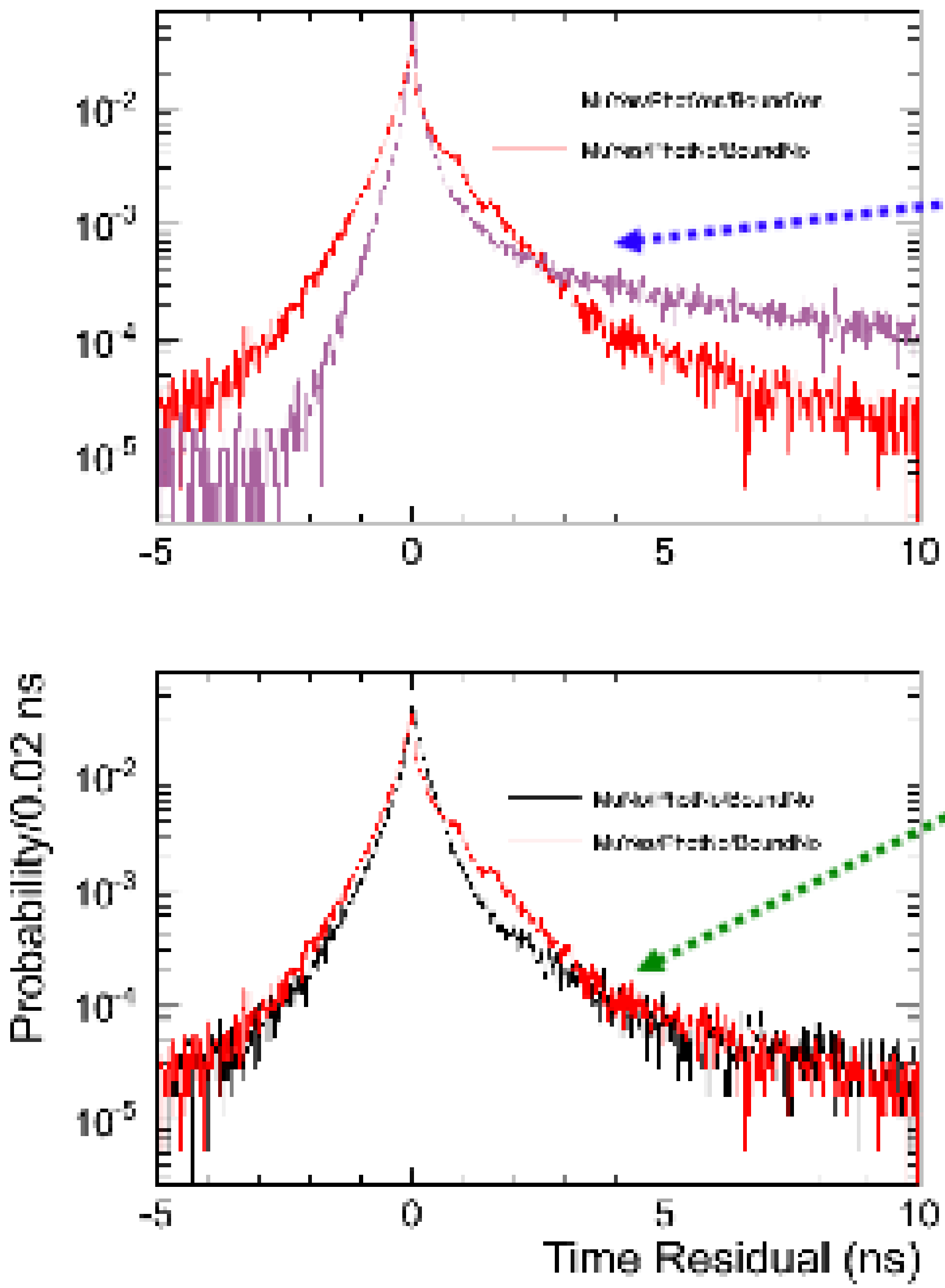


Figure: $B = 200$ gauss (top), $B = 1$ kgauss (bottom).

Work by Alexander Vostrikov (U. Chicago)

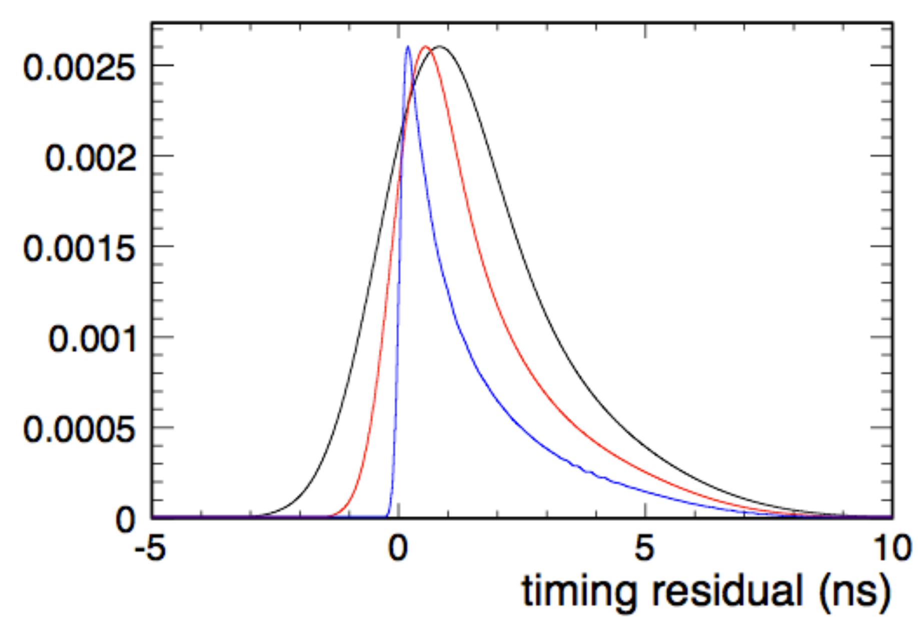
Timing and Spatial Resolution – Imaging Capabilities



Optical scattering broadens the tail of the timing residual but sharpens the rising edge

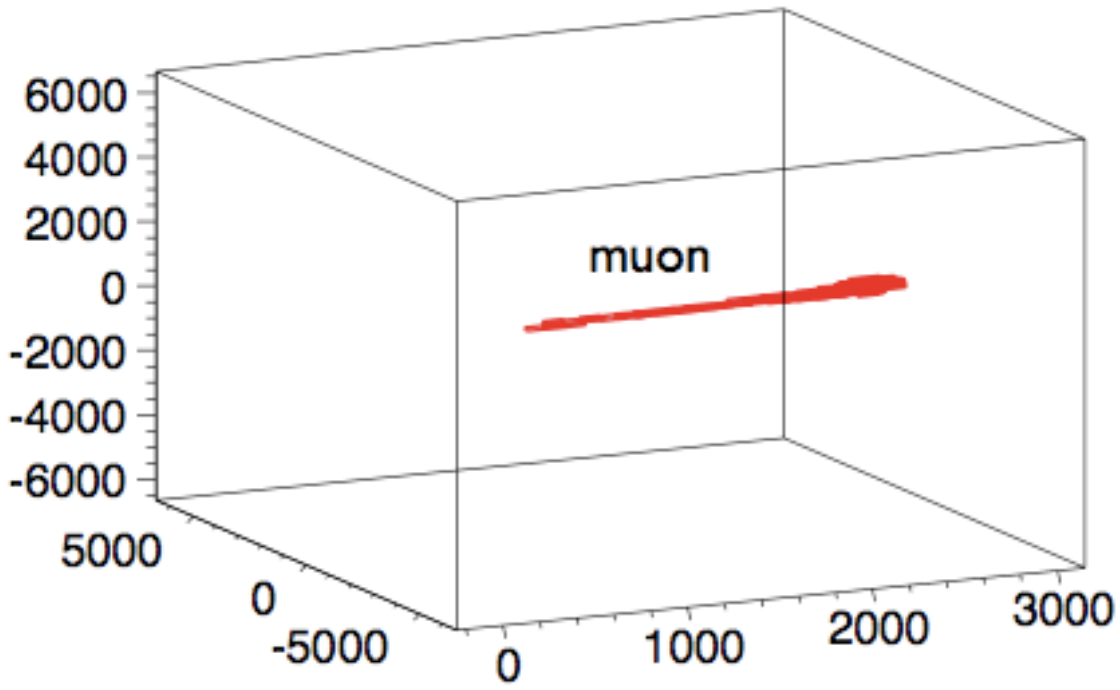
Forward scattering of muons can have shape effects on the timing resolution.

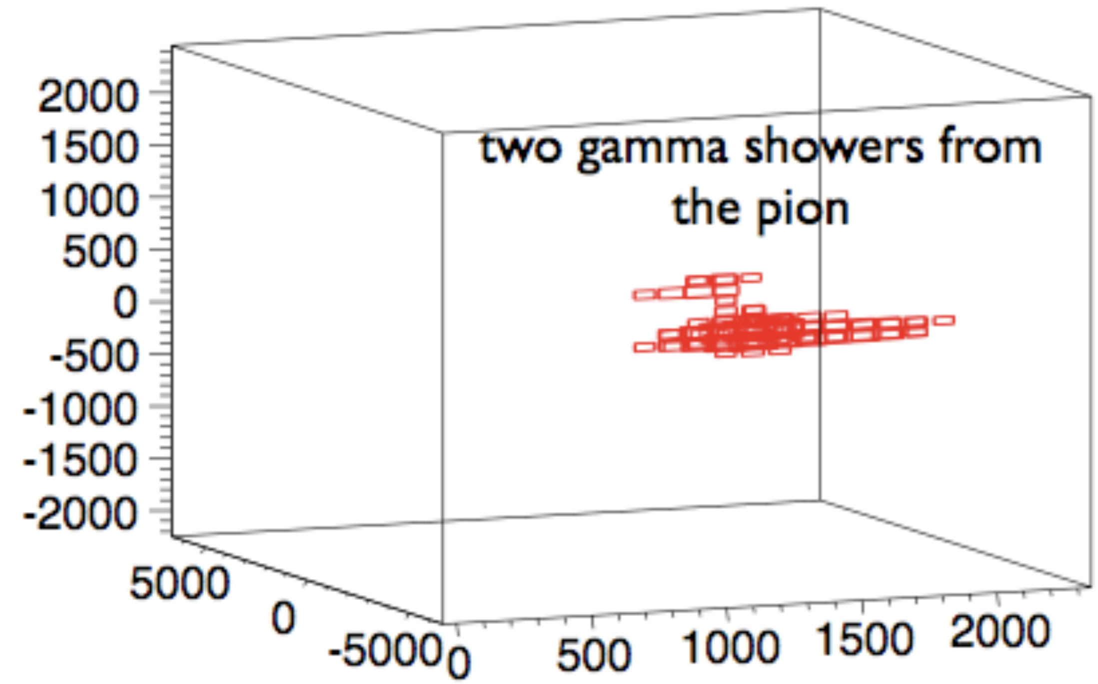
Shape of rising edge depends on distance and color composition, as well as detector resolution

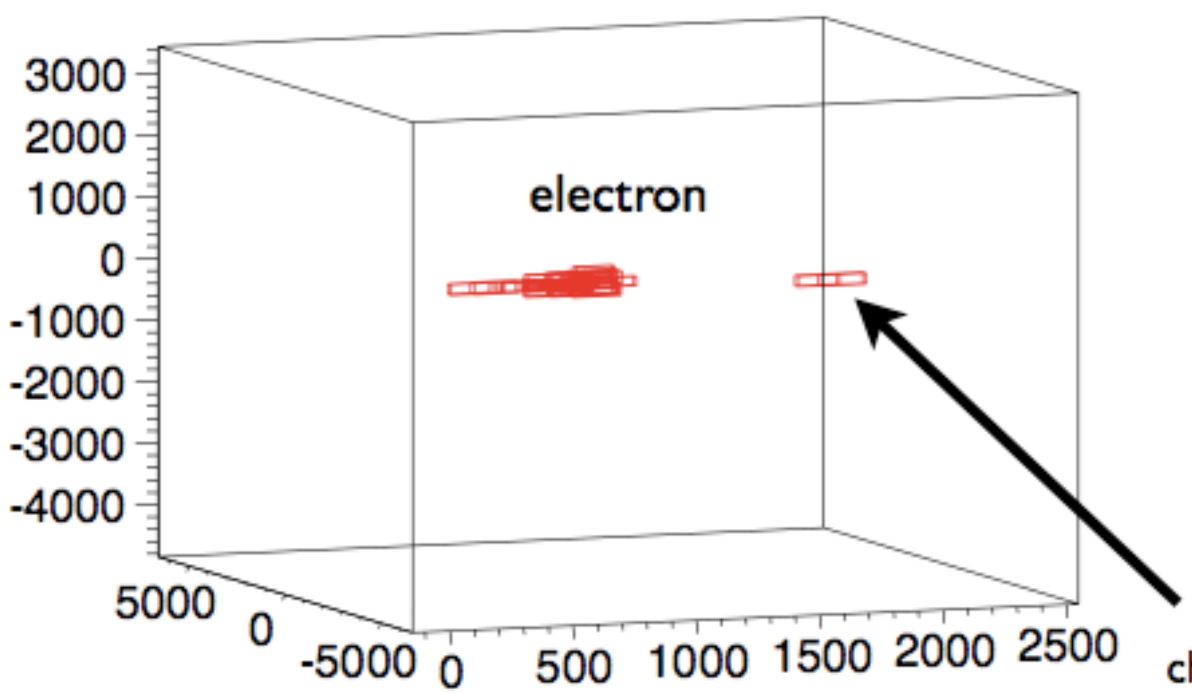


Work by Tian Xin (Iowa)

Reconstructing Geant Events



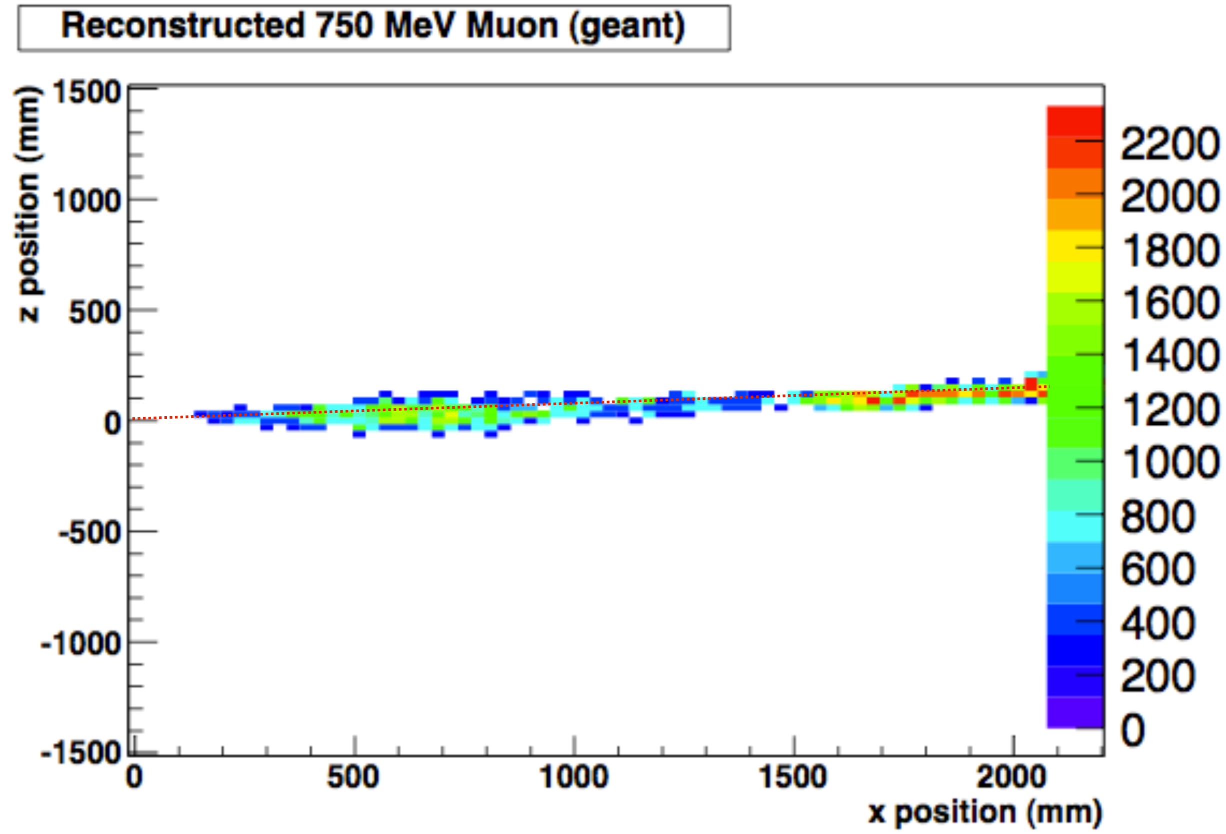


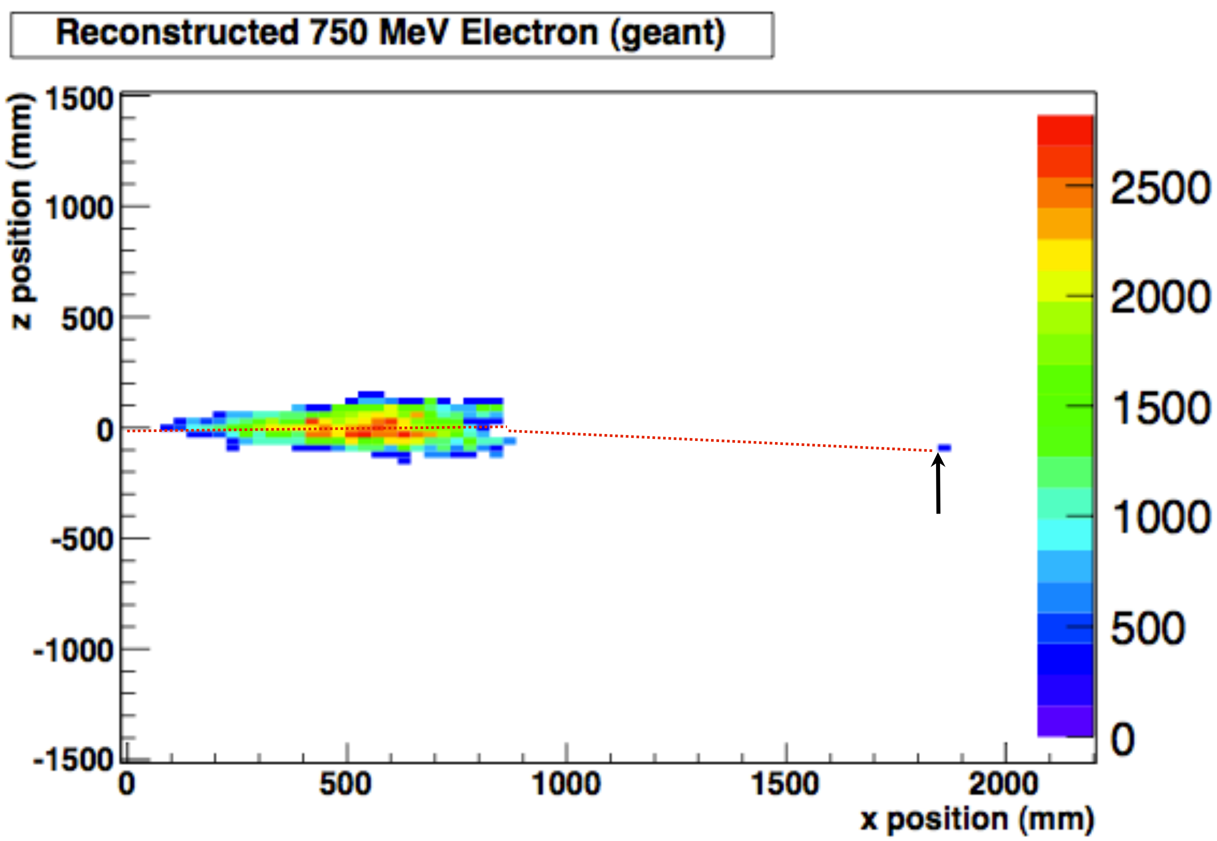


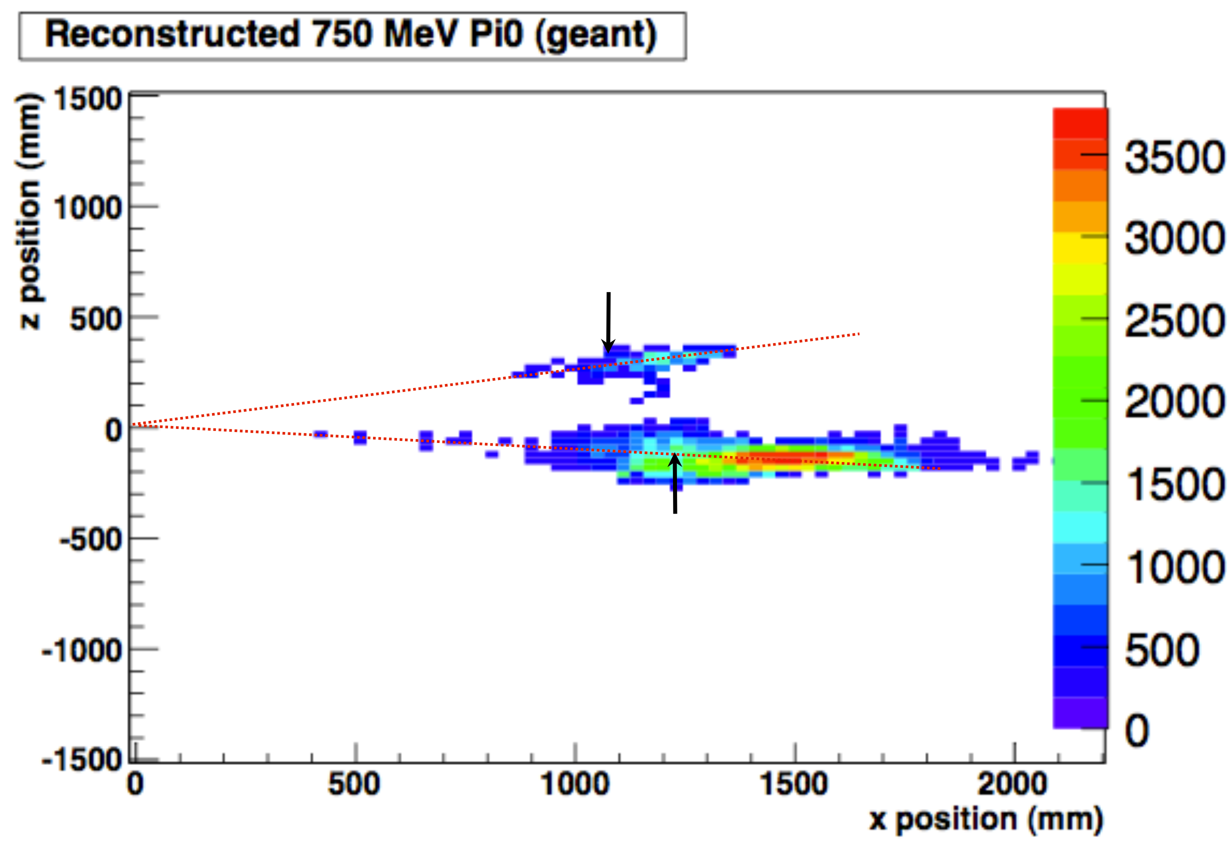
check out the detached shower from the bremstrahlung!!!

Comparing Isochron Reconstruction….

If I hand draw track hypotheses through these transforms…

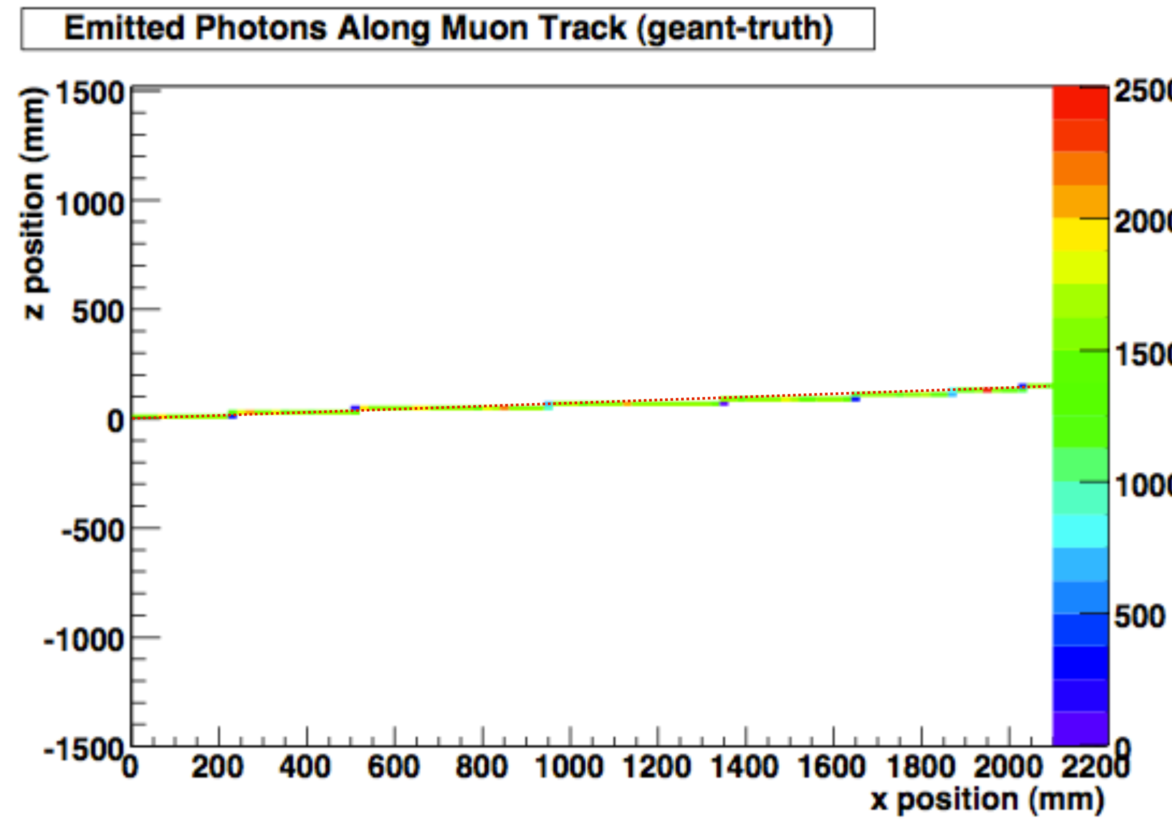


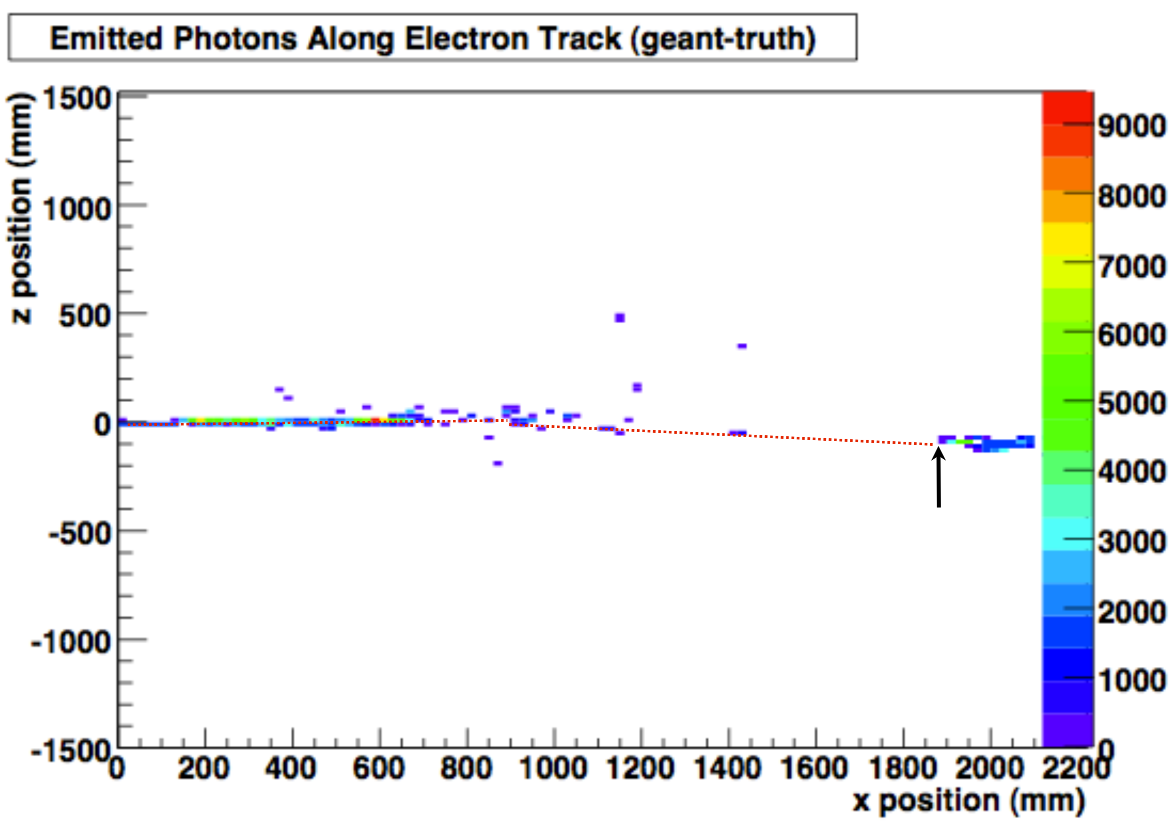


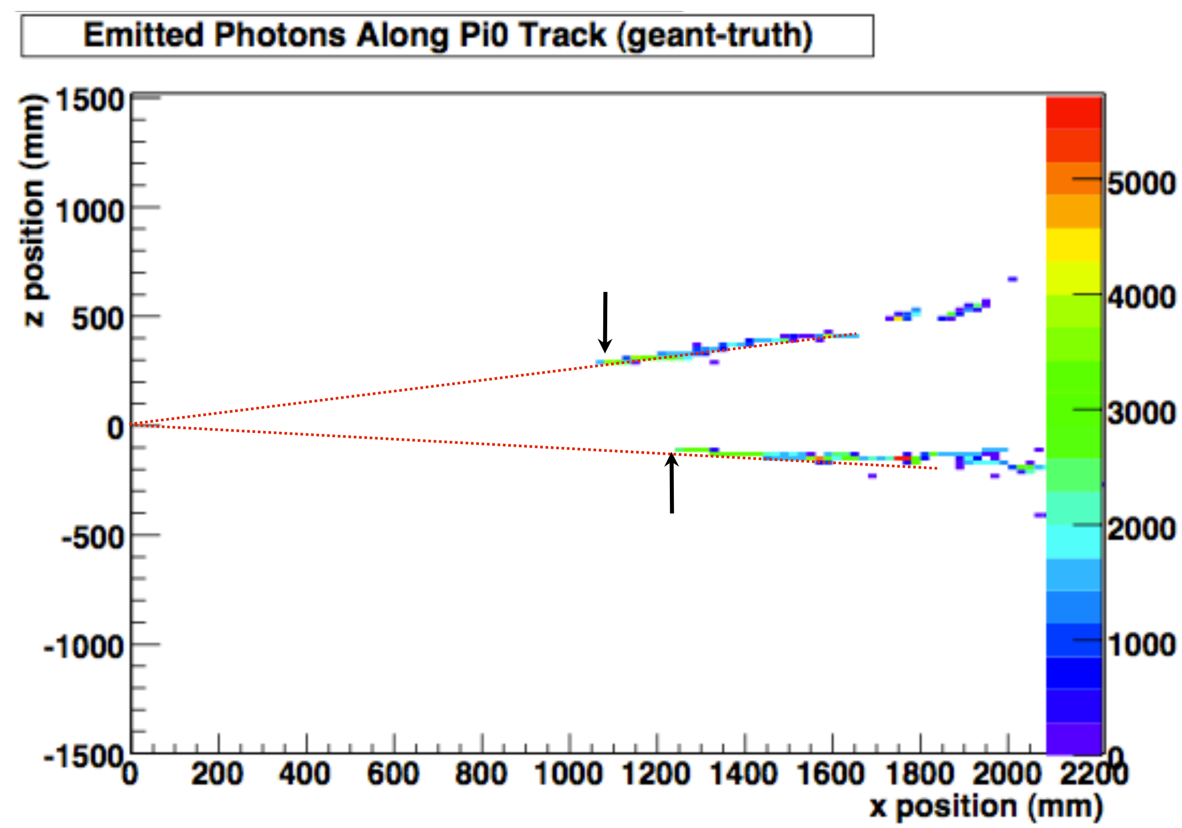


With True Tracks

They match very nicely with the truth-level tracks/shower constituents



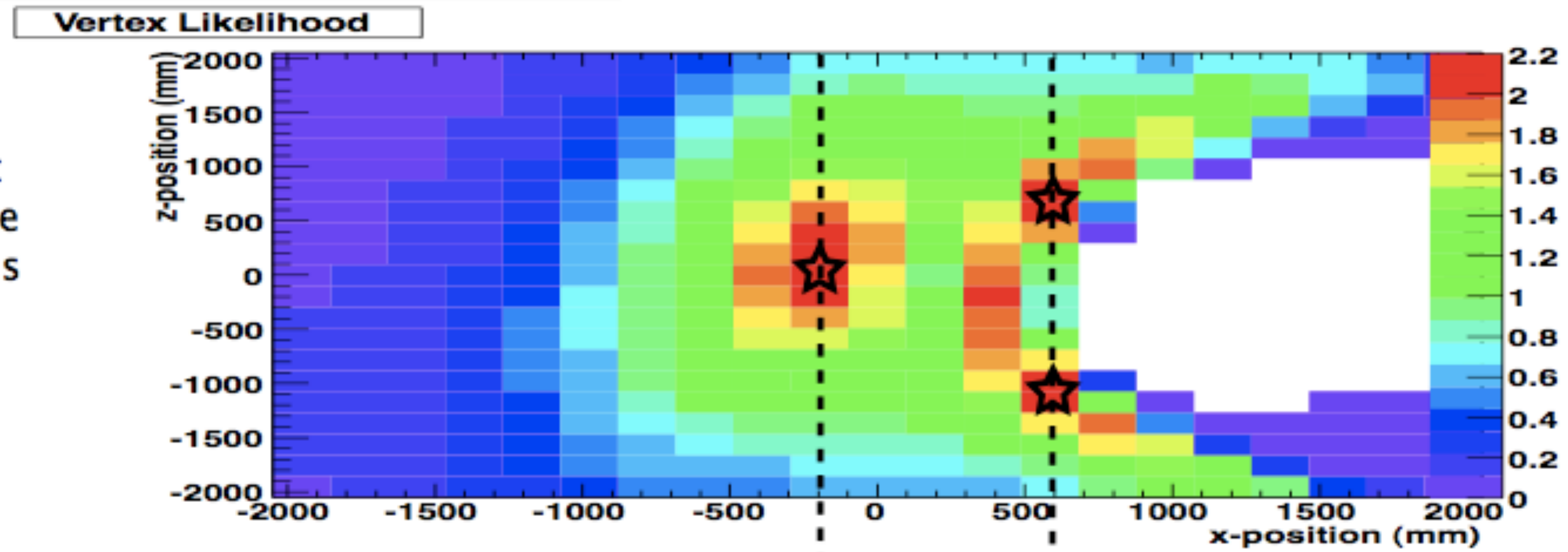




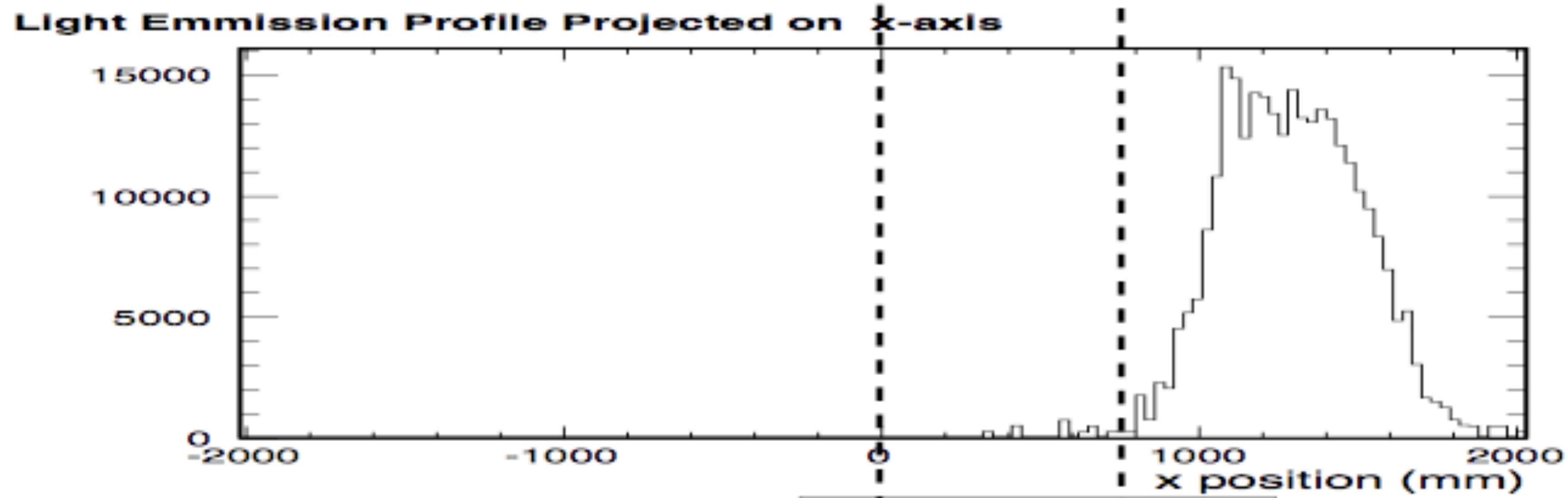
Vertex Separation As A Handle on PID

Pi0

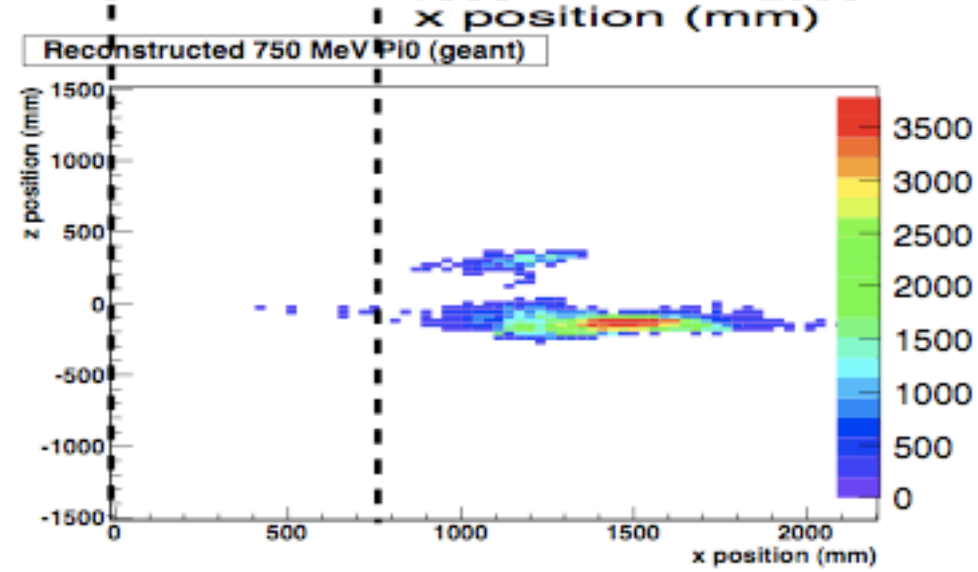
We have one strong vertex that causally connects the hit pattern, located far before the onset of Cherenkov light. This is followed by two vertex candidates, corresponding roughly with first light.



Location of the candidate vertices do not correspond perfectly to true vertices, probably due to an inappropriate choice of refractive index.



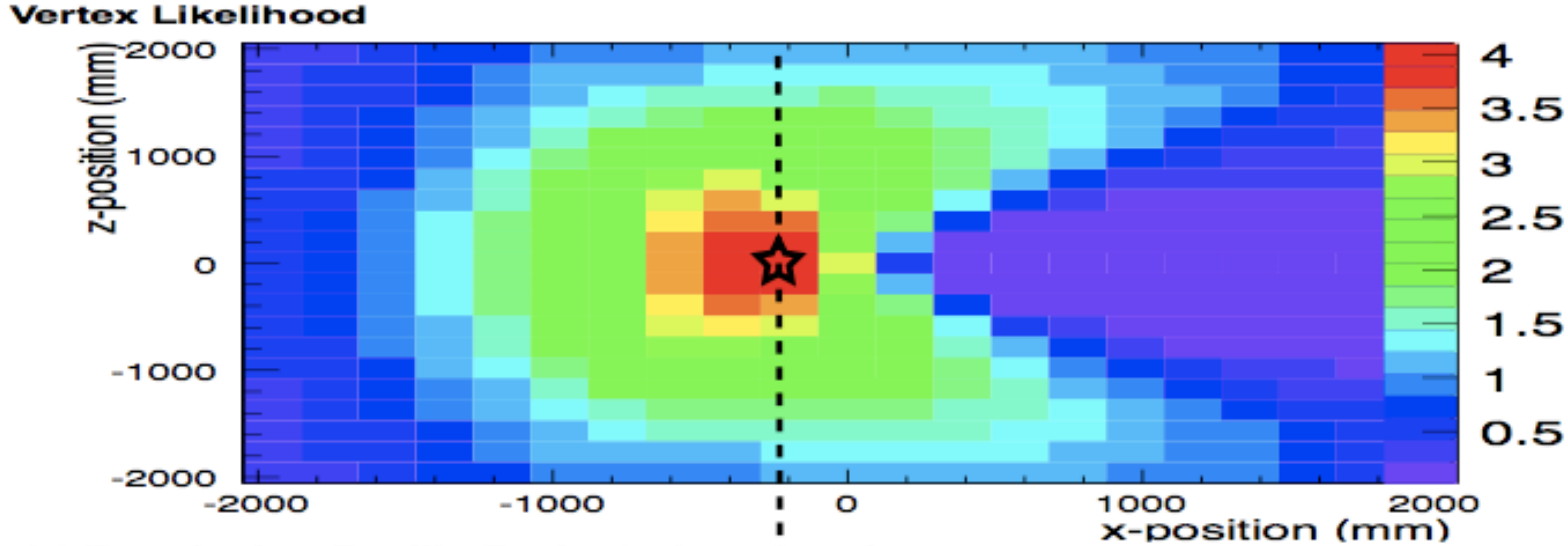
First light and vertex candidates correspond nicely with the two shower candidates reconstructed by the isochron method

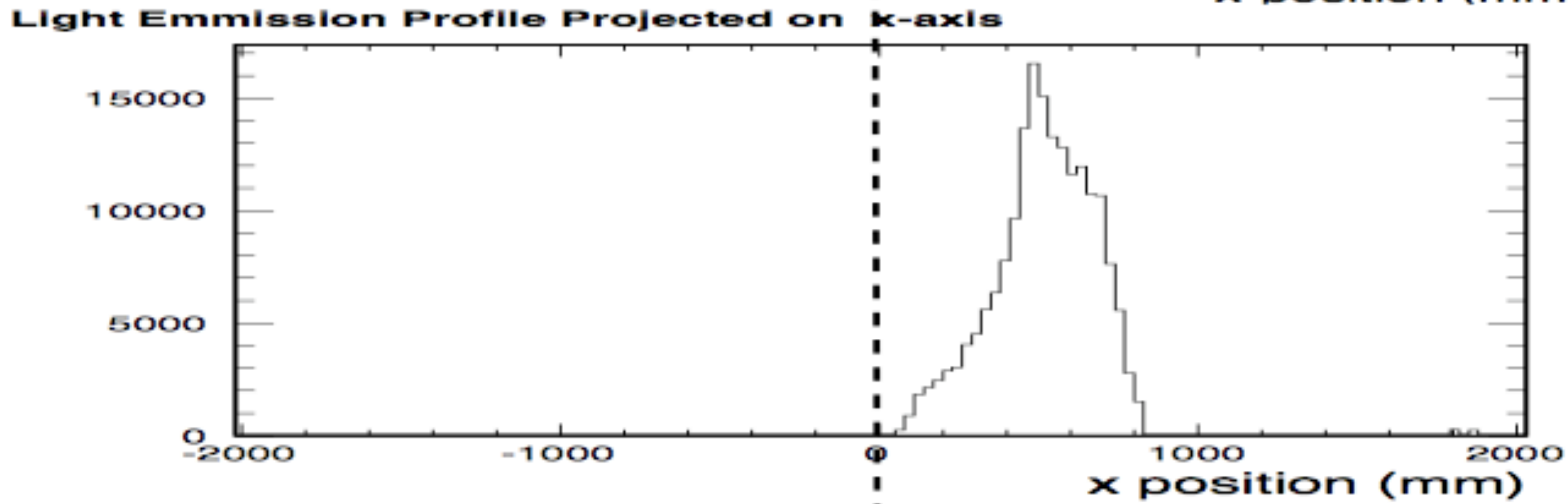


Vertex Separation As A Handle on PID

Electron

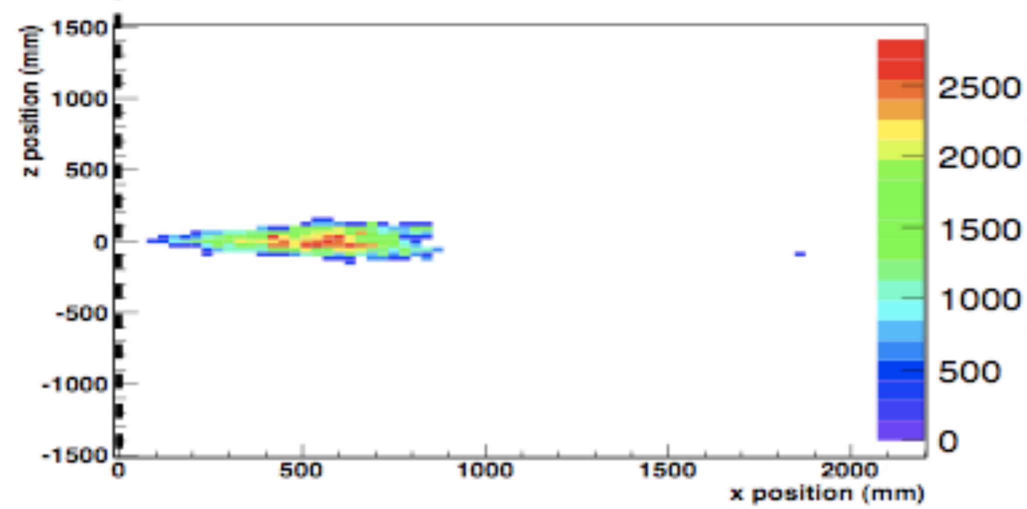
We have one strong vertex that causally connects the hit pattern, located far before the onset of Cherenkov light. This is followed by two vertex candidates, corresponding roughly with first light.





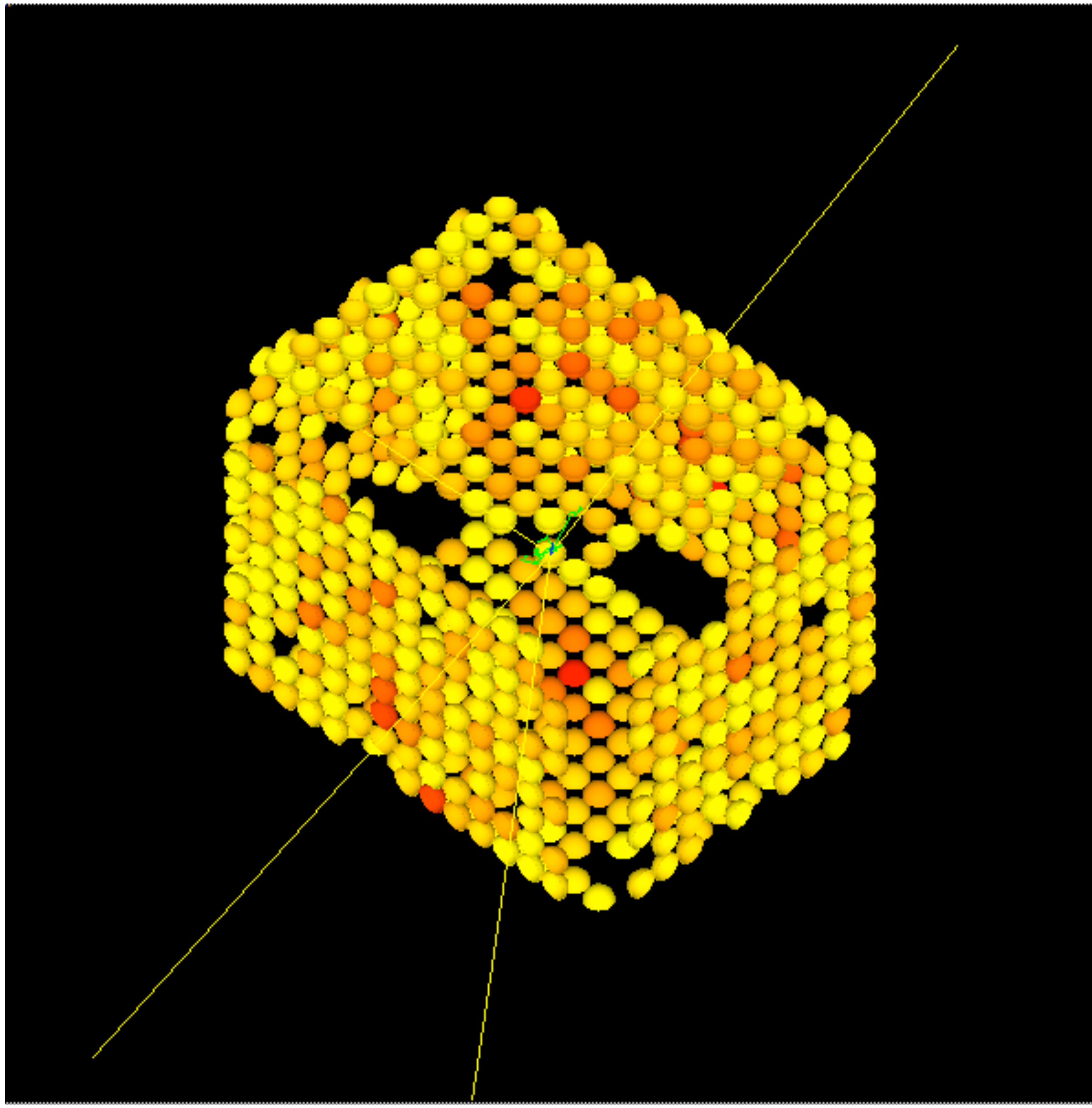
Location of the candidate vertices do not correspond perfectly to true vertex, probably due to an inappropriate choice of refractive index (I used the wrong value).

First light and vertex candidates correspond nicely with the two shower candidates reconstructed by the isochron method



Next Steps and Conclusions

- LAPPD detectors open up the possibility for advanced water and scintillator based neutrino detectors.
- Commercialization is the crucial first step.
- An important parallel step is to develop a strong simulations/reconstruction program. This work has already started
- It is also an interesting time to start thinking about application specific uses.
- Could they be useful in SNS-based experiments?



Work by Subhojit Sarkar