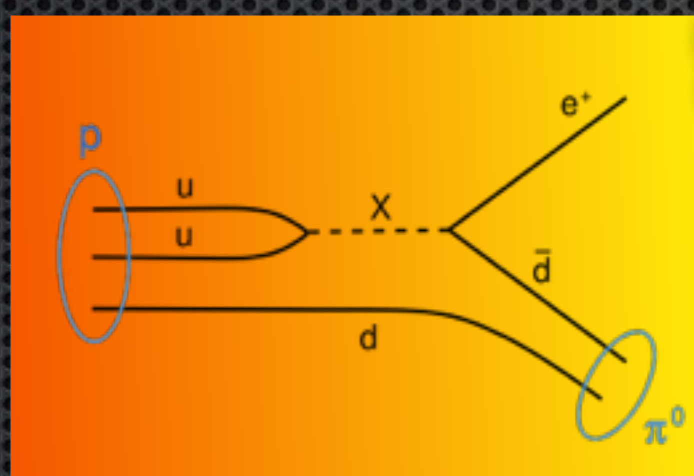
ANNIE:
The Accelerator Neutrino Neutron Interaction Experiment

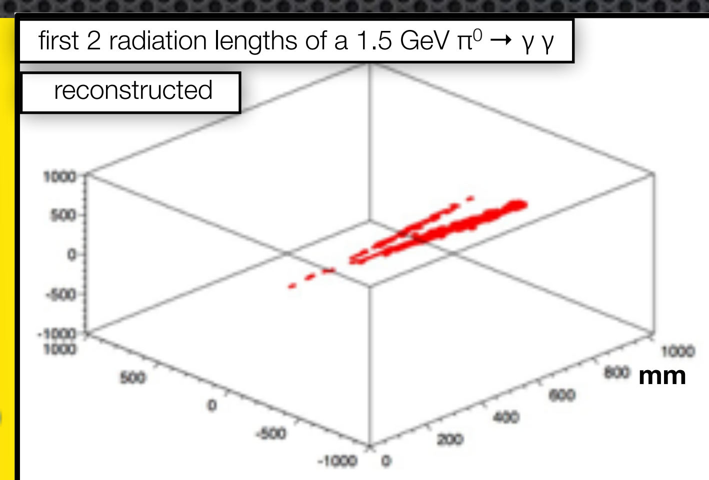
Mayly Sanchez for the ANNIE collaboration
Iowa State University

NuFact 2015 - Rio de Janeiro, Brazil - August 11, 2015

The ANNIE experiment

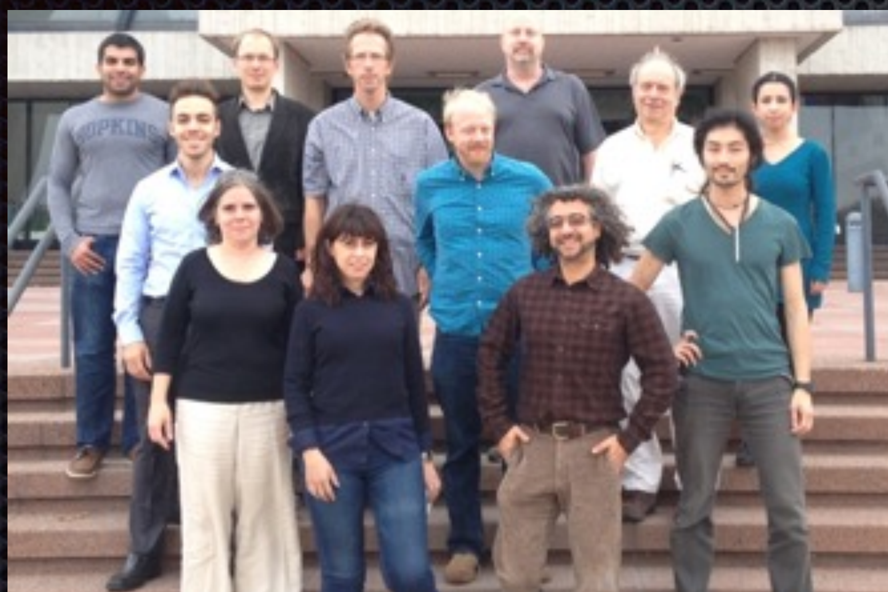
- ANNIE, seeks to measure the abundance of final state neutrons from neutrino interactions in water, as a function of energy (see arXiv:1409.5864 and arXiv:1504.01480).
- It is also the first application in a HEP experiment of LAPPDs (Large-Area Picosecond Photo-Detectors).

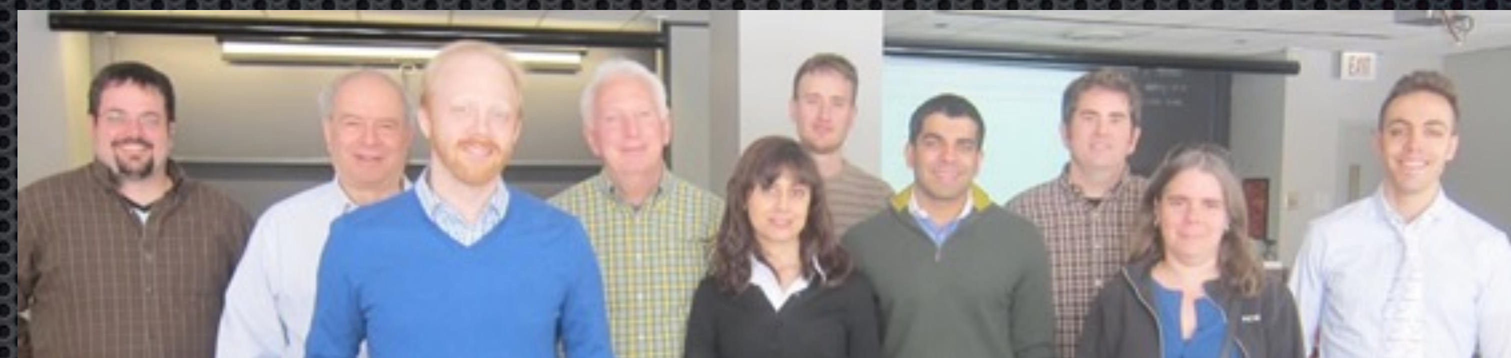




- A key physics measurement in understanding the nature neutrino-nucleus interactions.
- Application of a promising technology for detecting neutrinos.

The ANNIE collaboration





Argonne National Laboratory
Brookhaven National Laboratory
Fermi National Accelerator Laboratory
University of Sheffield
Iowa State University
Johns Hopkins University
MIT
Ohio State University
Ultralytics, LLC
University of California at Davis
University of California at Irvine
University of Chicago, Enrico Fermi Institute
University of Hawaii
Queen Mary University of London

2 countries **15 Institutions** **34 collaborators**

Neutrino-Nucleus interactions

- As highlighted yesterday, neutrino nucleus interactions are a **hot topic** for the upcoming oscillation measurements where uncertainties must be reduced from 10 to 1% (T2K today ~8%).
- Experiments rely on models to extrapolate and there are many different neutrino interaction models plus a convolution of cross section with final state interaction effects.

- Measurement of ν xsec at ND is **experimentally complicated:**
  - E_ν not known: xsec measurement always convoluted with flux → importance of minimization of uncertainties in flux modeling (and/or ratio measurements)
  - E_ν inferred from final state leptons/hadrons which have limited angular acceptance, threshold on low energy particles, very small info on recoiling nucleus...

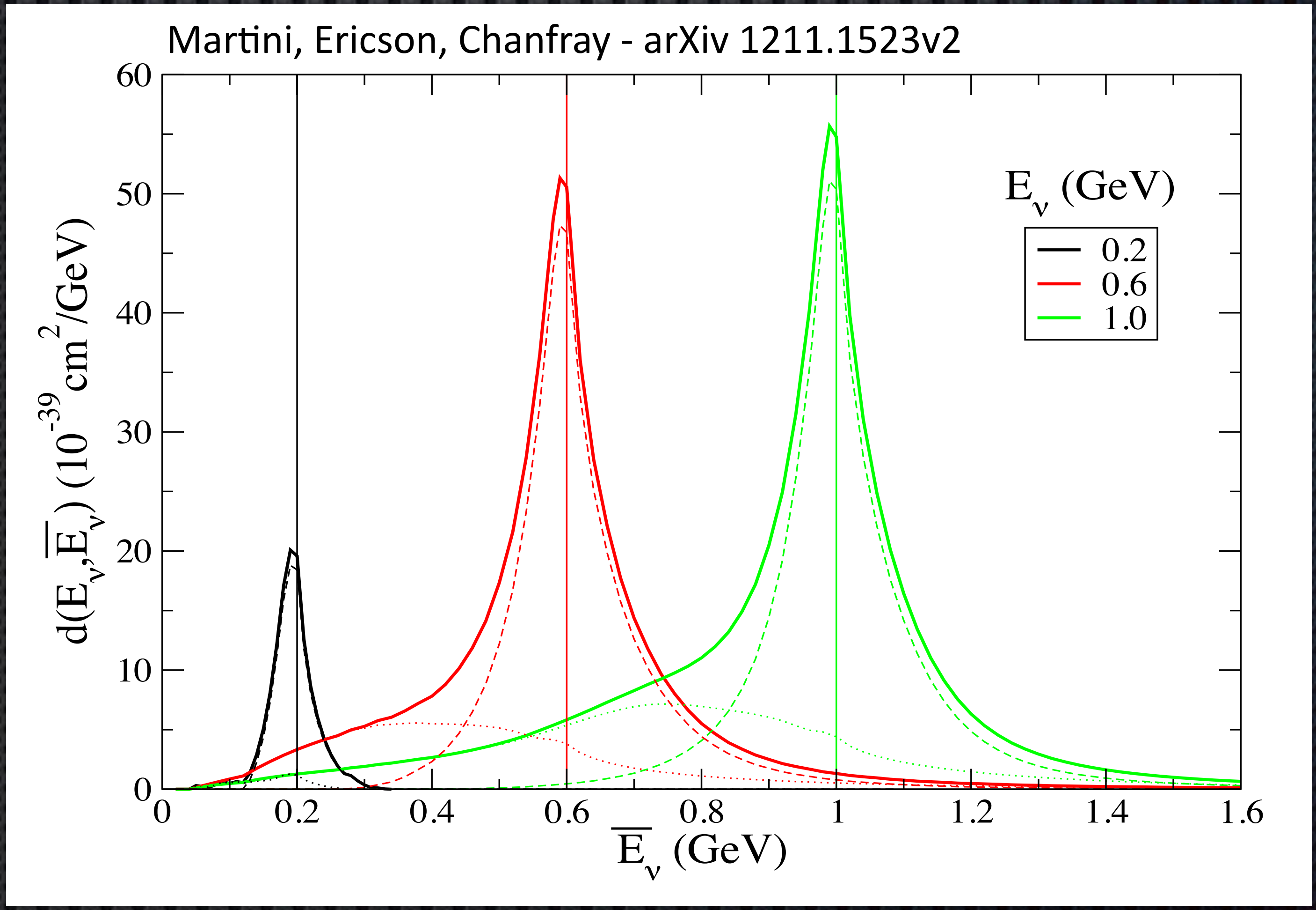
large model uncertainties convoluted with unfolding of detector effects
→ measurements also quoted in limited phase space, x-checks btw different selections

large model uncertainties on background
→ control regions and sidebands to constrain background from data

S. Bolognesi - Nufact 2015

Neutrino-Nucleus interactions

- Similarly, the recent rise of multi-nucleon and MEC processes demonstrates that we are entering an era where high statistics data is confronted with our understanding of neutrino-nucleus interactions.
- A variety of new neutrino data focused on understanding neutrino-nucleus interactions is needed.

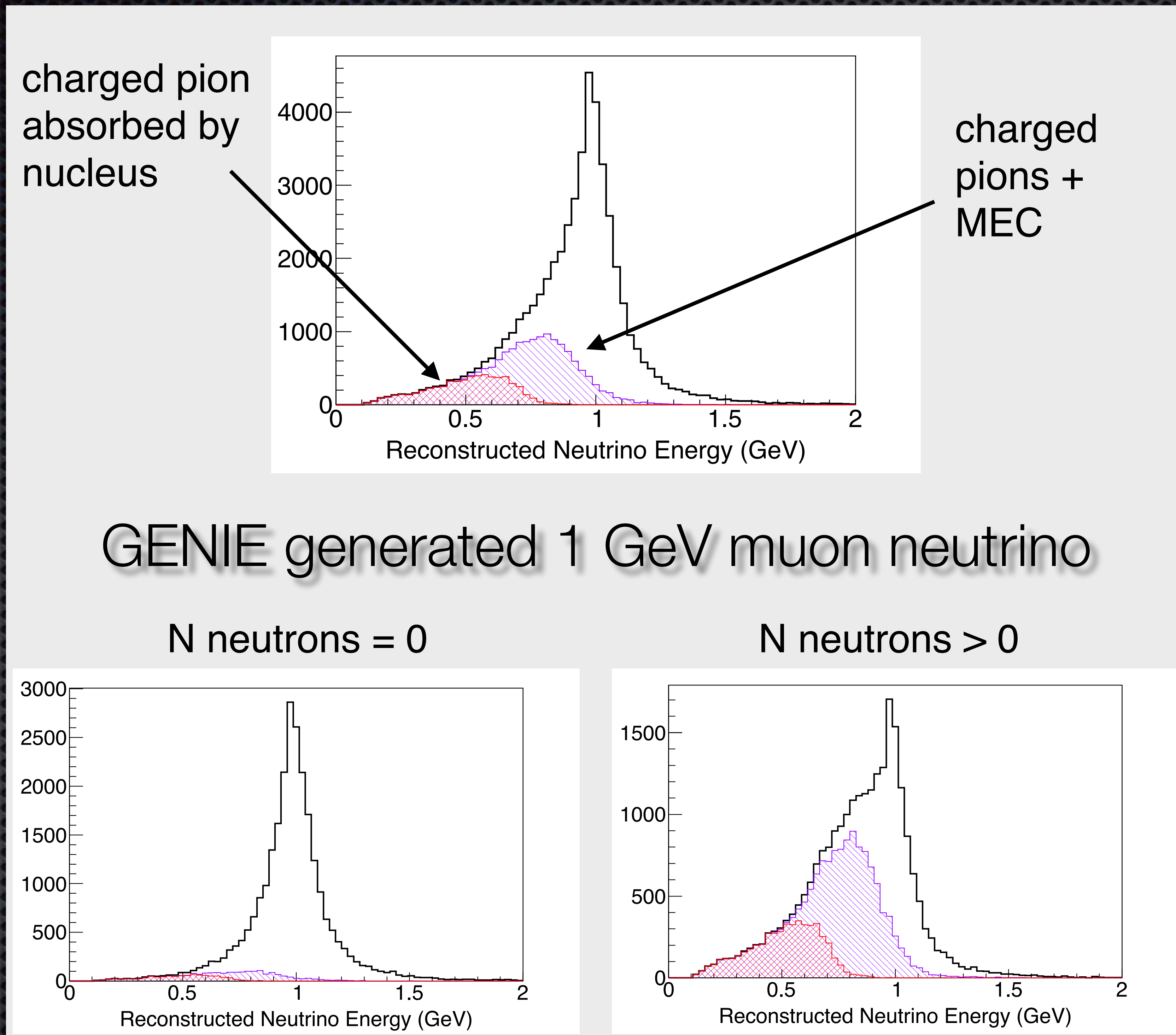


M. Martini - Nufact 2015

ANNIE is a final-state X + Nn measurement that complements X + Np in LAr

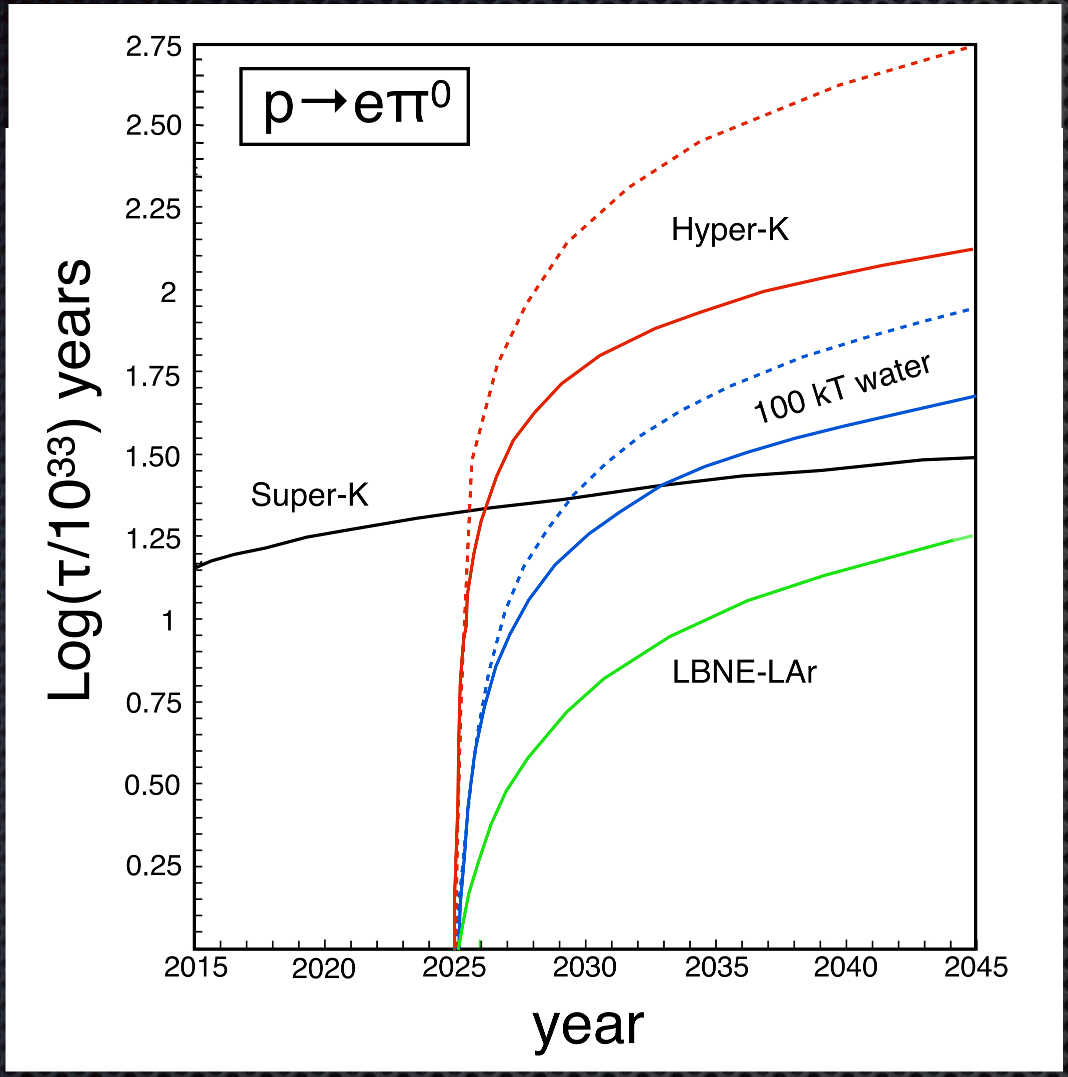
The presence, multiplicity and absence of neutrons is a strong handle for signal-background separation in a number of physics analyses!

Example: Neutrino energy reconstruction



Rejecting events with neutrons may enhance a CCQE sample, improving energy reconstruction

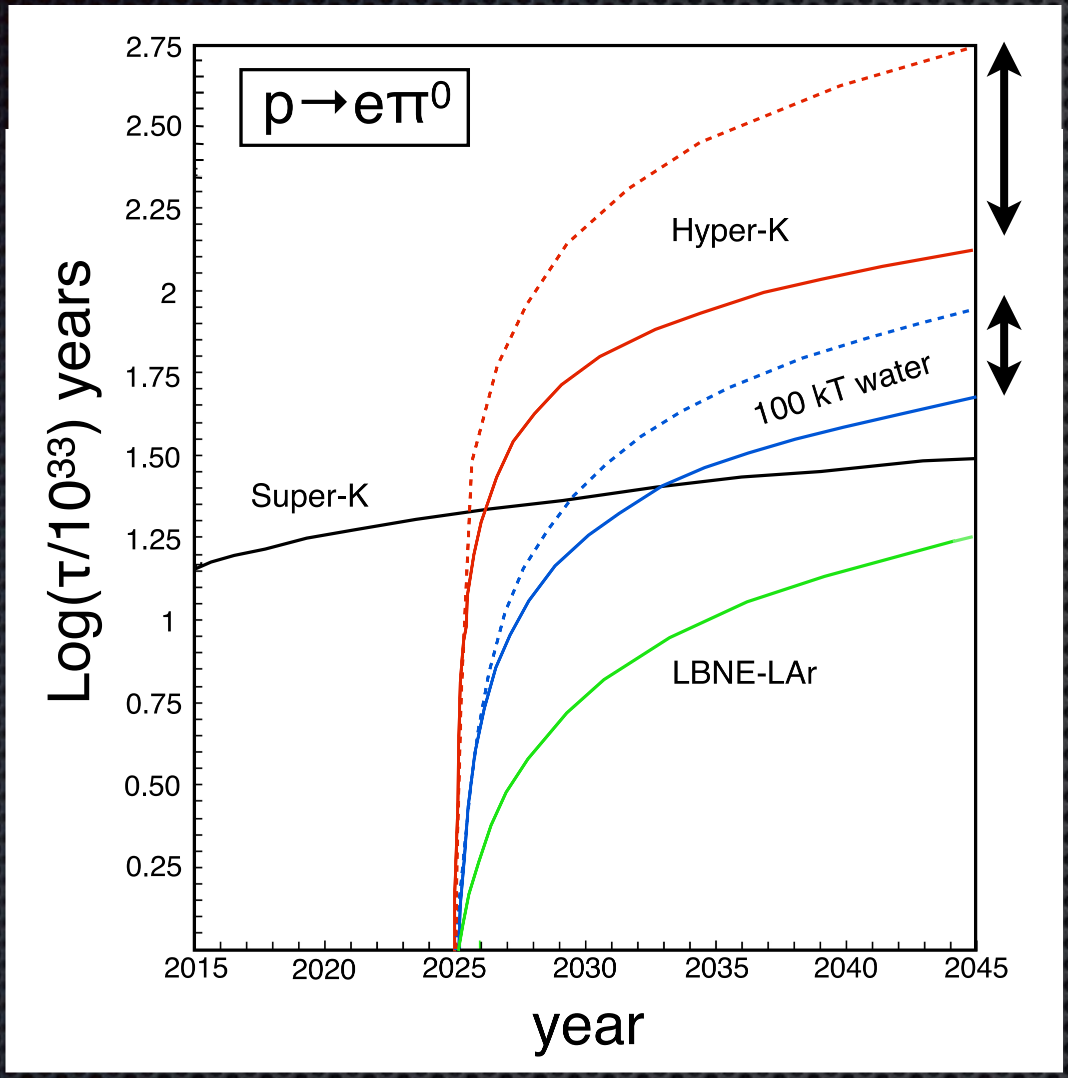
Another example: proton decay



- Next-generation proton decay (PDK) experiments will be background limited (from atmospheric neutrinos)
- It is expected that these backgrounds would produce final-state neutrons, whereas PDKs would not.
- The presence of neutrons detected with Gd-loaded water could be used to reject these (Beacom and Vagins).

Super-K could add Gd to enable improvement.

Another example: proton decay



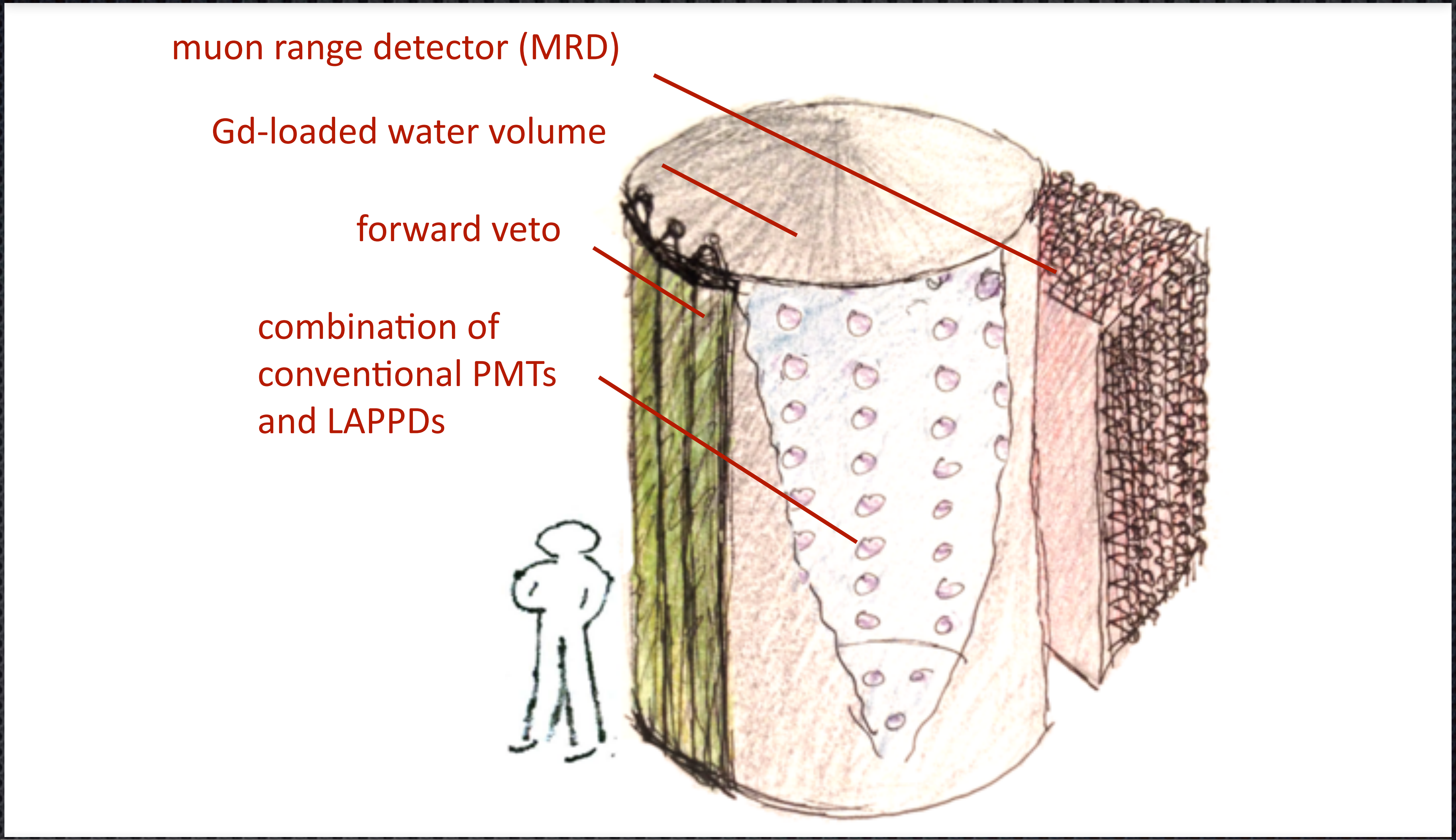
How much background does neutron tagging remove?

Background uncertainties are an even bigger problem if you have candidate events and want to attribute confidence to the measurement.

Super-K could add Gd to enable improvement.

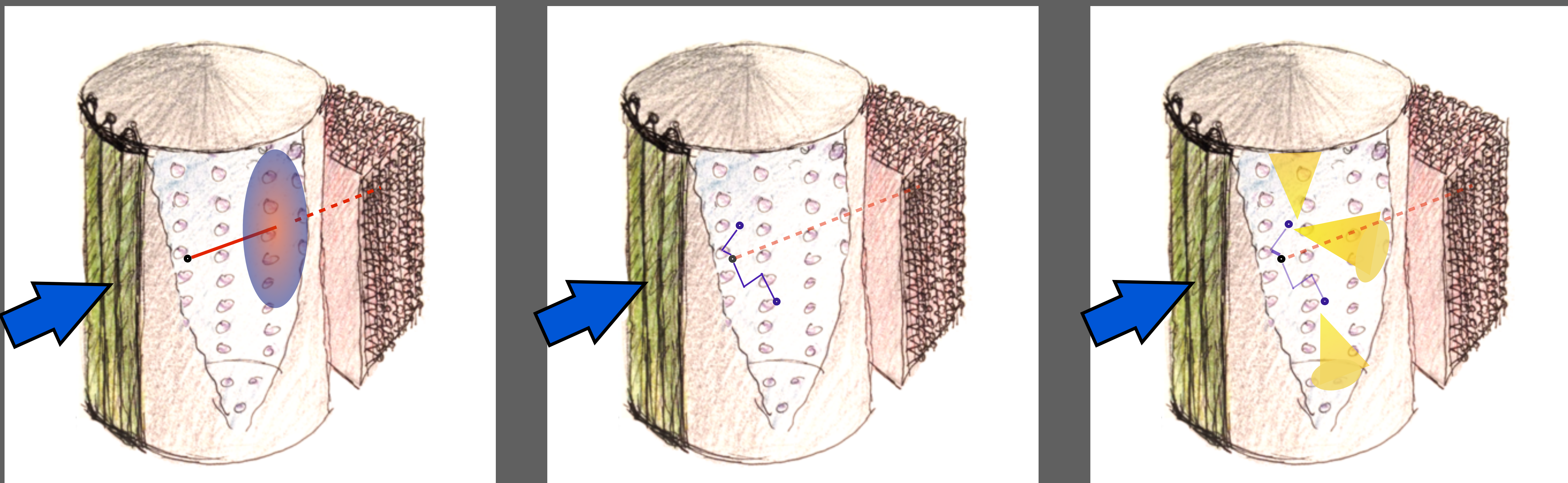
The ANNIE concept

A 30-ton tank filled with Gd-loaded water



The tank diameter is 9 ft and height is 13 ft.

The ANNIE concept



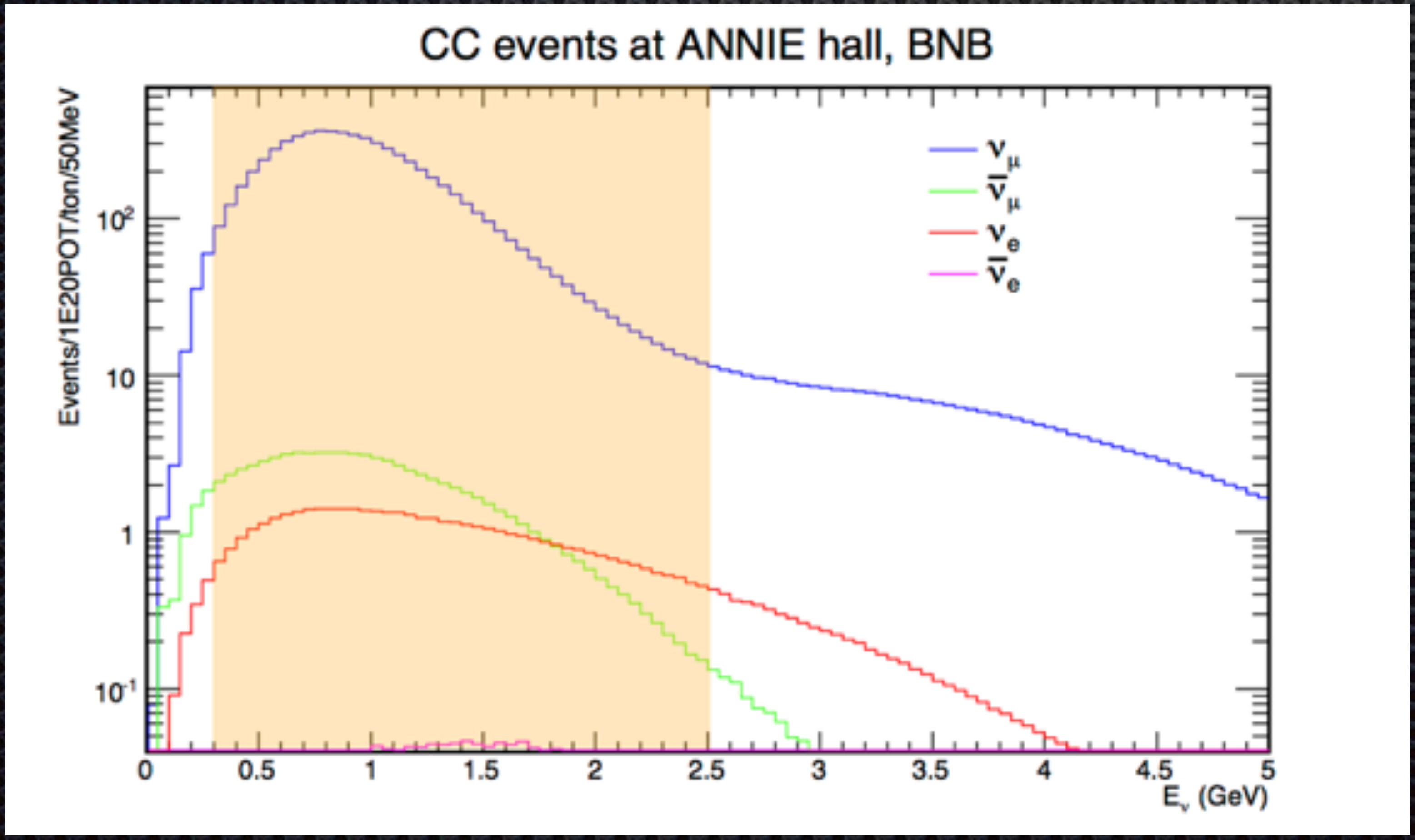
Prompt muon tracks through water volume, ranges in MRD

neutrons from the interaction thermalize and stop in water

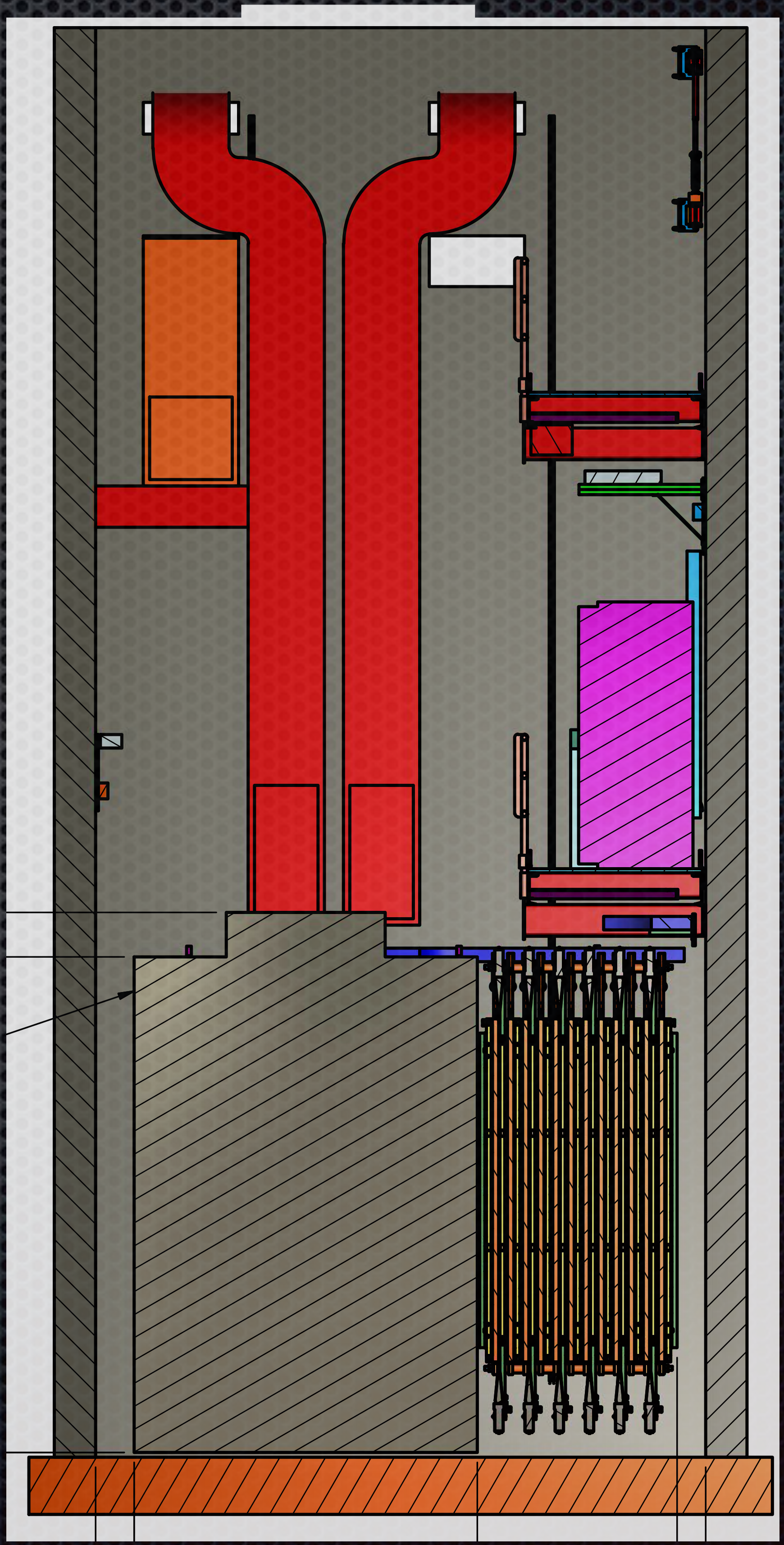
neutrons capture on Gd, flashes of light are detected

ANNIE concept

- Tank to be placed in the SciBooNE hall.
- Use existing Booster Neutrino Beam (BNB) running for MicroBooNE and the short baseline program at Fermilab.



SciBooNE hall section



Phased approach

Sep 2015

- Installation

Oct-Jun 2015

- Phase I: Test experiment:
  measurement of neutron backgrounds
  operate the water volume with PMTs
  ready for testing of limited number of LAPPDs when available

Oct-Jun 2016

- Phase II: First physics run:
  limited, but sufficient LAPPD coverage
  focus on CCQE-like events

Oct-Jun 2017

- Phase III: Second physics run:
  full LAPPD coverage (up to 5%)
  more detailed event reconstruction
  compare neutron yields for CC, NC, and inelastic

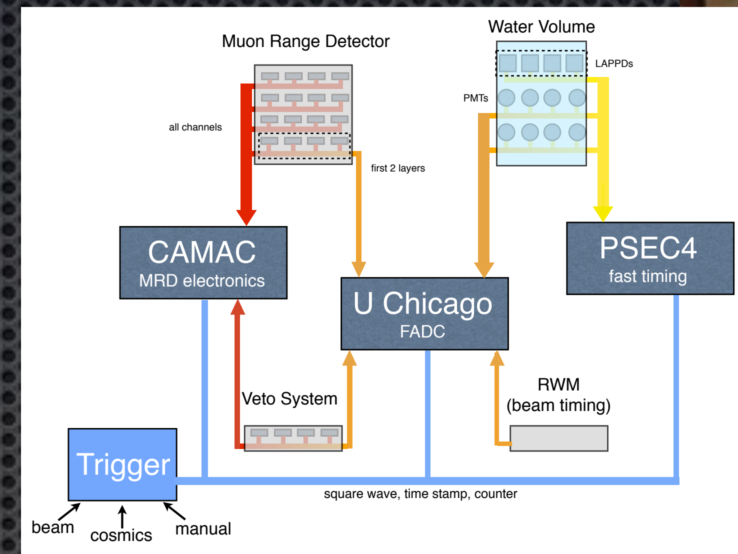
Status of the ANNIE experiment

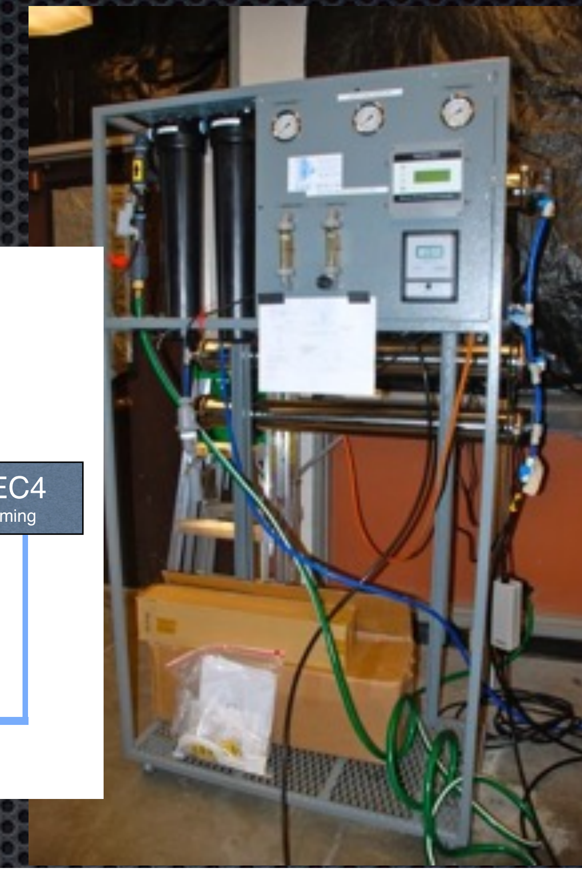
> "The PAC therefore recommends that the ANNIE collaboration be granted stage 1 approval and be supported to proceed with Phase I of their proposed work."

- ANNIE has been approved for Phase I construction by the Fermilab directorate and is on schedule.
- Fermilab and the community have provided significant support.
- A proposal for the Intermediate Neutrino Program FOA is under preparation for Phase II.

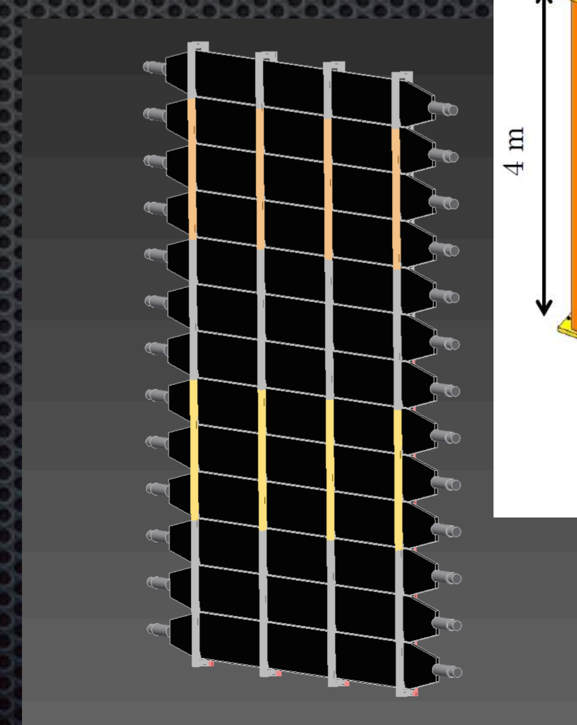
New collaborators are welcome!

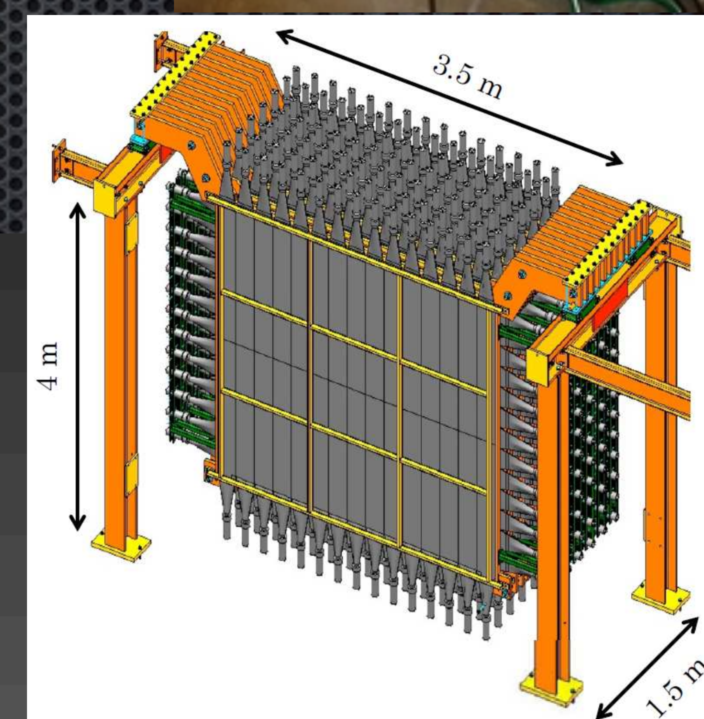
Status of the ANNIE experiment



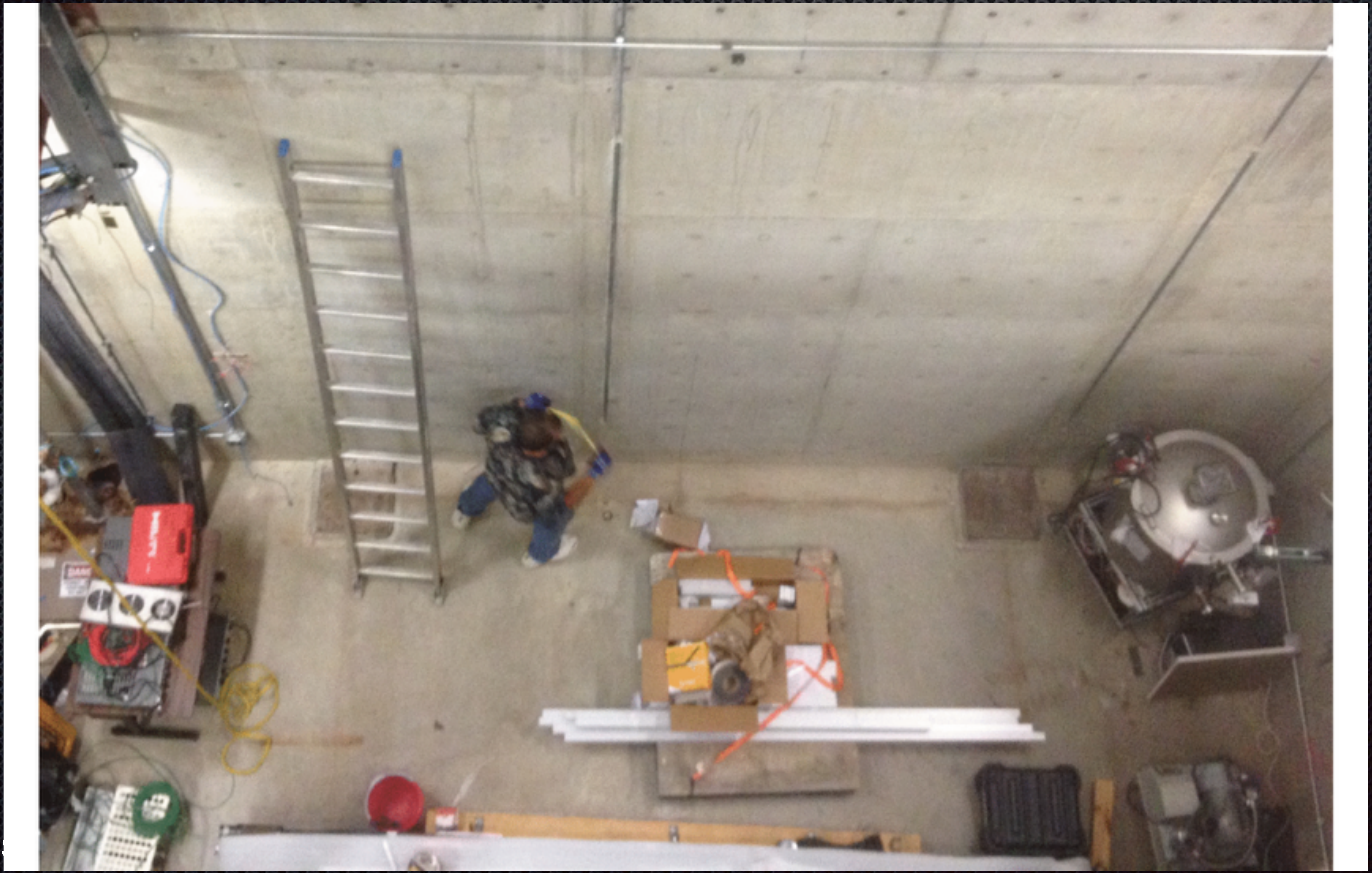


- Work is underway to deploy the water system, recommission the MRD, integrate the electronics, prepare the PMTs, and develop full simulations and reconstruction.
- **The forward veto has been completed!**
- The tank is purchased and is to be delivered around Sept 1.
- Work on the inner volume is planned to occur over September.
- Water filling and commissioning is to begin in early October
- Aim to be data-ready when the Booster Neutrino Beam (BNB) turns back on, mid-October.





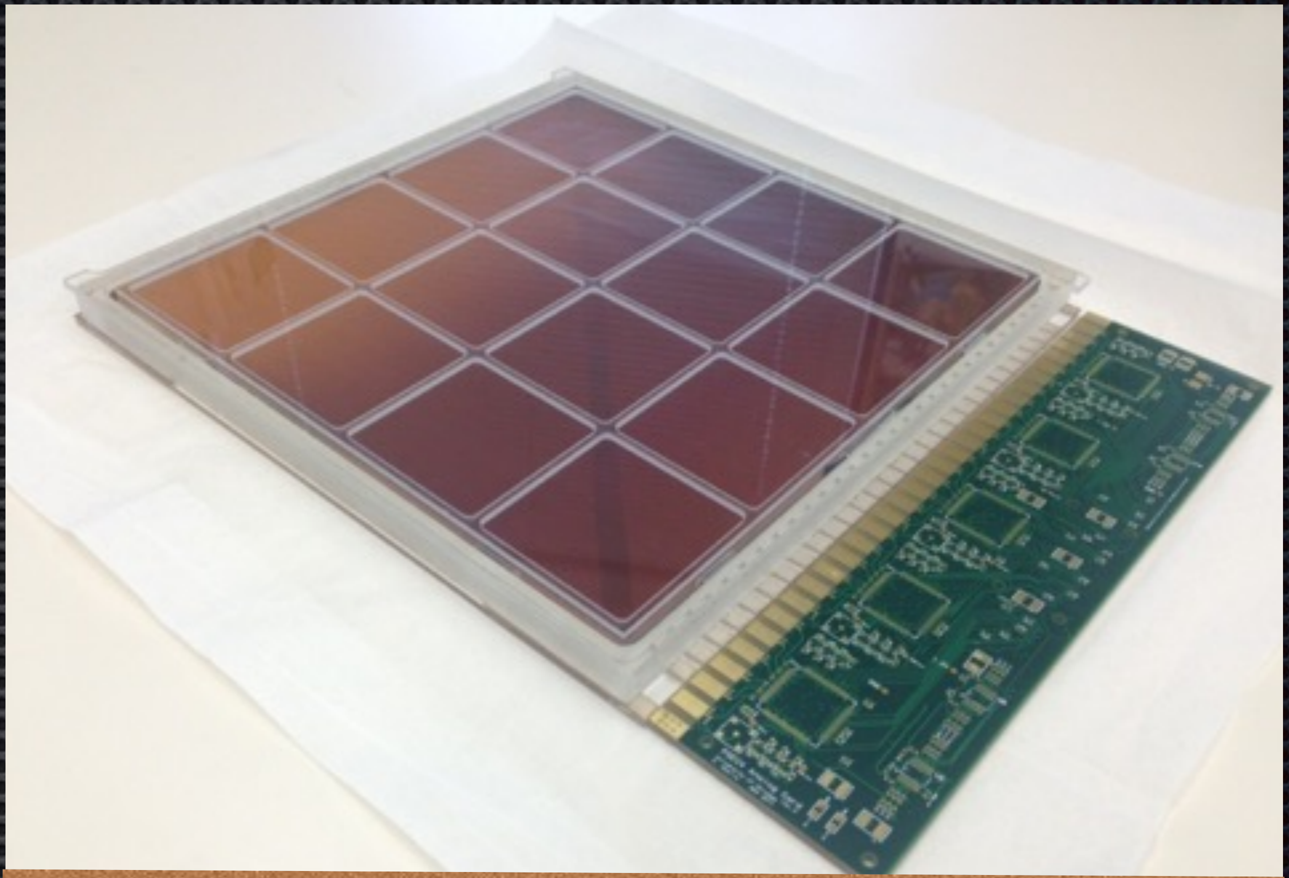
Status of the ANNIE experiment



Status of the ANNIE experiment

Using LAPPDs for ANNIE

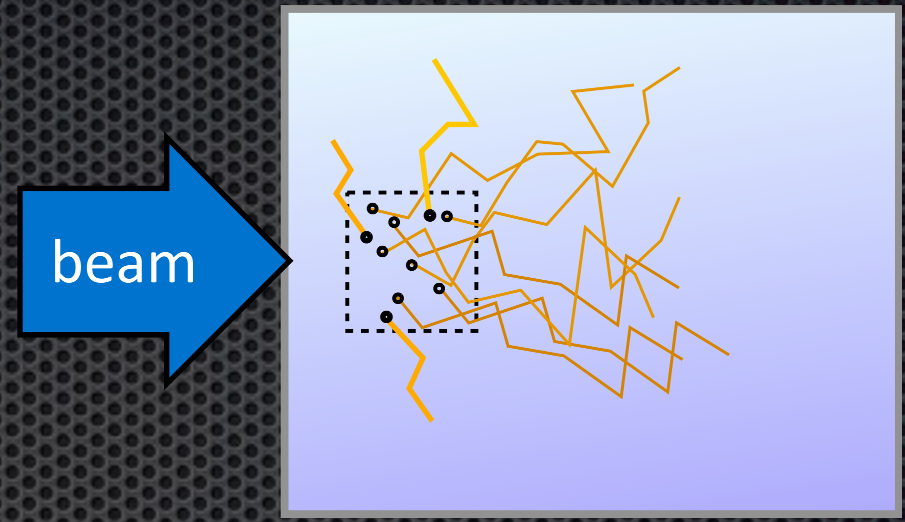
- **Large-area picosecond photodetectors (LAPPD)** based on microchannel plates are being developed by collaboration of US universities, labs and private companies.
- Microchannel technology makes electron path very small.
- For a **neutrino application**, the characteristics of these can be tuned to:
  - Timing resolution of **~100 psec**
  - Spatial resolution of **~1cm**

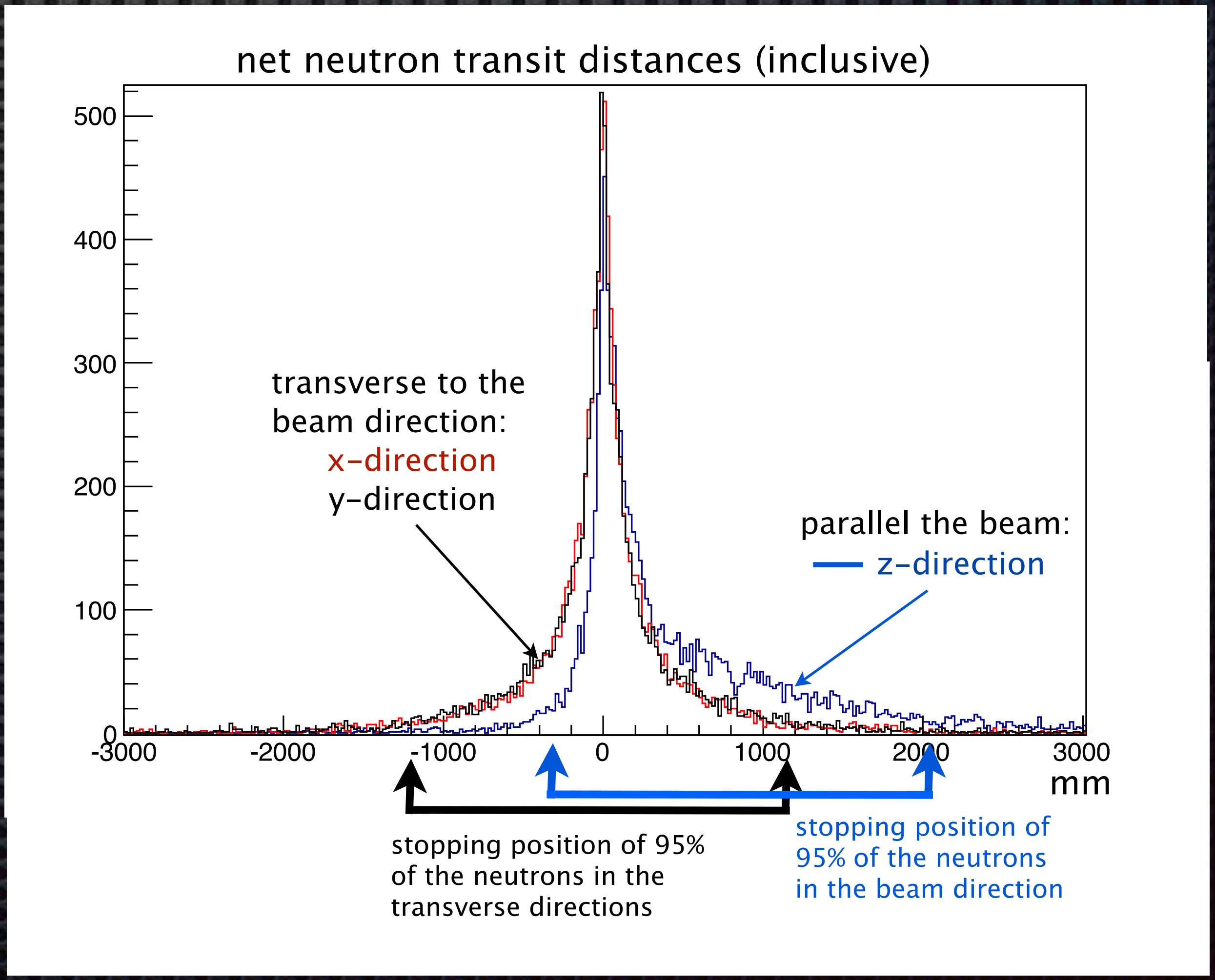


- A pilot production line is being built at Incom Inc as part of a 3 year technology transfer program.
- On track for first prototypes in 2016.

Using LAPPDs for ANNIE

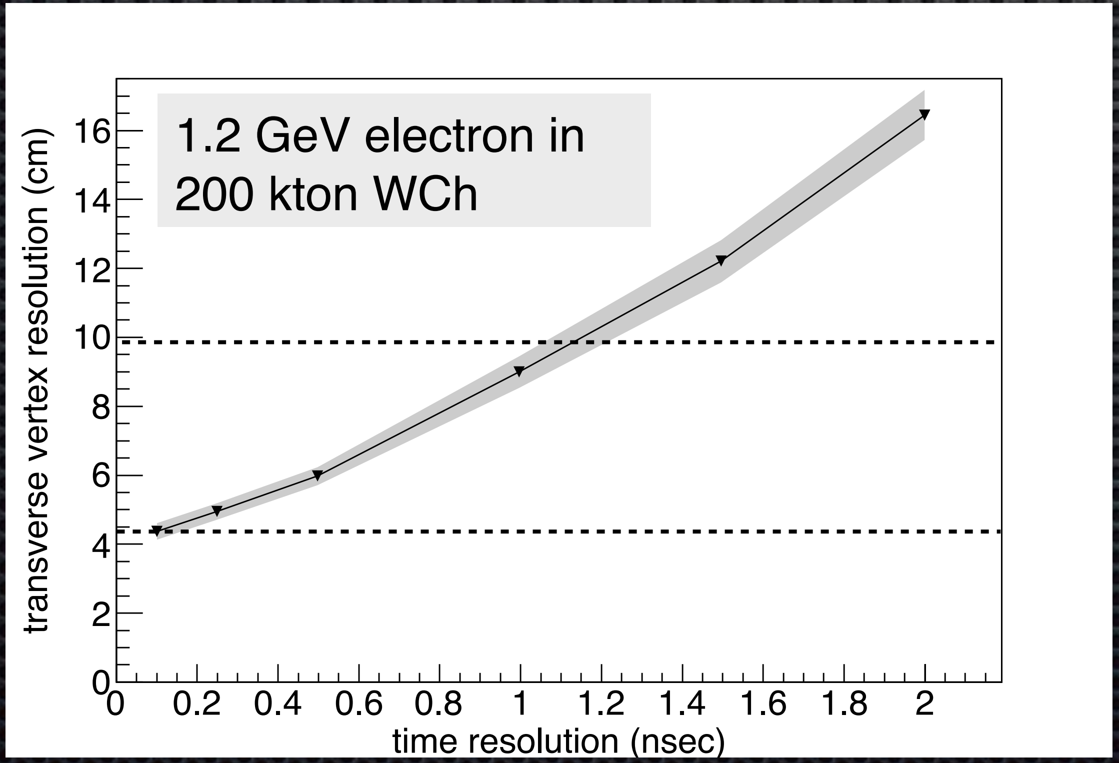
- Interactions must be sufficiently far from the walls of the detector, so that neutrons do not escape.
- The interaction point must be known to define this small fiducial volume (dashed square). LAPPDs provide excellent position and time resolution.
- The majority of neutrons stop within ± 1 m of their starting point in the directions transverse to the beam.
- They fall in a ~ 2m forward region from their starting position in the beam direction.

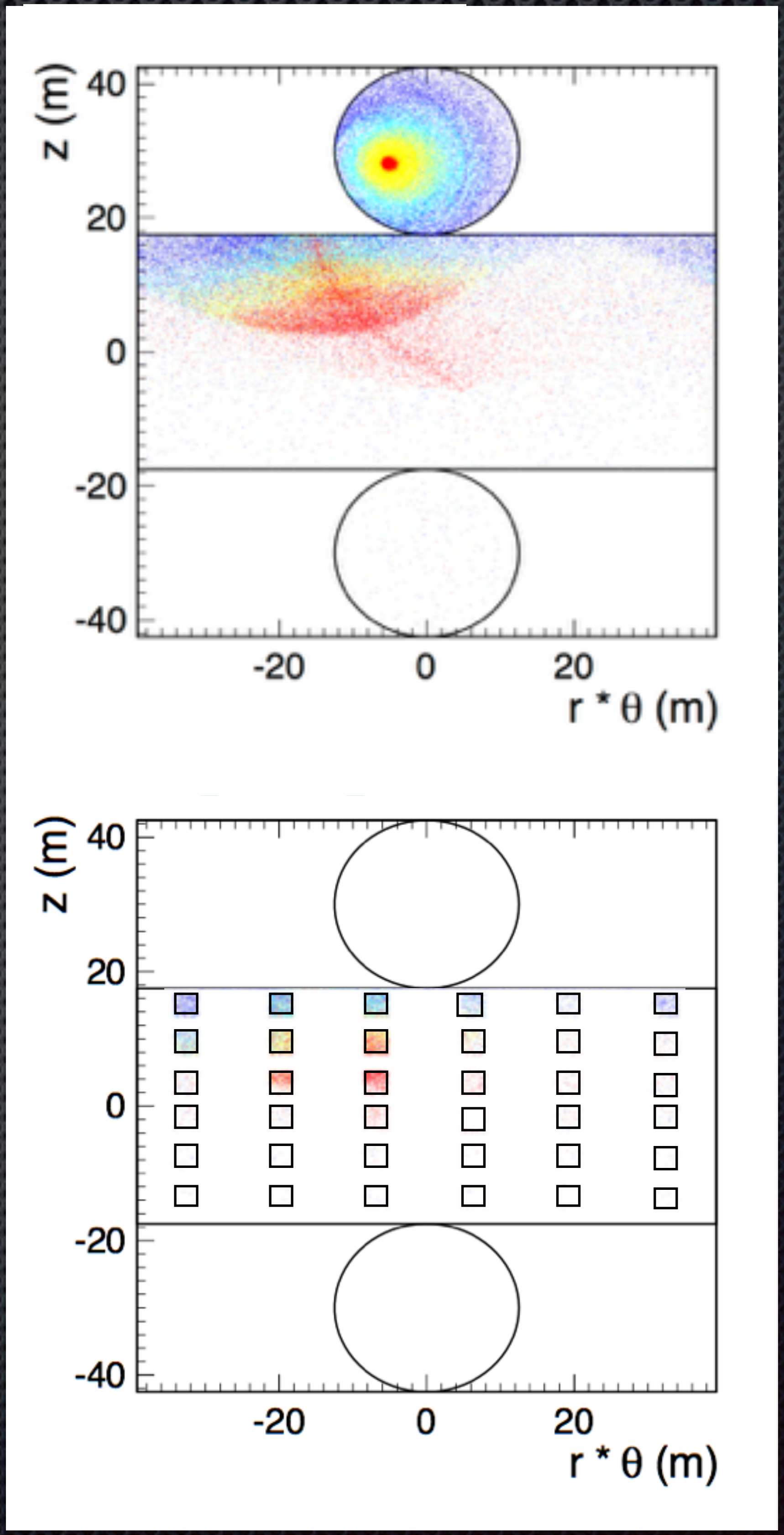




Using LAPPDs for ANNIE

- Fine granularity can help resolve the cone edges even under limited photosensor coverage.
- Need to separate between 1 track vs multi track events.
- Fast timing allows for high vertex resolution even in large detectors.

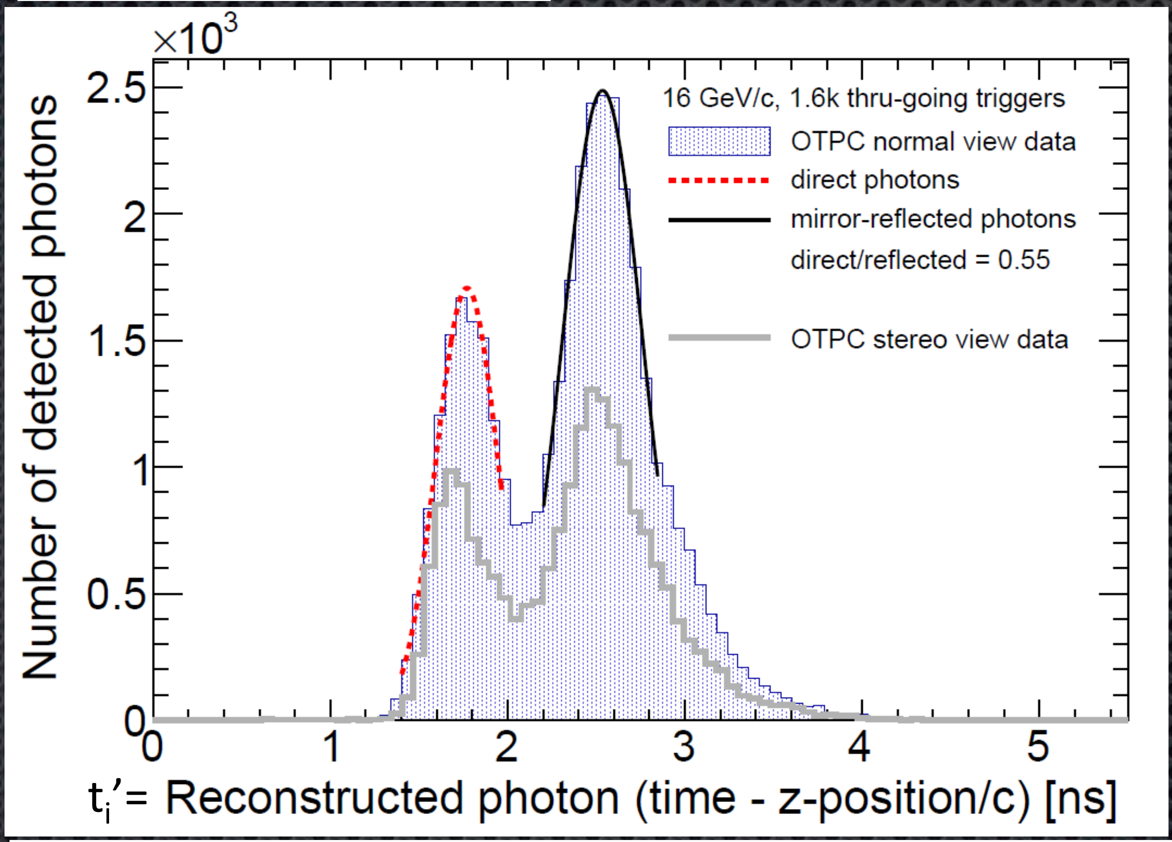


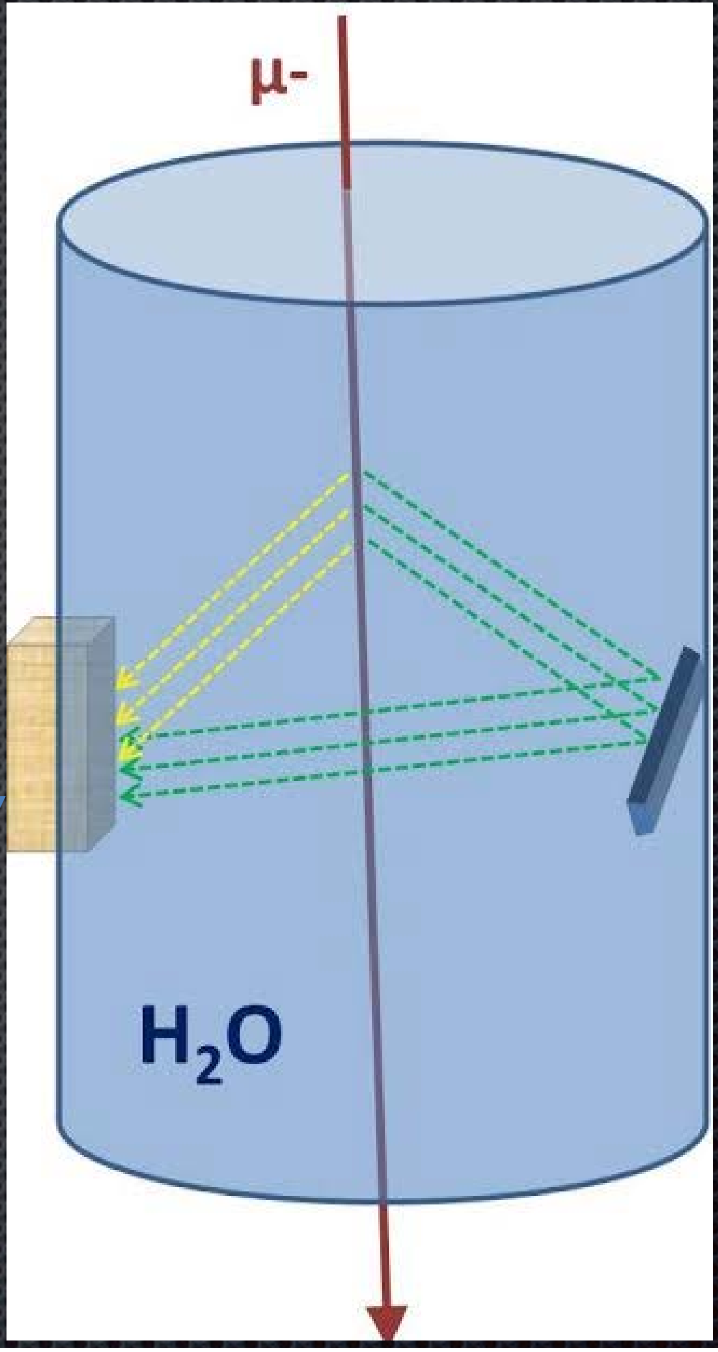


Optical TPC proof of concept

The detector is constructed from a 24 cm inner-diameter PVC cylndrical pipe cut to a length of 77 cm

- Photodetector modules (PM) are mounted on 2 columns along the longitudinal axis with an azimuthal separation of 65 degrees ('normal' and 'stereo' view)
- For each PM, an optical mirror is mounted on the opposing wall, facing the PM port
- Remaining exposed PVC surfaces painted black
- Detector volume is 40 L of water



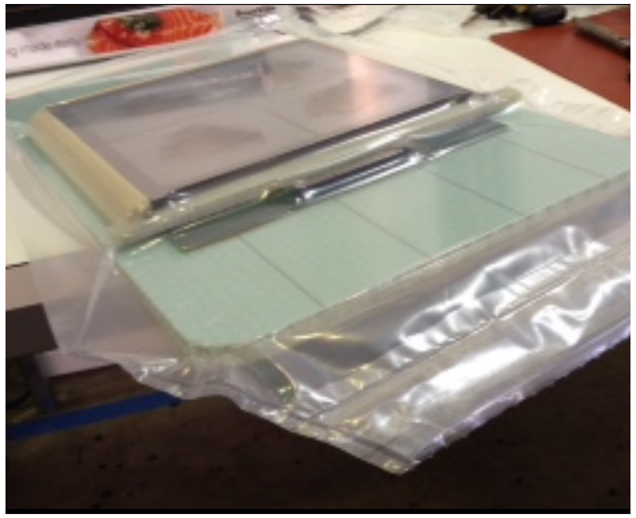


By time and space resolving, we measure an angular resolution of a few degrees (50 mrad) and a spatial resolution on particle tracks of 15 mm

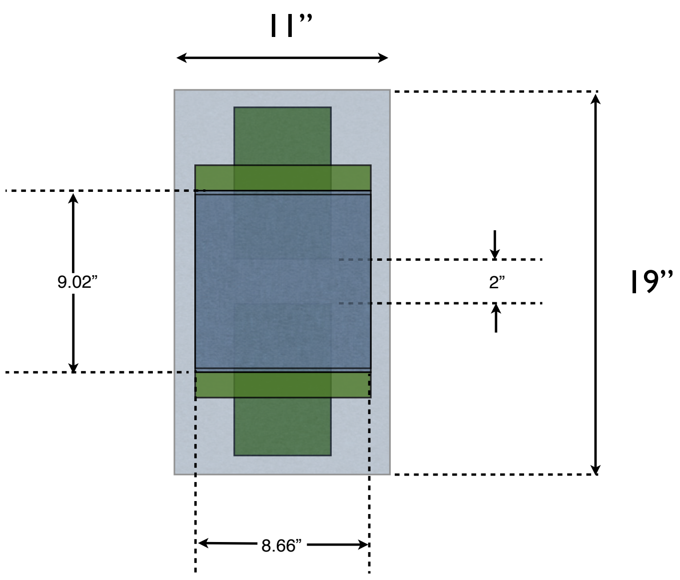
E. Oberla - UChicago Ph.D. Thesis - 2015

LAPPD R&D for ANNIE and beyond

- ANNIE not only benefits from the capabilities of LAPPDs, but it will carry out R&D to enable these to be used in future detectors.
- Operation in water (or other liquid environments) is a key step for ANNIE and potential future liquid-based experiments.
- UChicago is pursuing several paths for the WATCHMAN effort:
  - Vacuum sealing LAPPD assemblies in a plastic envelope (“Sous Vide”).
  - Commercially available water-tight casing.

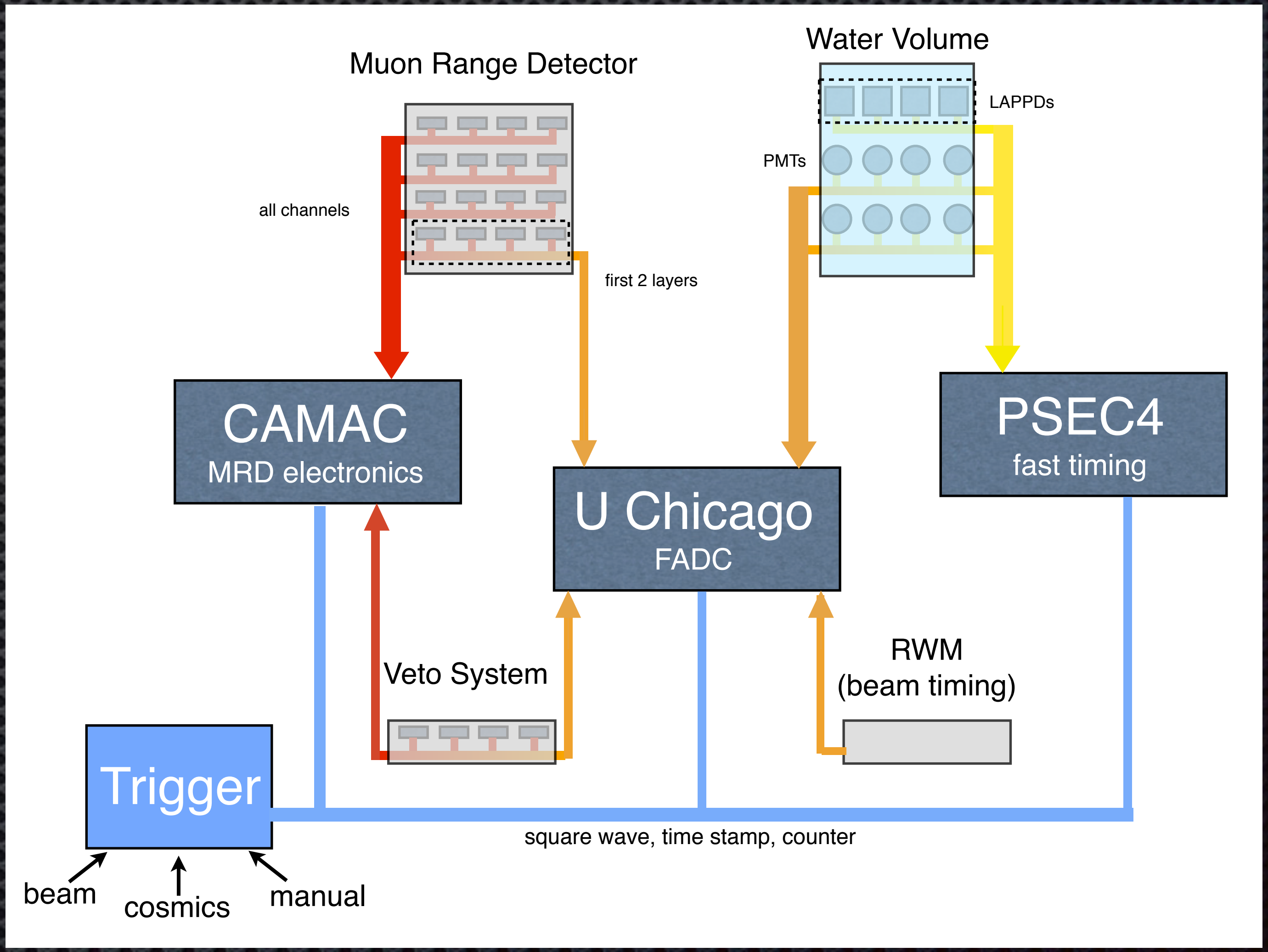


credit: Brooke Adams



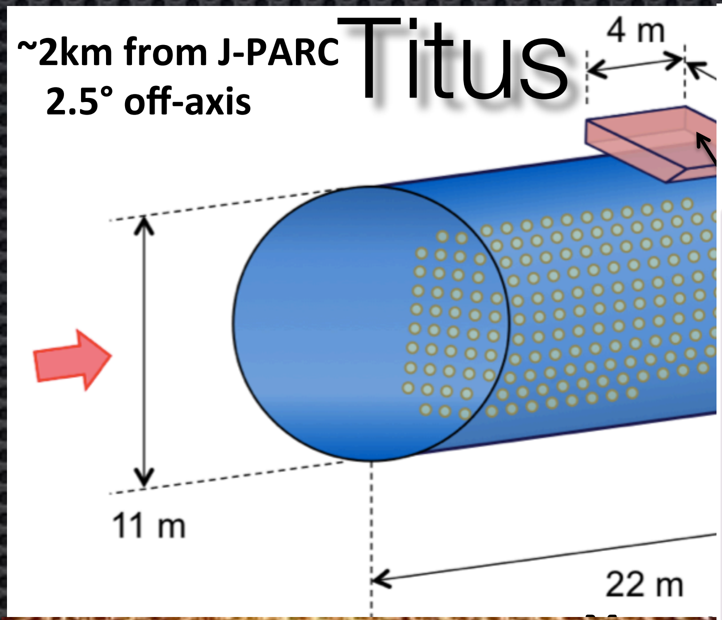
LAPPD R&D for ANNIE and beyond

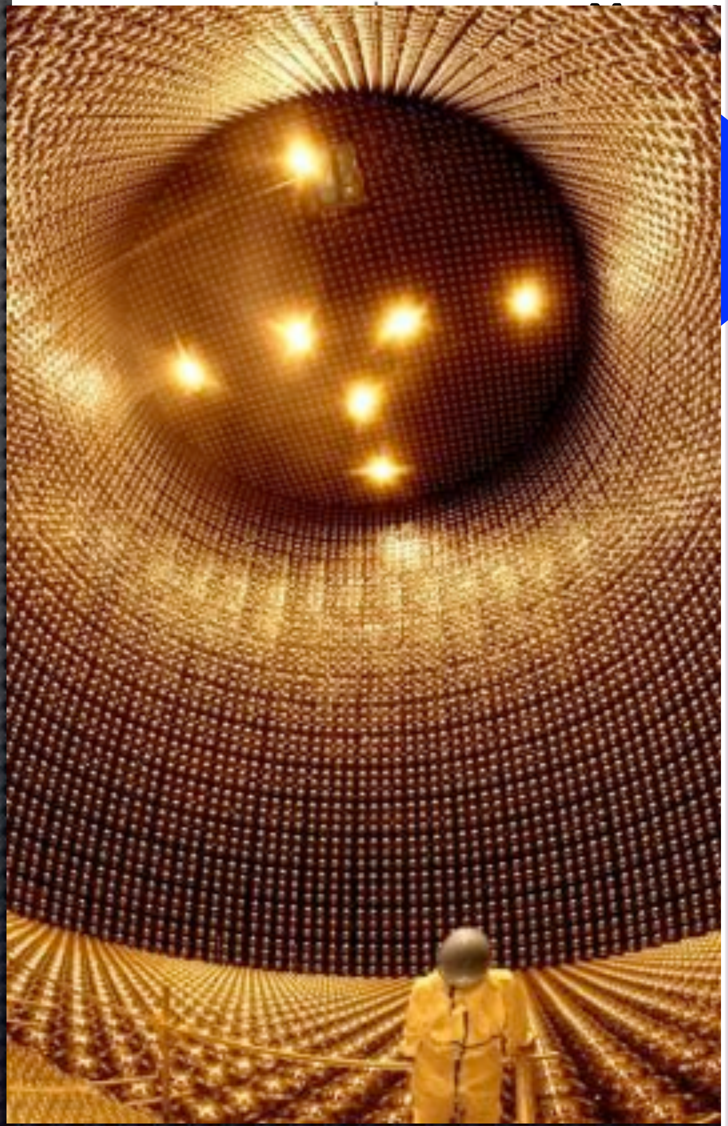
- A working 240 channel DAQ system with self-triggering already exists, thanks to the U Chicago optical TPC (E. Oberla, H. Frisch, M. Bogdan).
- The next step is to generalize to higher channel counts and integrate LAPPDs with more complicated detector systems.
- The ANNIE electronics group (ISU, UChicago, Queen Mary) is developing a dual readout system for digitizing both the conventional PMTs and LAPPDs.

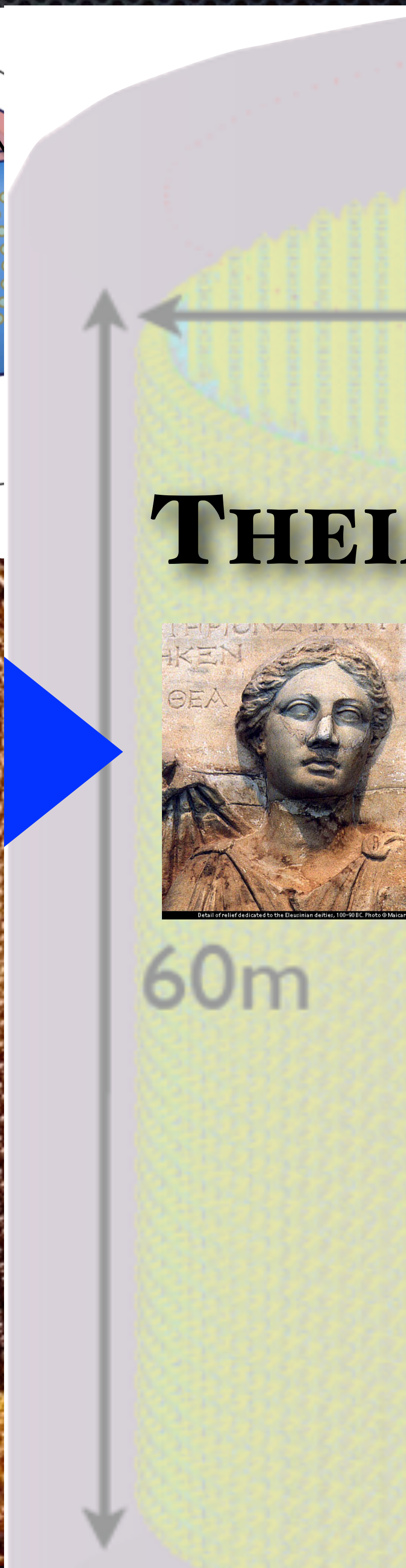


ANNIE and then…

- ANNIE is ideal as a first test for the application LAPPDs as it is small enough that is feasible with the expected initial limited availability.
    - It enables a promising technology for neutrino detection.
- A 30-ton detector using Gd-enhanced water for neutron capture. It is an interesting application of this technique.
    - Potentially of interest to Super-K if adding Gd.
    - Collaborators are developing the TITUS concept as a ND to Hyper-K (see A. Minamino's talk).
- It is a critical first step for efforts to develop an advanced water-based liquid scintillator detector concept: Theia (see G. Orebi-Gann's talk).







Conclusions

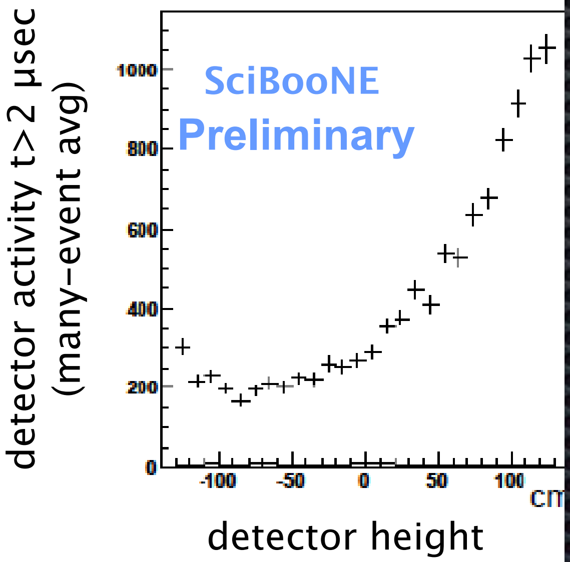
- A detailed understanding neutrino nucleus interactions is necessary to meet the demands of future precision neutrino measurements.
- Experiments are planned to measure final states w/ X + Np. ANNIE is set to contribute to the X + Nn measurements.
- ANNIE will also provide a demonstration of techniques that open the path for future liquid-based precision detectors both large and small.

Backup

ANNIE phase I

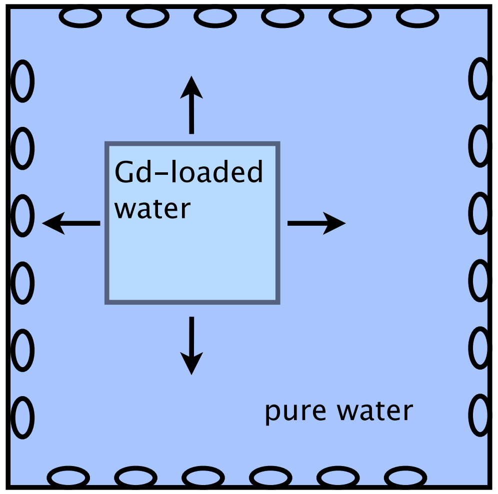
ANNIE will see neutron backgrounds from 2 sources:

- **skyshine:** neutrons from the beam dump migrating into the Hall from above
- **dirt neutrons:** neutrons produced by neutrino interactions in the rock, upstream of the detector



We need to understand these backgrounds before we determine the final configuration of ANNIE.

With a Phase I detector, we can test the first LAPPDs submerged in water, as they become available.

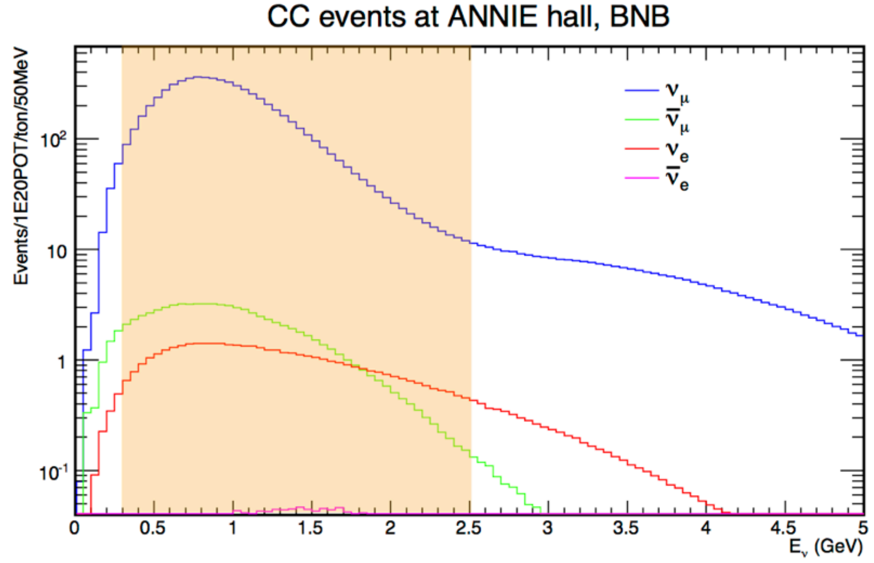


Requires input and coordination with Fermilab.

Beam rates and requirements

We need 3 things in a beam:

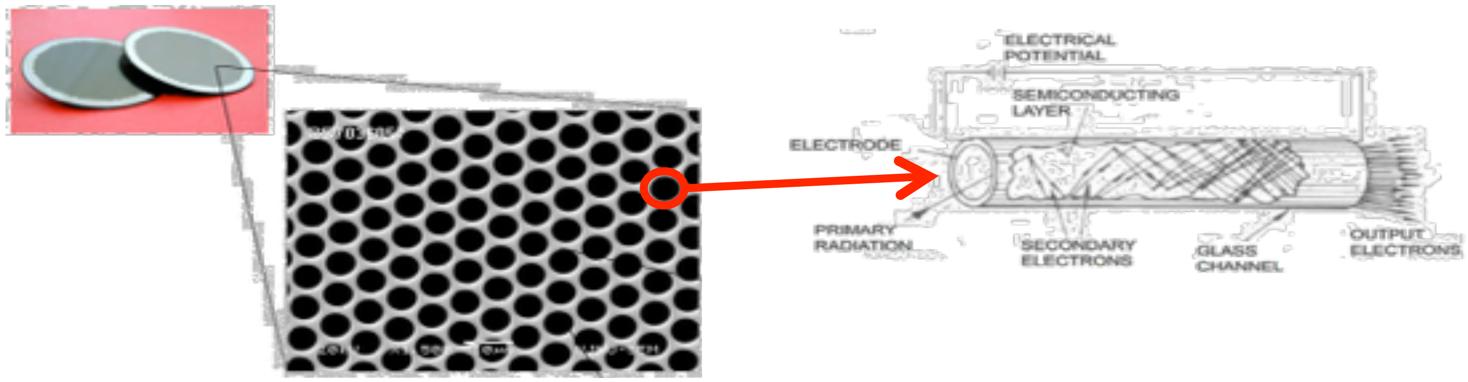
- Energy peaked in the range of the proton mass/atmospheric neutrino flux (1-2.5 GeV)
- Statistics
- Low pileup rate



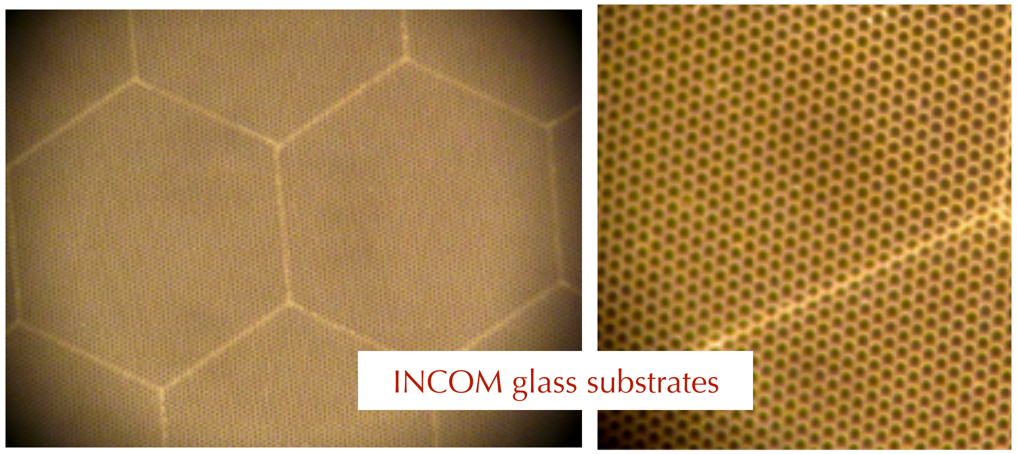
Location	ν_μ CC [0.25-2.5 GeV]	ν_μ CC [0-10 GeV]	Percentage
SciBooNE Hall	6626	6991	95%
SciBooNE surface	708	847	84%
MINOS ND	3362	168078	2%
NOvA ND	8115	12074	67%
NDOS	76	91	84%

events/ton/10^{20} POT

Key innovation: large micro-channel plates



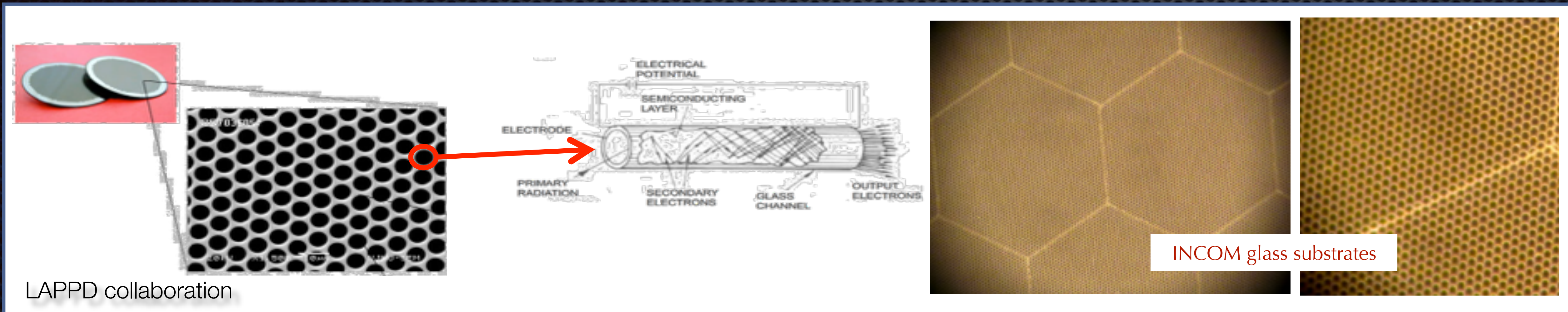
LAPPD collaboration



- Conventional MCP Fabrication:
  - Pore structure formed by 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.
- Approach for LAPPD:
  - Separate out the three functions: resistive, emissive and conductive coatings.
  - Handpick materials to optimize performance.
  - Use Atomic Layer Deposition (ALD), a cheap industrial batch method.

Approach demonstrated for 8-inch tiles

Key innovation: large micro-channel plates



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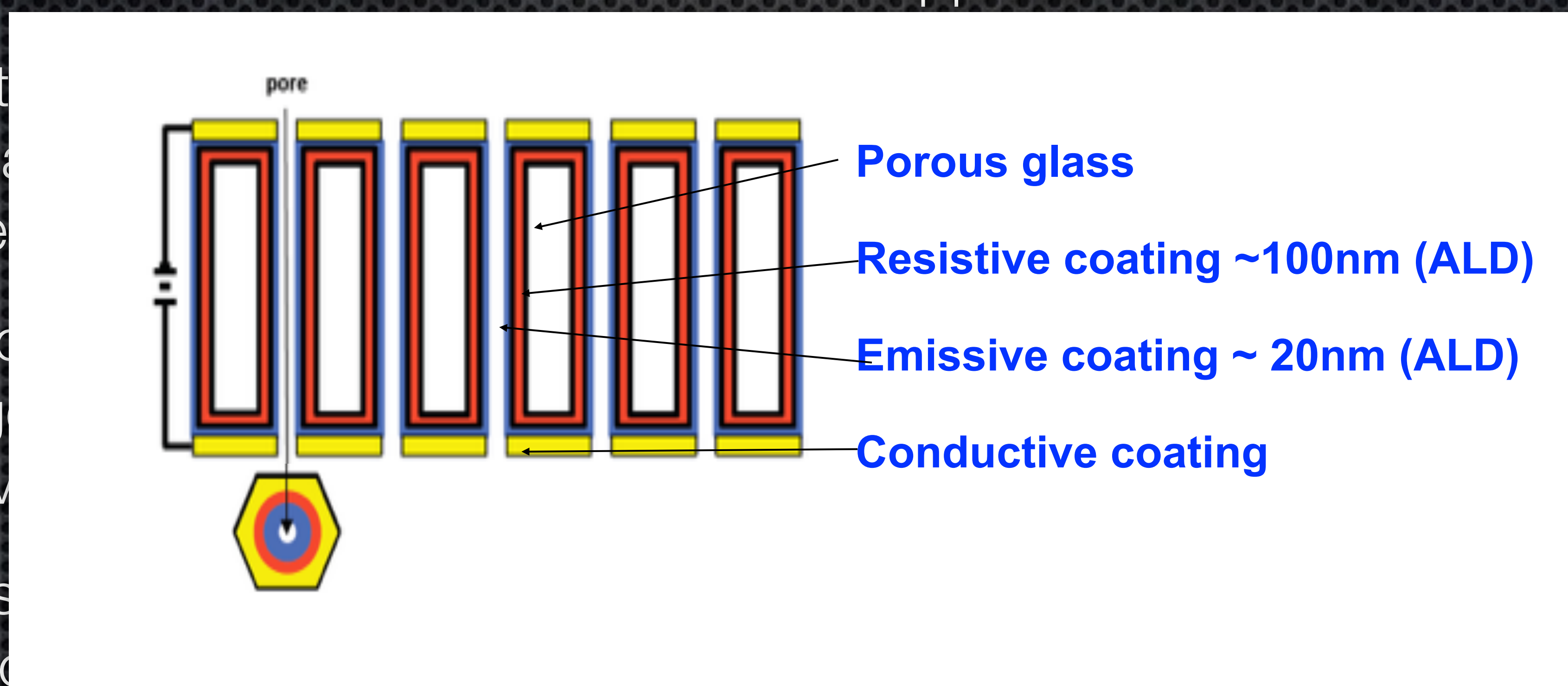
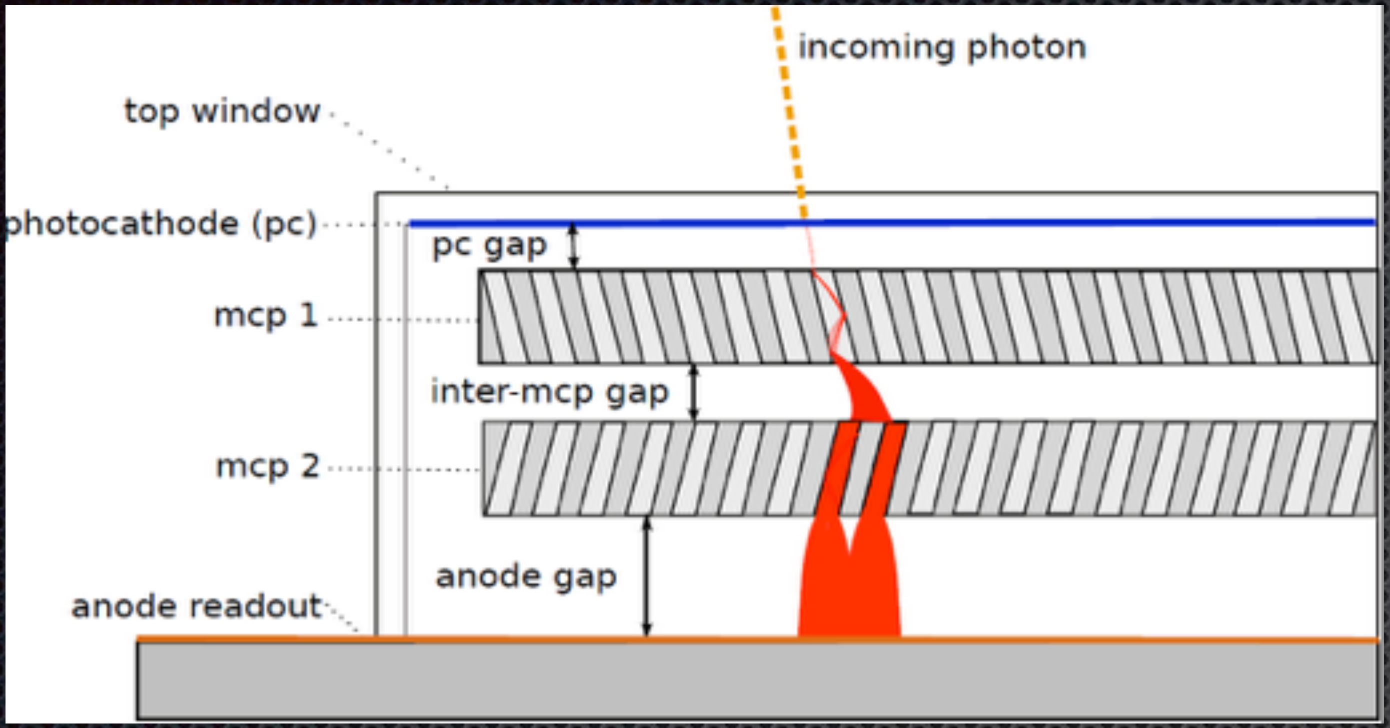
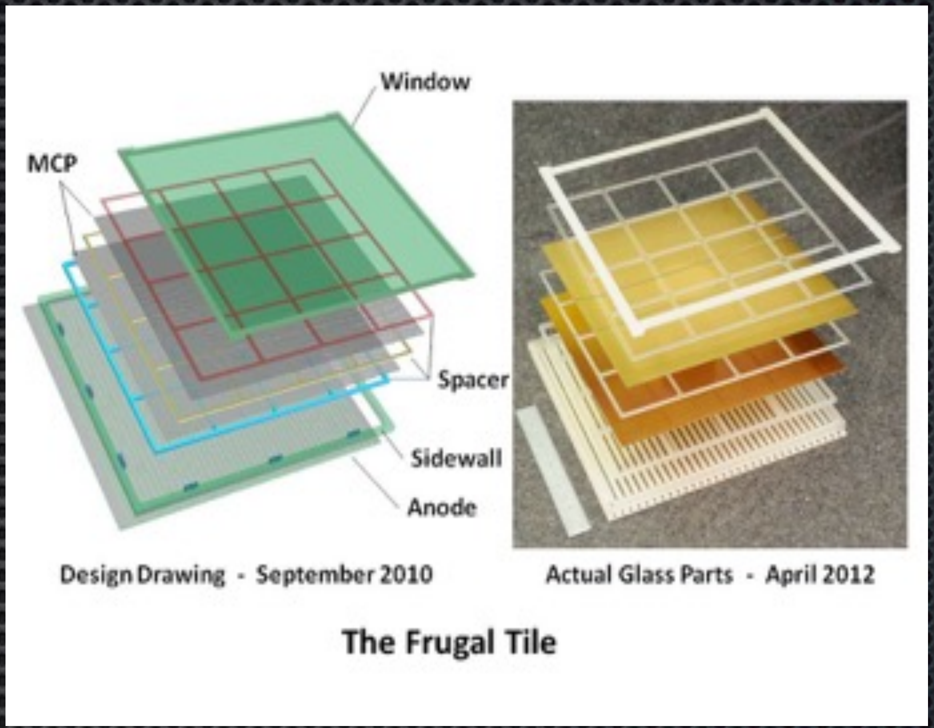


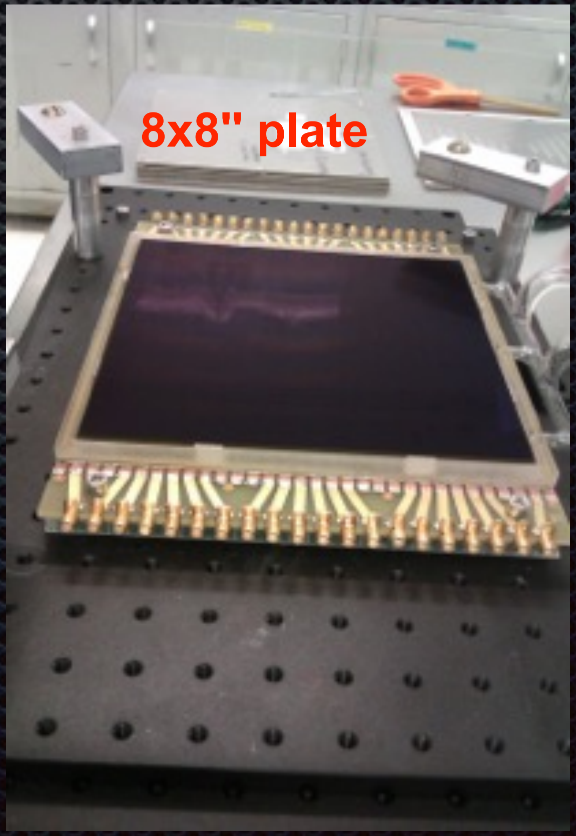
Approach demonstrated for 8-inch tiles

The 8-inch LAPPD glass tile





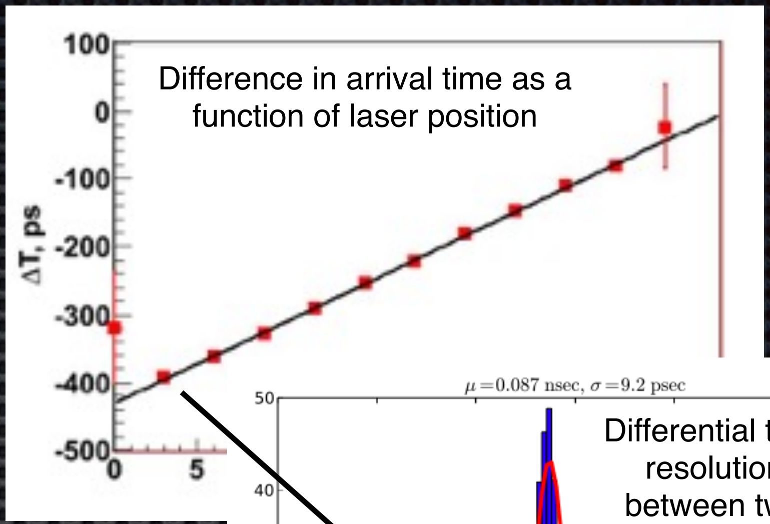
- Cheap, widely available float glass
- Anode is made by silk-screening
- Flat panel
- No pins, single HV cable
- Modular design
- Designed for fast timing
- Alternative more traditional ceramic packaging developed at Berkeley/SSL.

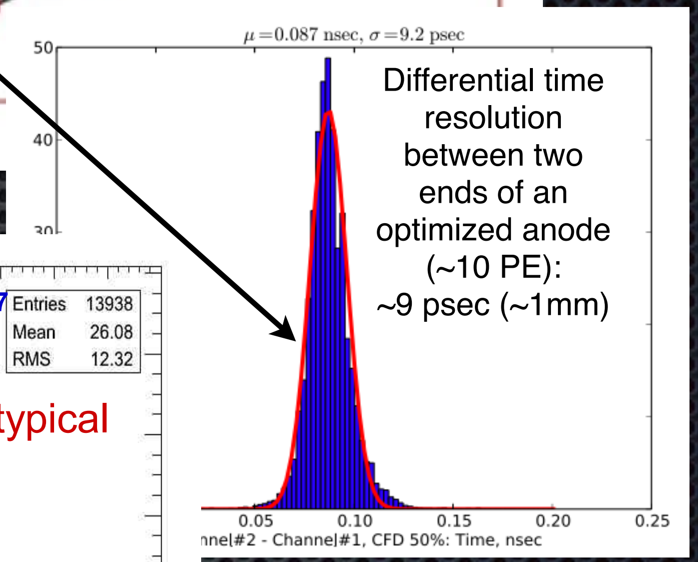


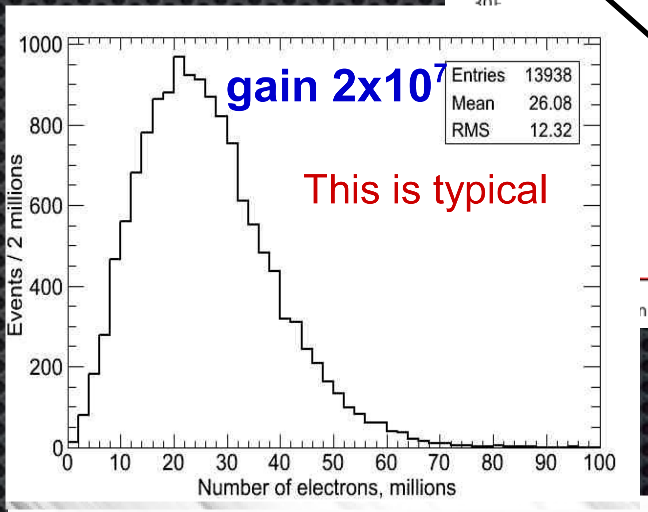
Packaging is to some extent application specific

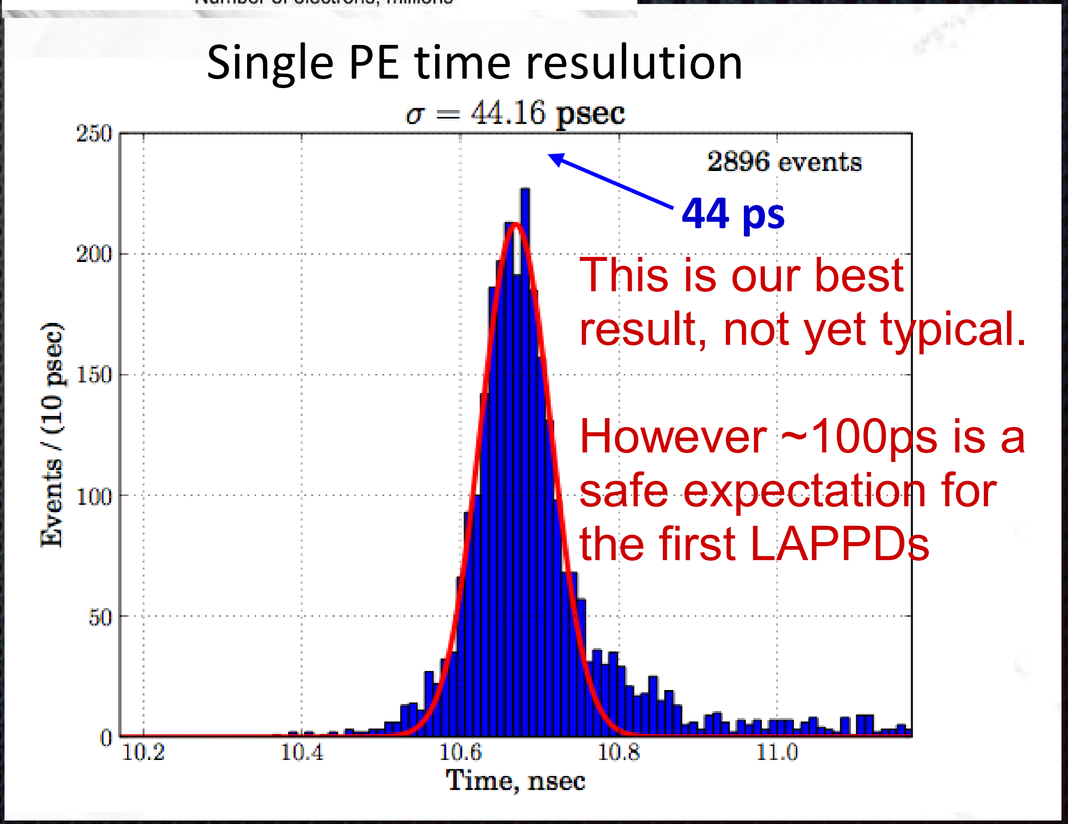
LAPPD Status

- Testing 8” x 8” (20 x 20 cm) MCPs:
  - Typical pulse height peaked at **2 x 10^{7} gain**.
  - Differential time resolution between two ends of delay-line anode <10 psec.
  - **2 mm spatial resolution** parallel to the strip direction, <1 mm in transverse.
  - Best single PE **time resolution ~44 psec**. Order of 100 psec is safe expectation for first generation.
  - Tests of gain stability and uniformity also done. Demonstrating little burn is required to achieve stable gains.





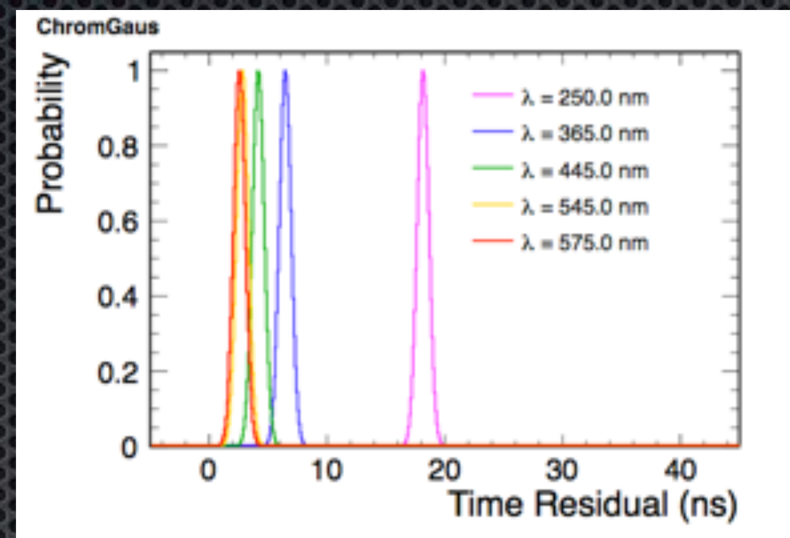




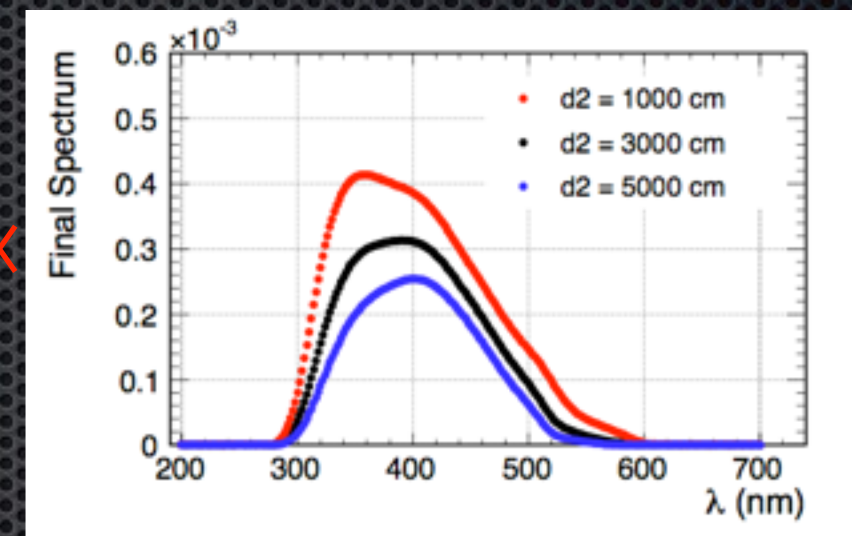
More on status in backup

Using Time Residuals

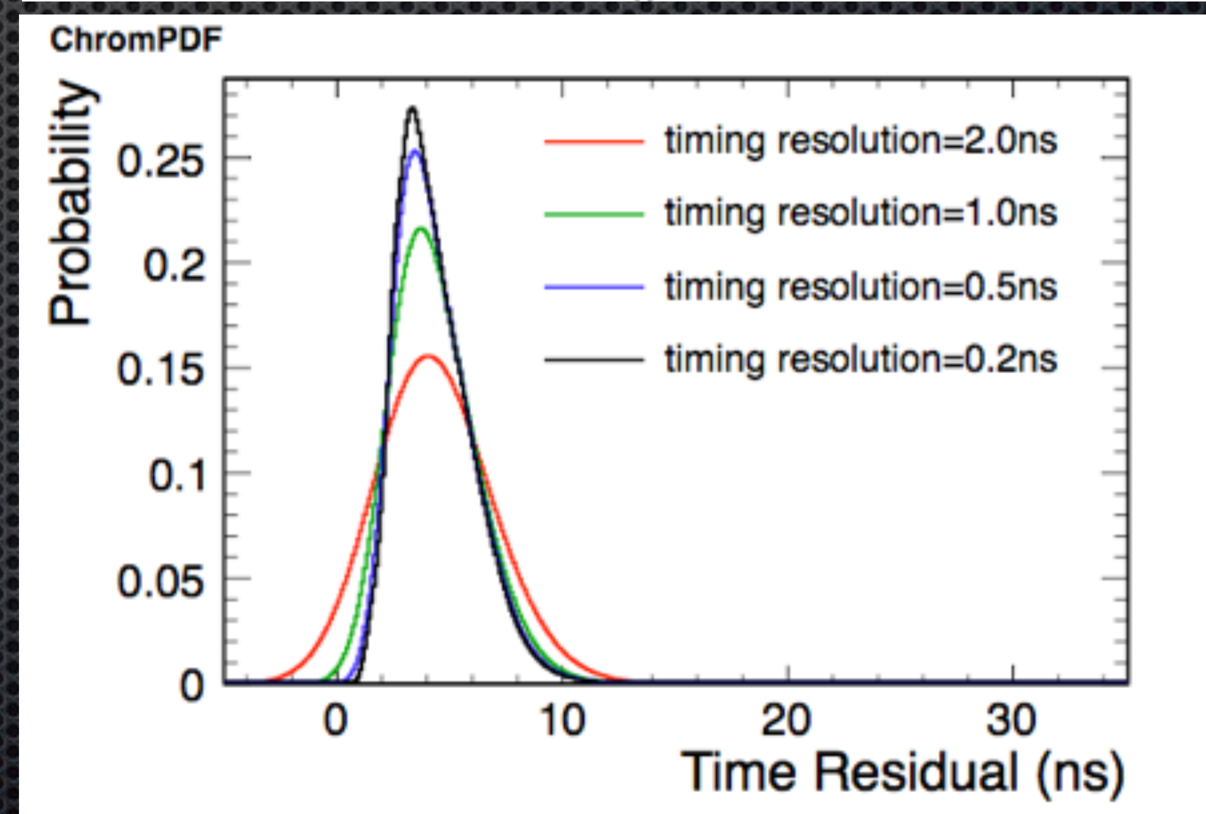
- We build a timing residual-based fit assuming an extended track.
- The model accounts for effects of chromatic dispersion and scattering.
  - Separately fit each photon hit with each color hypothesis, weighted by the relative probability of that color.
- For LAPPDs, we fit each photon rather than fitting integrated charge for each PMT.



X



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

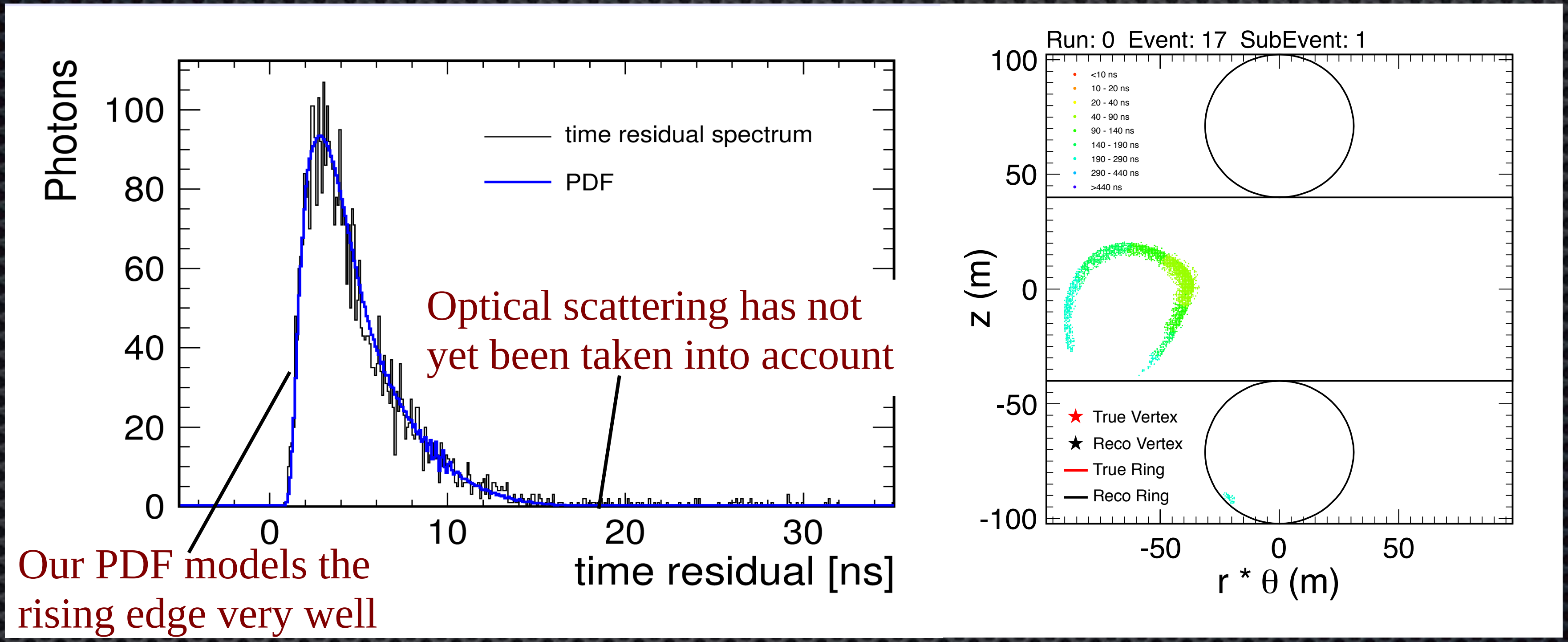


T. Xin, I. Anghel, M. Sanchez, M. Wetstein

Using Time Residuals

- 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.

T. Xin, I. Anghel, M. Sanchez, M. Wetstein

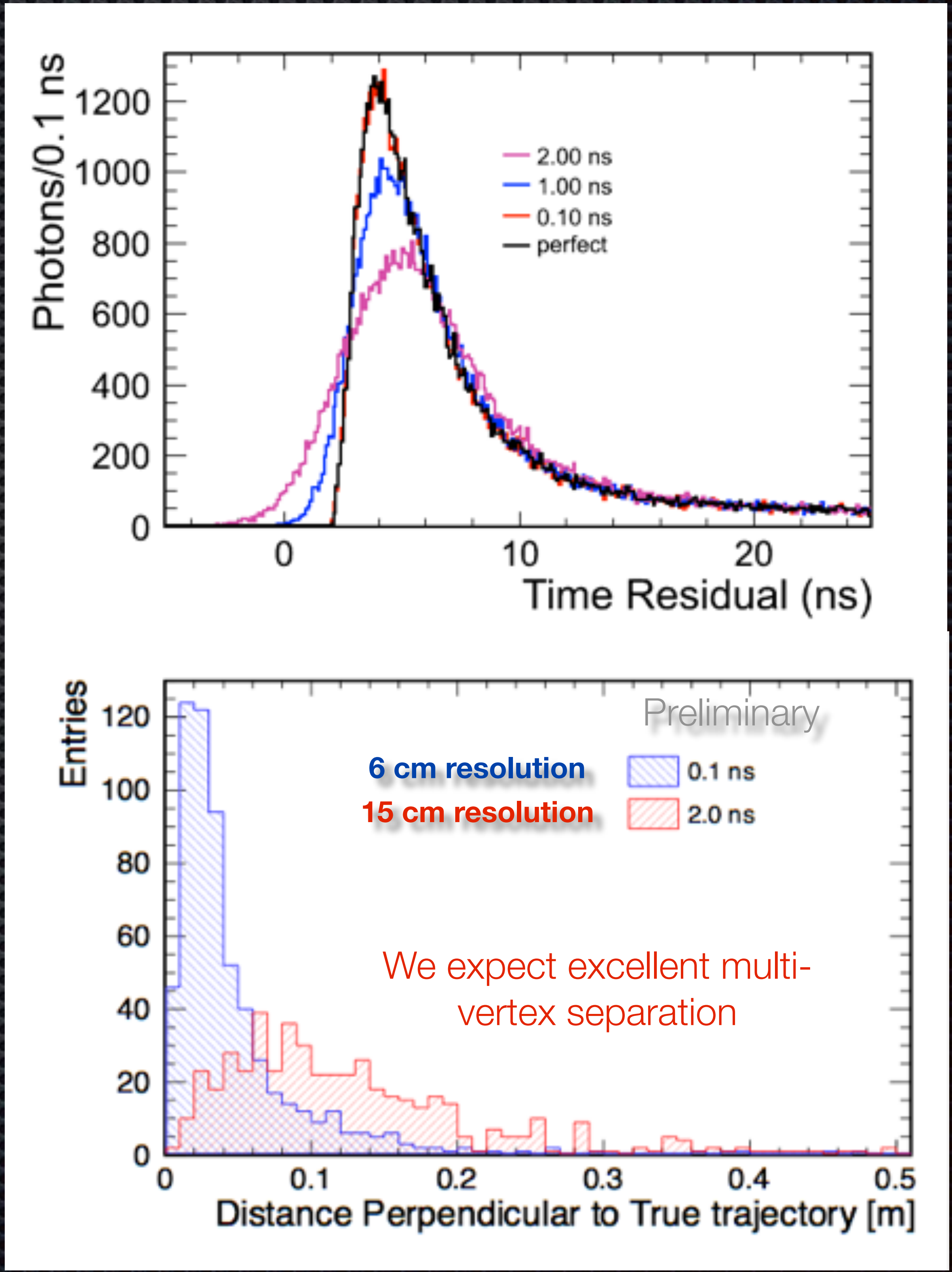


- It is not as sophisticated as full pattern-of-light fitting.
- However in local fits, all tracks and showers can be well-represented by simple line segments on a small enough scale.

Using WCSim (C. Walter - Duke U.) simulation for these studies. Modifications in digitization appropriate for LAPPDs. Reconstruction developed within WCSimAnalysis framework used in LBNE Water Cherenkov design.

Using Time Residuals

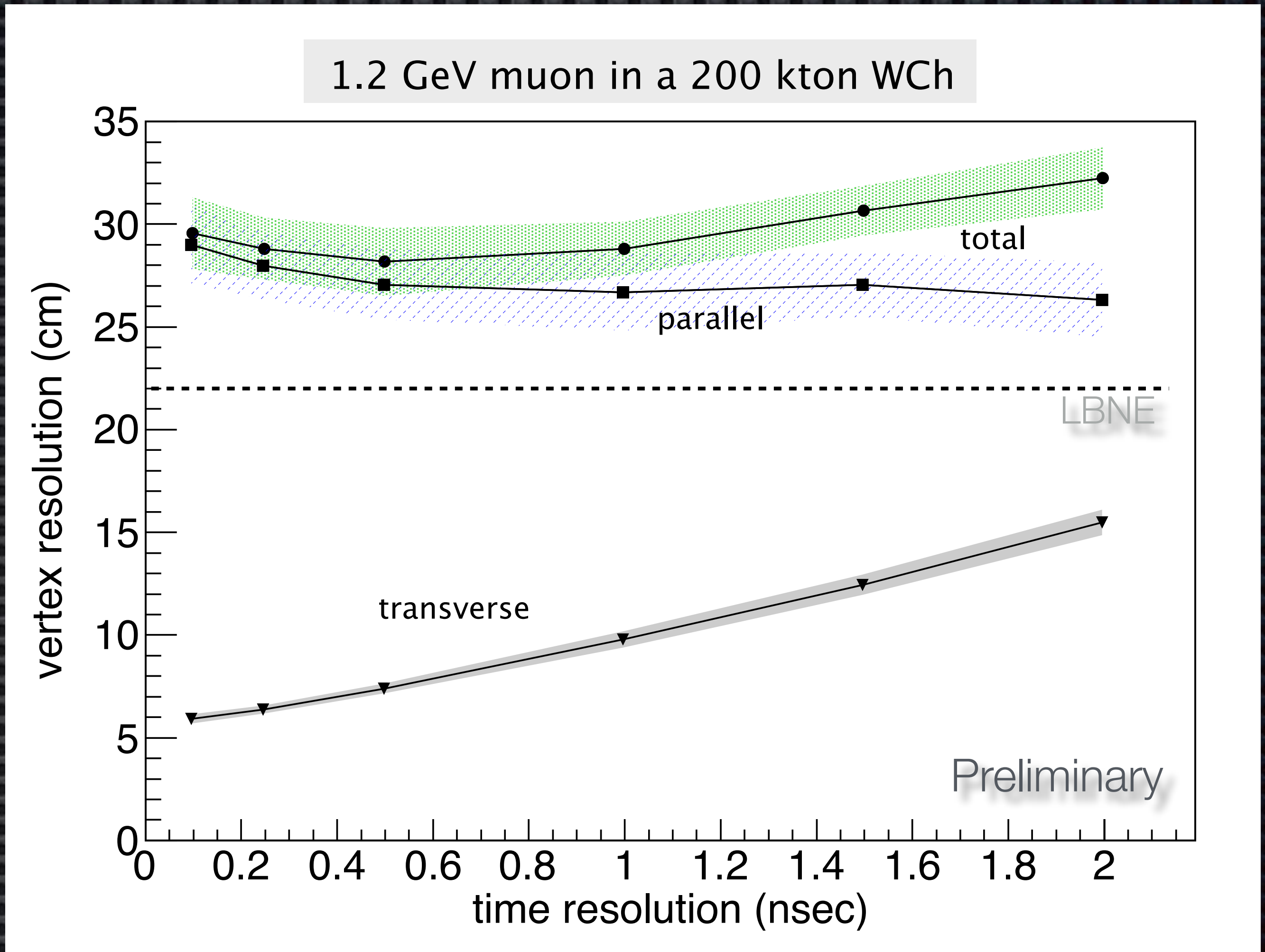
- Our studies show that beyond 100 psec there are no gains to be had when using time residual distributions in a 200kton detector.
- If we use a 200 kton simulated detector with 13% photodetector coverage.
  - 1.2 GeV muons uniformly distributed.
  - Our studies indicate a **factor of 3 gain** in the perpendicular vertex resolution.



M. Sanchez (ISU/ANL), M. Wetstein (U Chicago/ANL), I. Anghel (ISU), E. Catano-Mur (ISU), T. Xin (ISU)

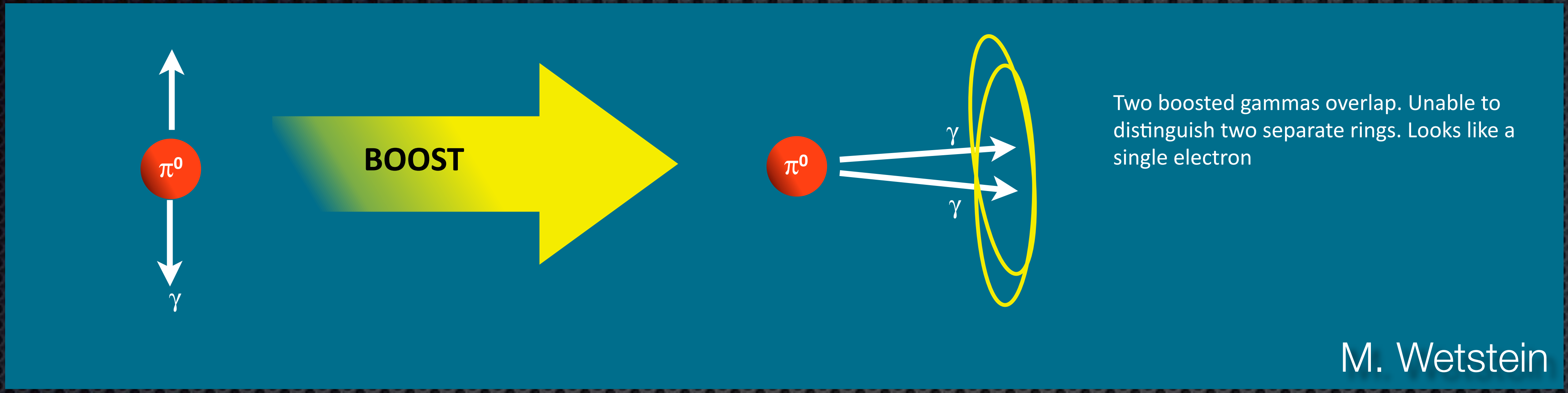
More Time Residuals results

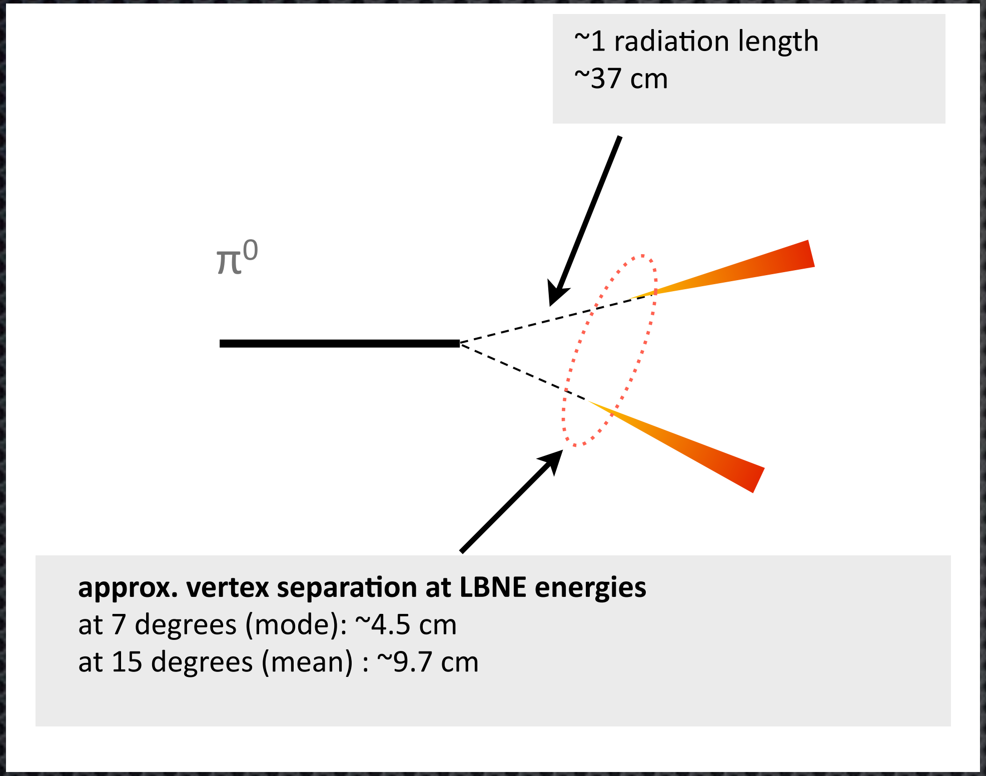
- Our studies indicate a **factor of 3 gain** in the perpendicular vertex resolution.
  - Compare this vertex resolution to ~22 cm for LBNE WCh design using similar fits with no chromatic corrections and standard digitization.
- Based on pure timing, vertex position along the direction parallel to the track is unconstrained.
  - Must use additional constraint: fit the "edge of the cone" (first light).
  - Better algorithms using full pattern of light with better spatial resolution could help here.

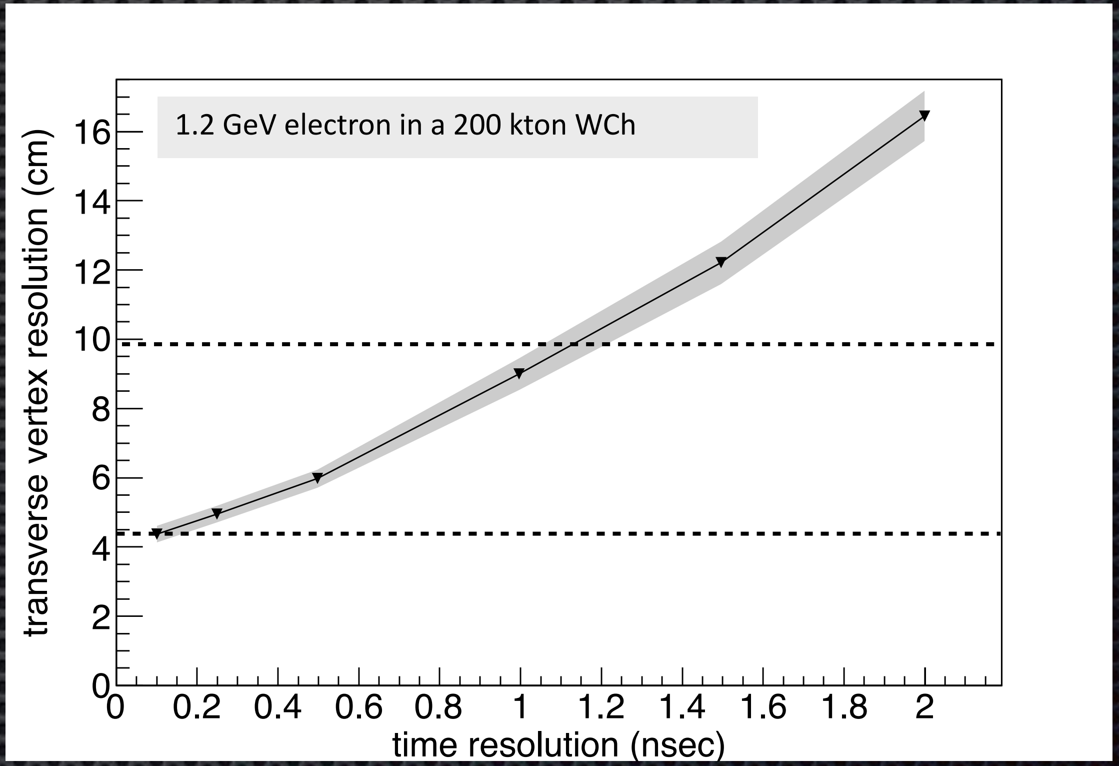


- Note that we also find that, for a given detector, the size of the uncertainties on the transverse vertex resolution scale with coverage consistent with $\sqrt{n}$.

Transverse vertex resolution



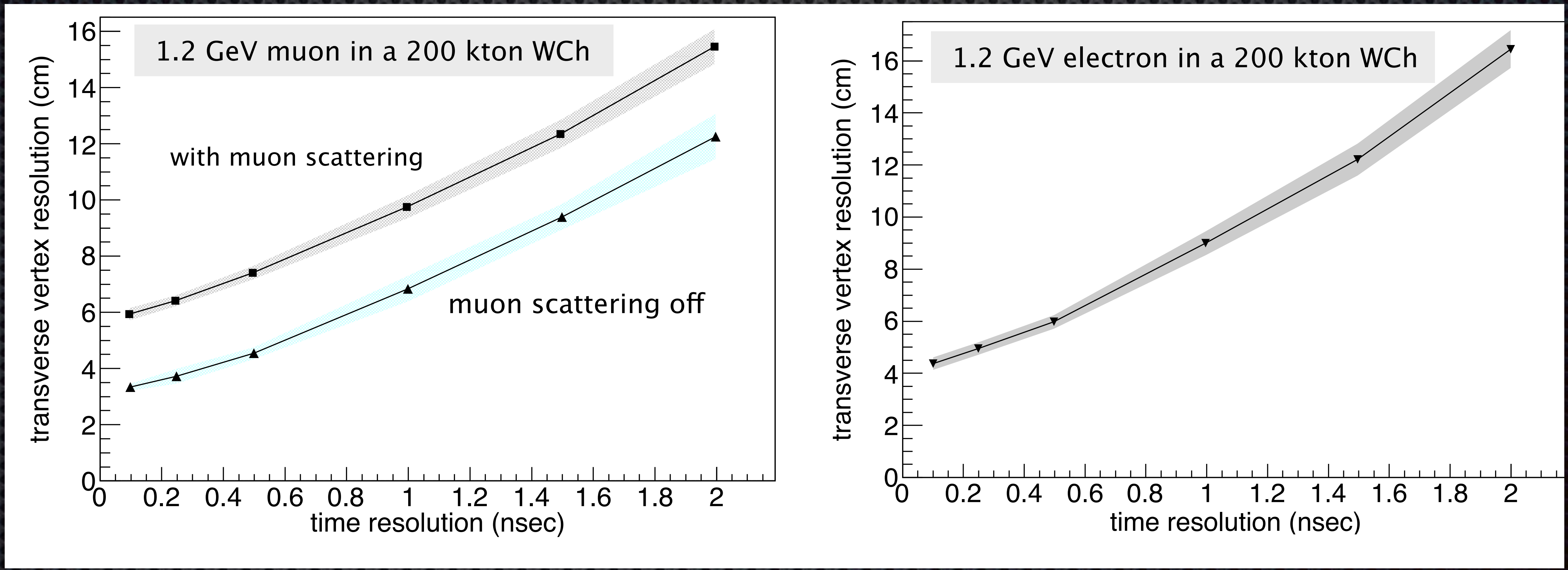




- Transverse vertex resolution is useful in rejection boosted neutral pions.
- Better time resolutions could help to cut deeper into this background.

Transverse vertex resolution

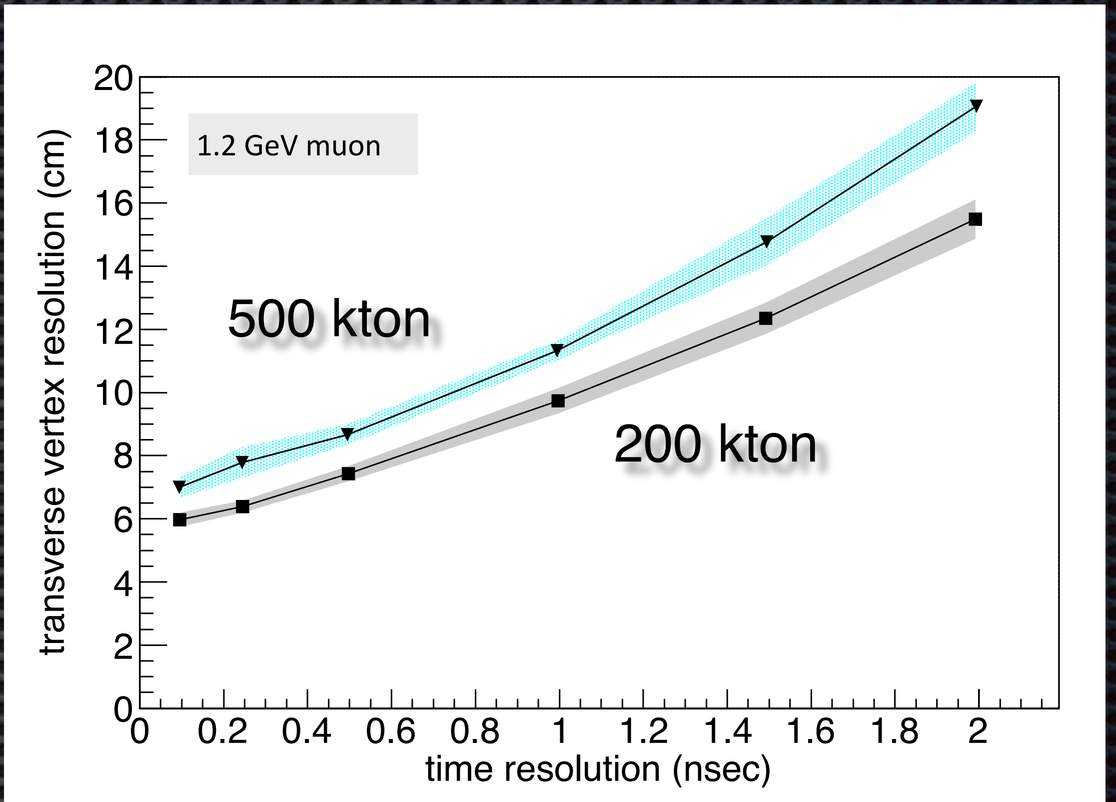
- Muon scattering is not a limiting factor for the gains observed.
- Electrons show slightly better vertex resolutions.

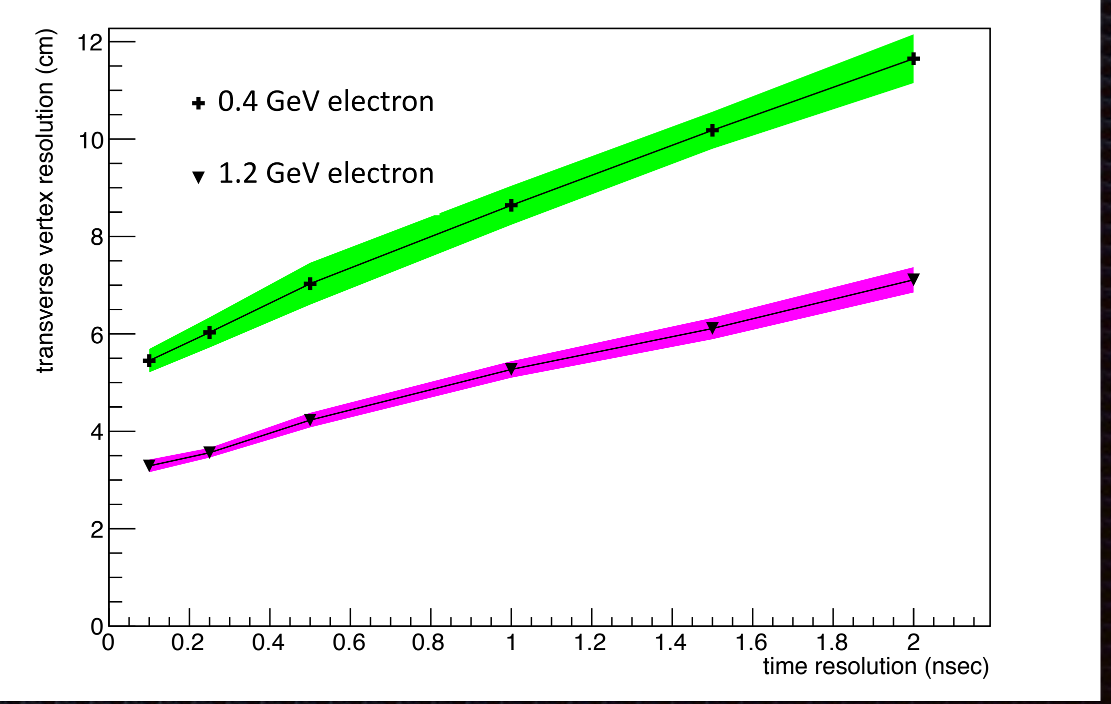


Other detector configurations

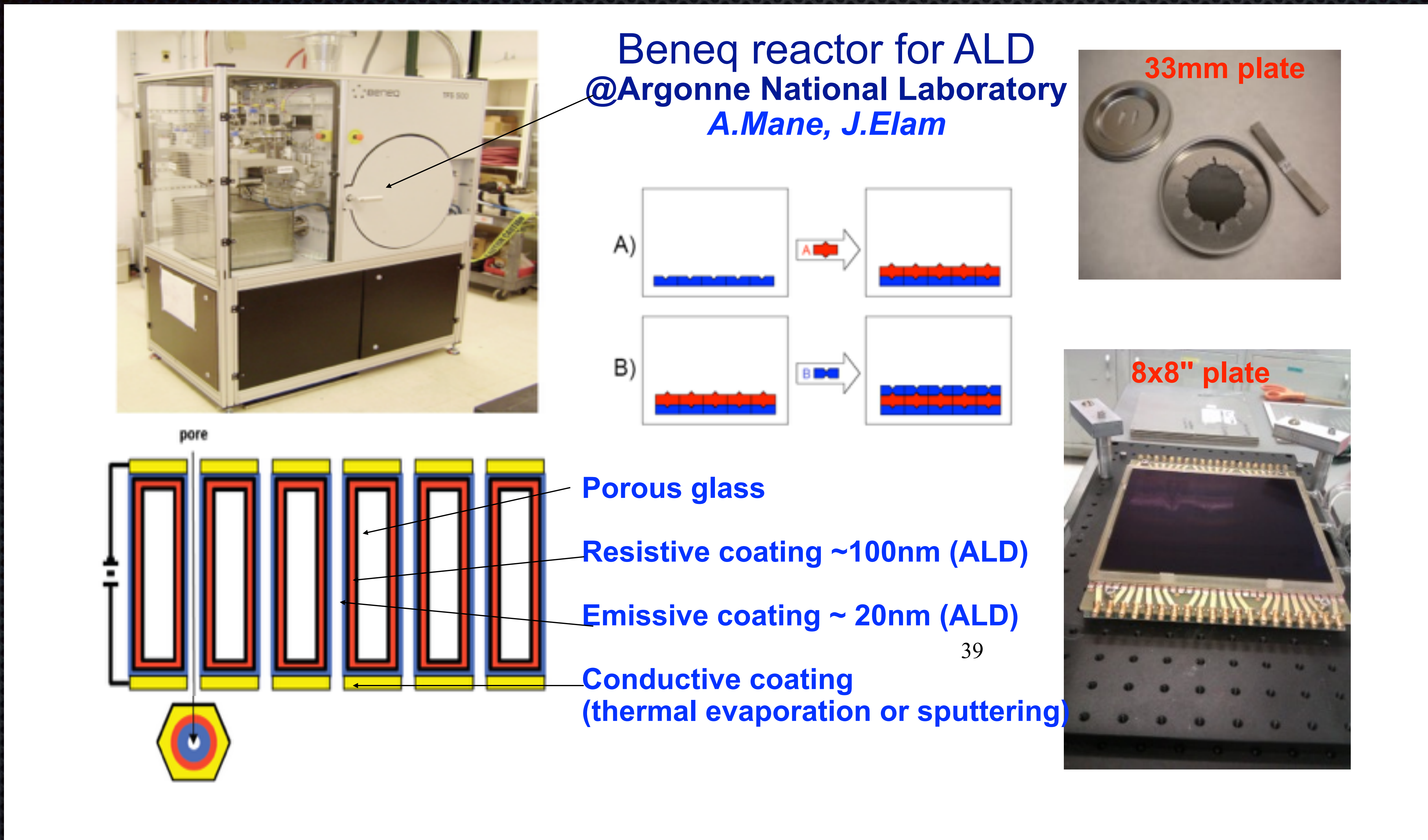
- Currently exploring a variety of detector configurations and particle energies.
- Gains are preserved going from 200 to 500 kiloton detectors. Shown for 1.2 GeV muons.
- Lower energies do have some resolution loss. Shown for 0.4 and 1.2 GeV electrons.

publication coming soon!





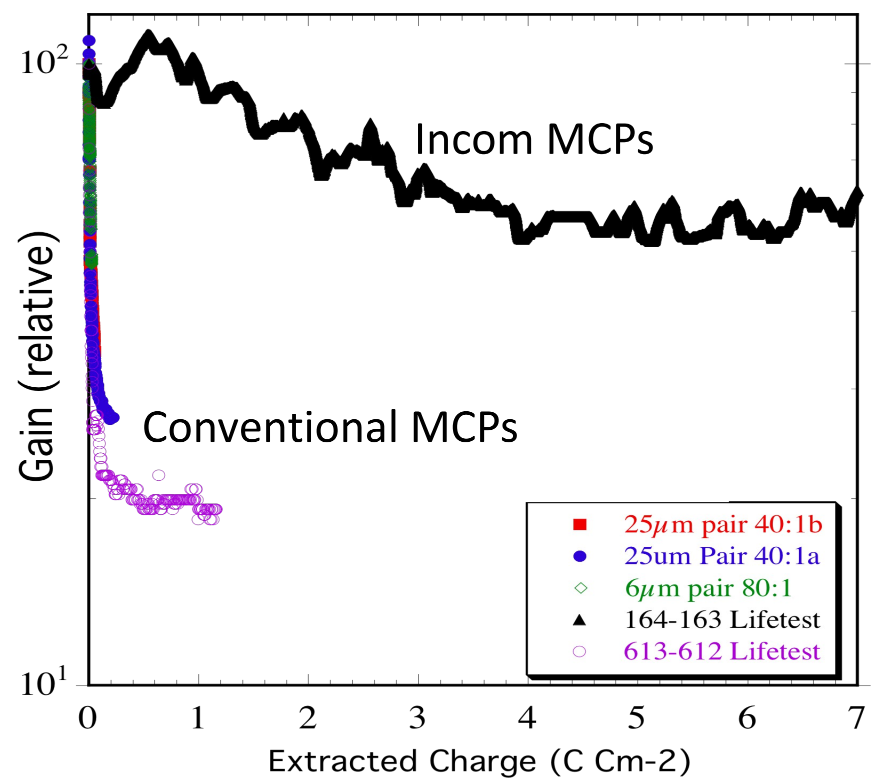
The MCP using Atomic Layer Deposition (ALD)

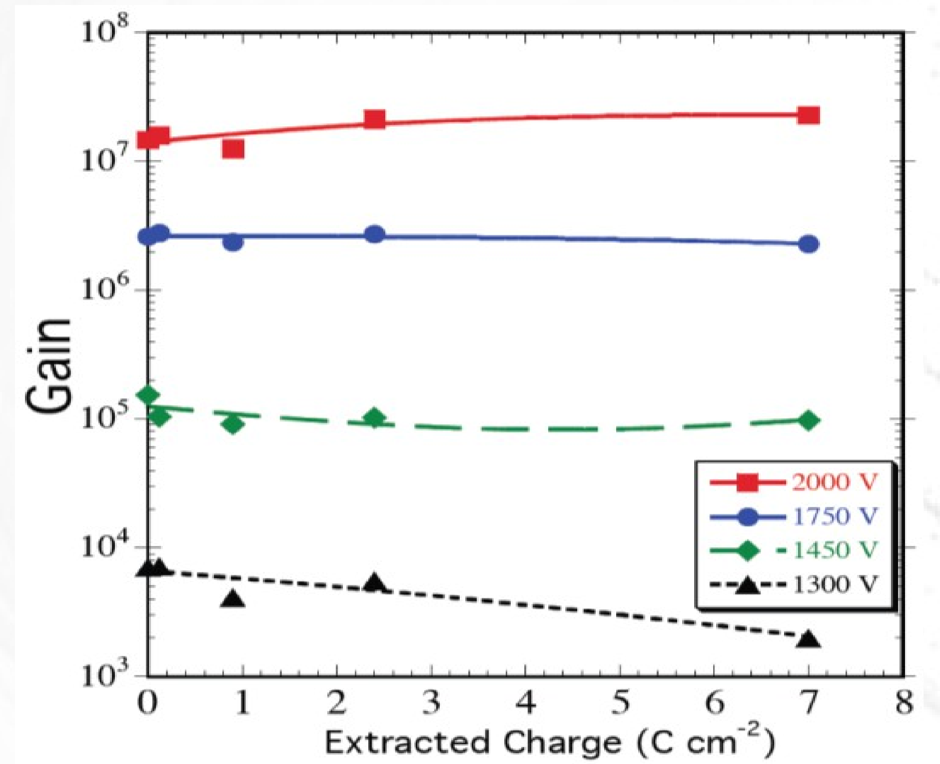


A. Elagin

Gain Stability

A. Elagin - ANT 2014





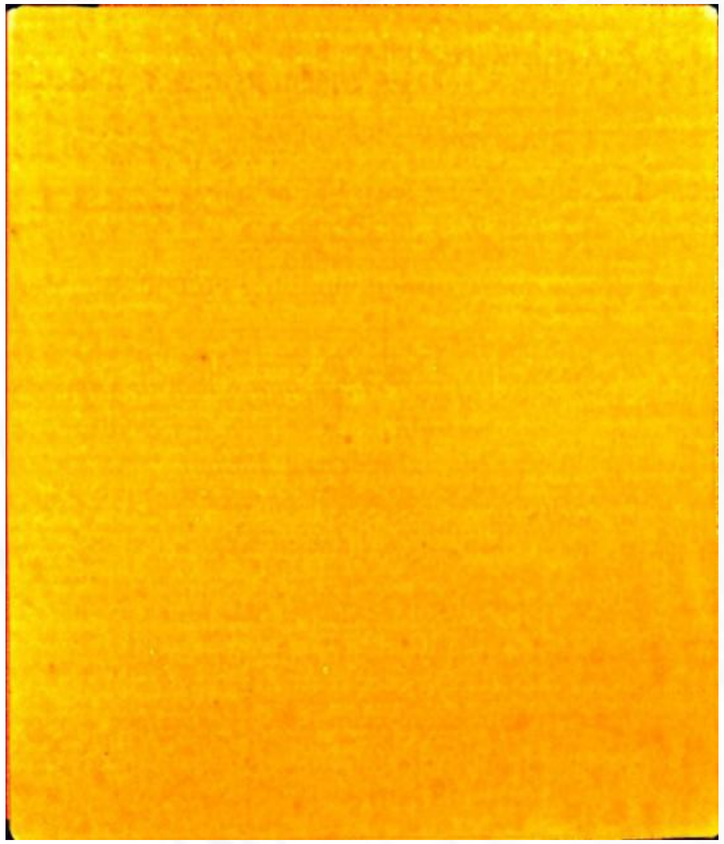
Conventional MCPs require an extensive "burn-in" to achieve a stable gain. Little burn-in is required for Incom MCPs.

O.H.W. Siegmund, J.B. McPhate, S.R. Jelinsky, J.V. Vallerga, A.S. Tremsin, R.Hemphill, H.J. Frisch, R.G. Wagner, J. Elam, A. Mane and the LAPPD Collaboration, "Development of Large Area Photon Counting Detectors Optimized for Cherenkov Light Imaging with High Temporal and sub-mm Spatial Resolution," NSS/MIC, IEEE.N45-1, pp.2063-2070 (2011)

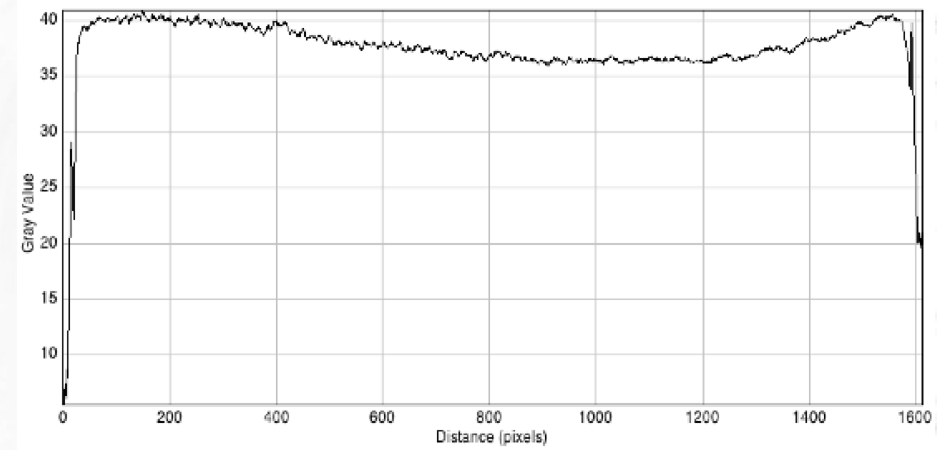
Gain is high and stable vs. extracted charge. Plot is of MCP gain at several fixed voltages during a "burn-in" test extracting 7 C/cm2 at ~3 μA output current for a pair of 33 mm, 60:1 L/D, 20 μm pore ALD MCPs.

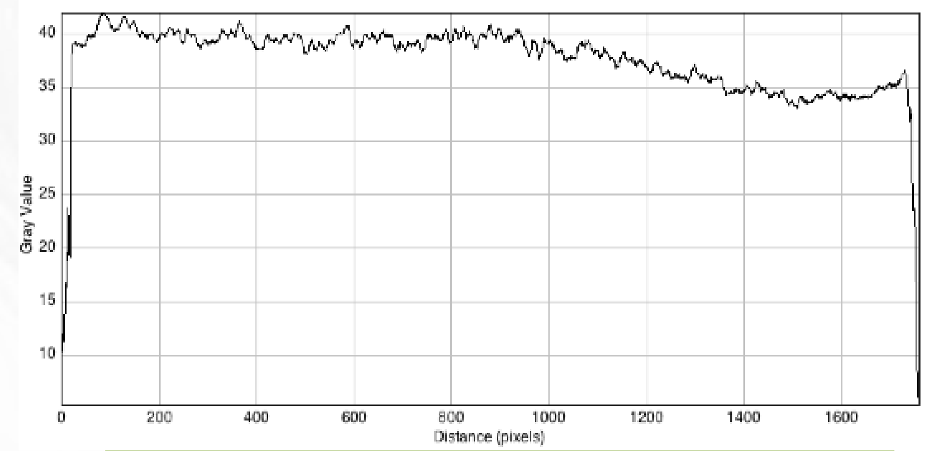
Oswald H. W. Siegmund, John V. Vallerga, Anton S. Tremsin, Jason B. McPhate, Xavier Michalet, Shimon Weiss, Henry Frisch, Robert Wagner, Anil Mane, Jeffrey Elam, Gary Varner, "Large Area and High Efficiency Photon Counting Imaging Detectors with High Time and Spatial Resolution for Night Time Sensing and Astronomy," Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, in press, (2012).

Gain Uniformity



Gain map image for a pair of 20 µm pore, 60:1 L/D, ALD borosilicate MCPs, 950 V per MCP, 184 nm UV





Gain is uniform within ~15% across full 20 x 20 cm^2 area

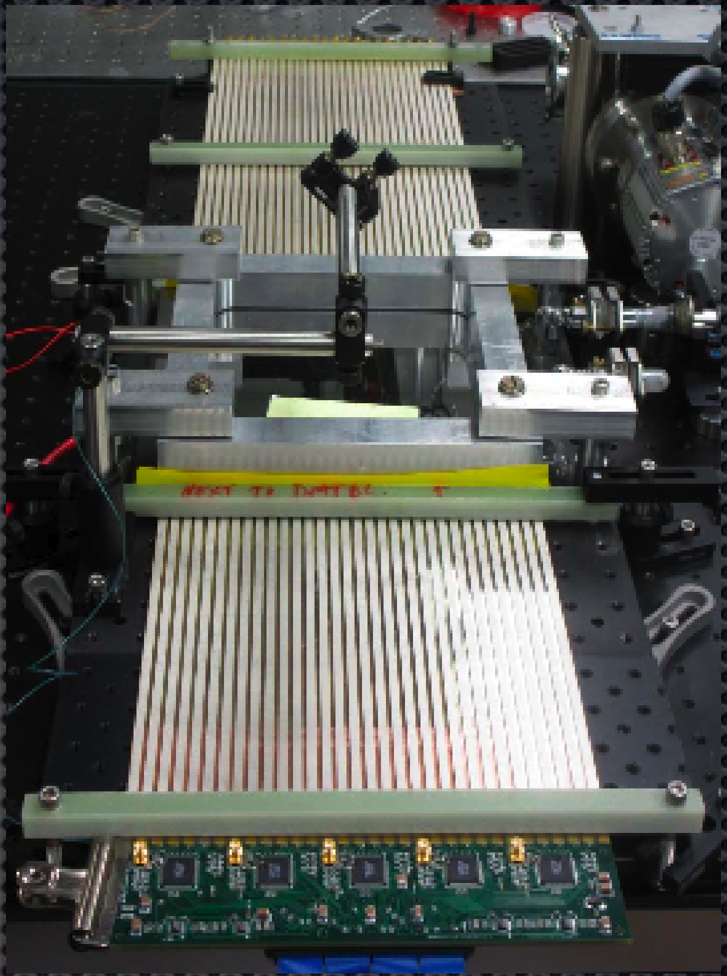
O.H.W. Siegmund, N. Richner, G. Gunjala, J.B. McPhate, A.S. Tremsin, H.J. Frisch, J. Elam, A. Mane, R. Wagner, C.A. Craven, M.J. Minot, "Performance Characteristics of Atomic Layer Functionalized Microchannel Plates" Proc. SPIE 8859-34, in press (2013).

Also, very low noise: <0.1 counts cm^{-2} s^{-1}

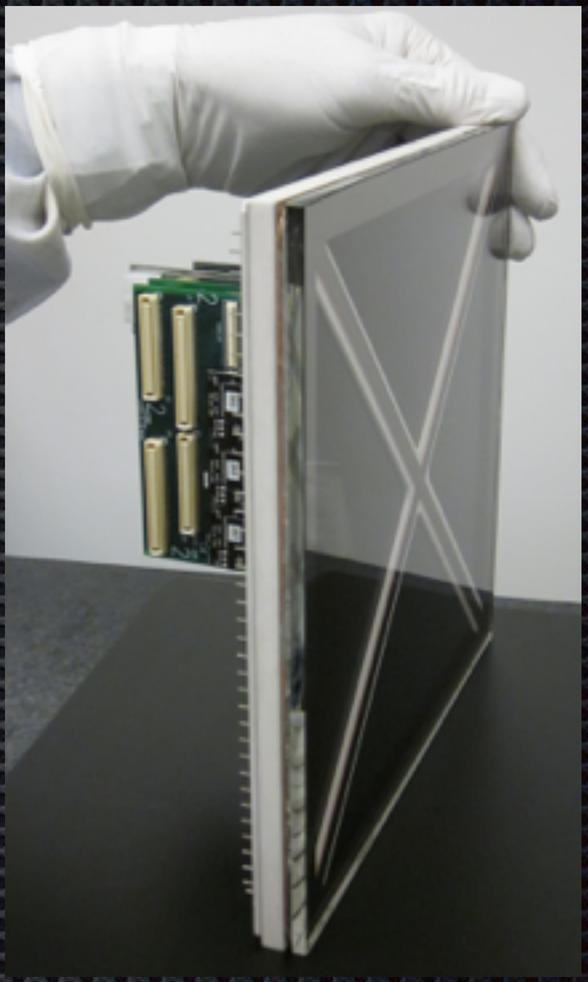
a factor of ~4 lower compared to conventional MCPs

LAPPD Status

- Tested end-to-end detector system:
  - "demountable" glass-body 8" MCP-detector with full readout and front-end electronics.
- An 8" Sealed-Tube processing tank at Berkeley SSL is being used to produce sealed tiles.
- An effort at UChicago for a lightweight in-situ assembly is also in progress.
- ANL has a setup to produce smaller 6x6 cm prototype tiles.



ANL "demountable" detector system - glass body LAPPD



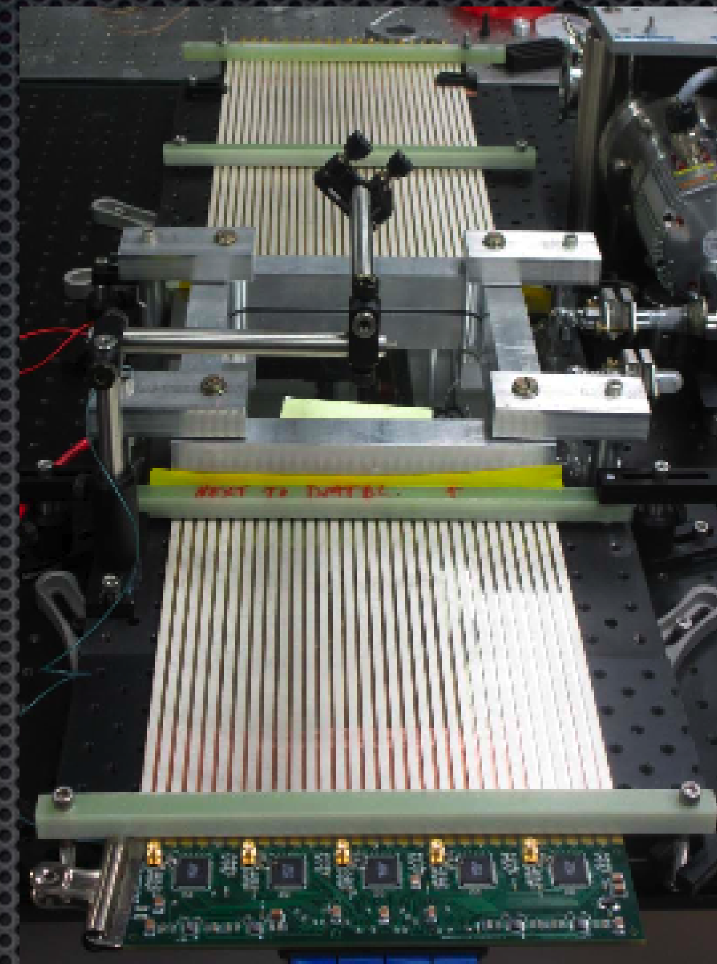
Berkeley SSL detector system- ceramic body LAPPD

UChicago lightweight in-situ assembly

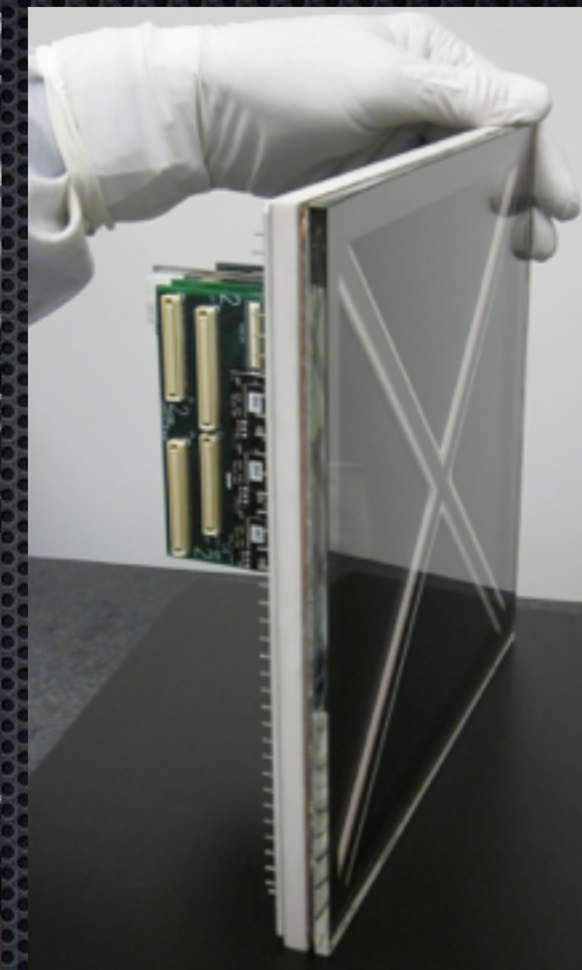
Berkeley SSL Sealed-Tube Processing Tank

LAPPD Status

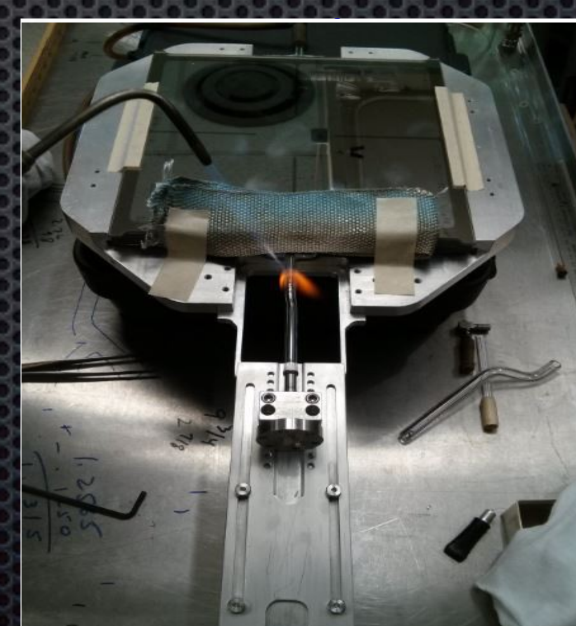
- Psec4 chip benchmarked at:
  - 1.6 GHz analog bandwidth,17 Gsamples/second, ~ 1mV noise
- Psec electronics system is capable of shape-fitting the LAPPD pulses for time, position, and charge at the front-end.
  - NIMA 735, (2014) 452-461. E.Oberla, J.-F. Genat, H. Frisch, K.Nishimura, G.Varner
- A pilot production line is being built at Incom Inc as part of a 3 year technology transfer program.
- SBIRs with different companies to improve performance of: photocathodes, electronics and micro-channel plates.



ANL “demountable” detector system - glass body LAPPD



Berkeley SSL detector system- ceramic body LAPPD



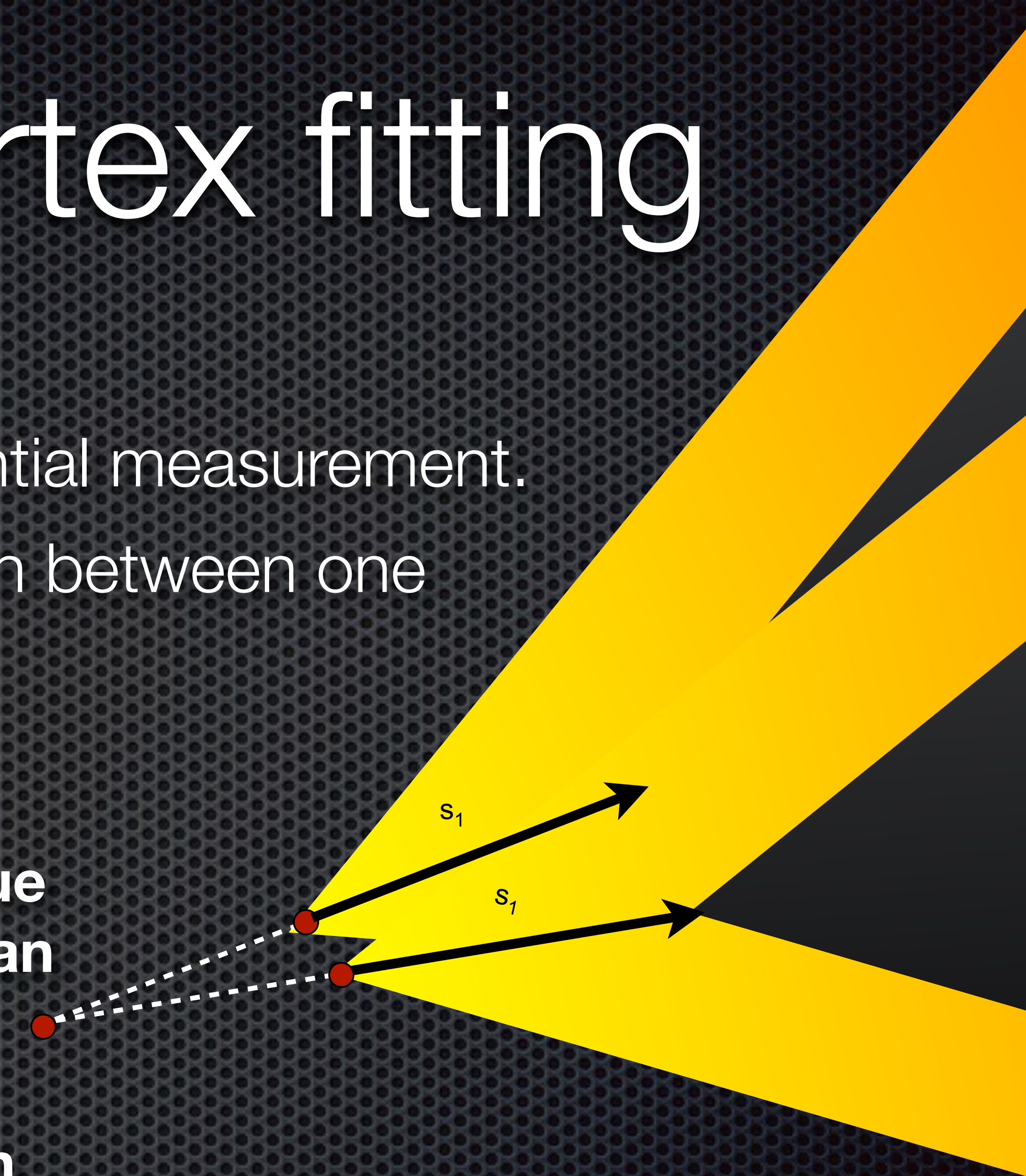
UChicago lightweight in-situ assembly

Berkeley SSL Sealed-Tube Processing Tank

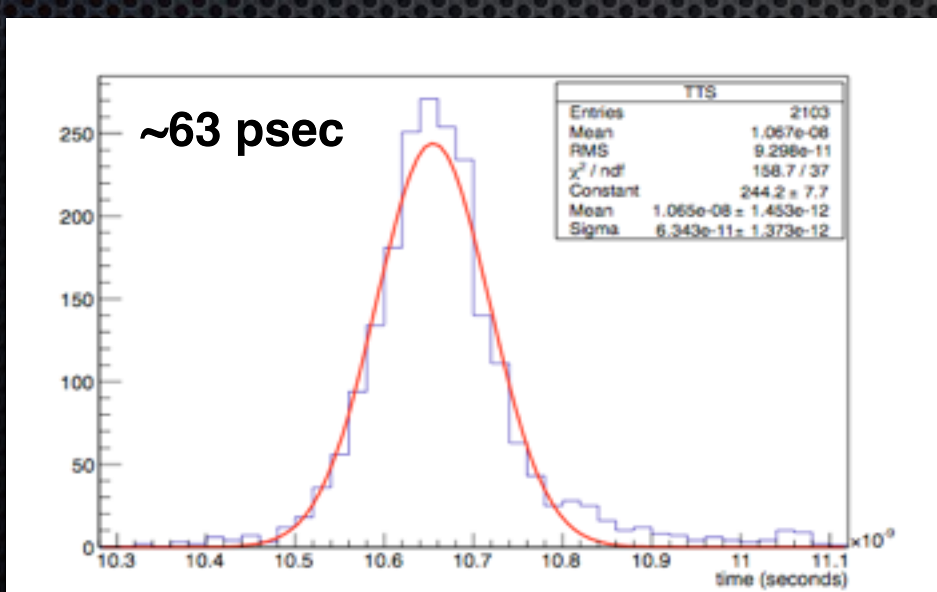
Timing-based vertex fitting

Fortunately, multi-vertex separation is a differential measurement.

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



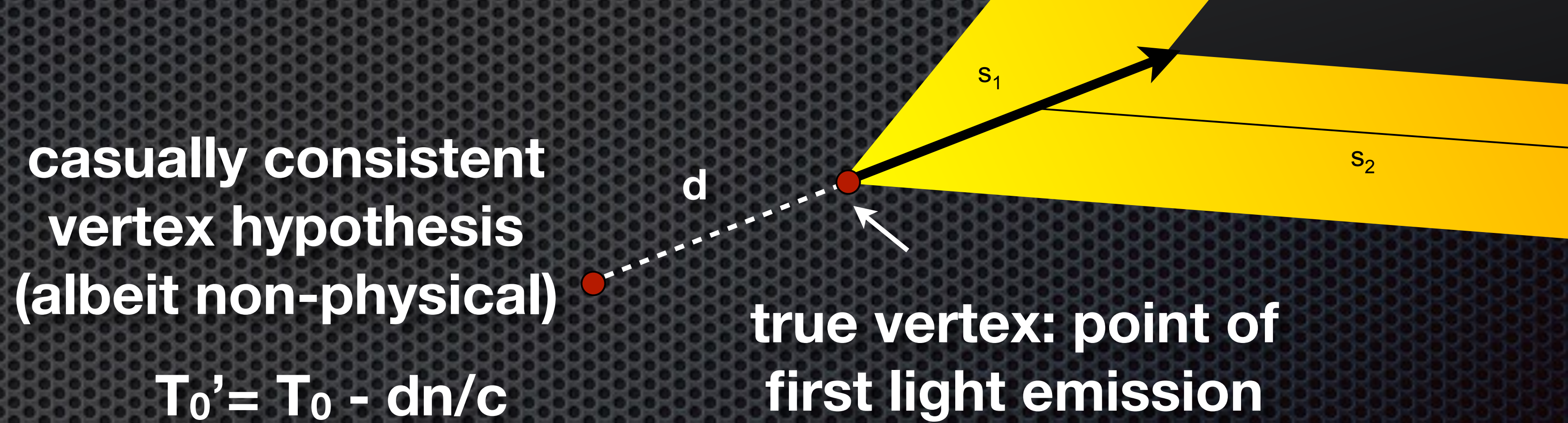
Only one unique solution that can satisfy the subsequent timing of both tracks



100 picoseconds ~ 2.25 centimeters

Timing-based vertex fitting

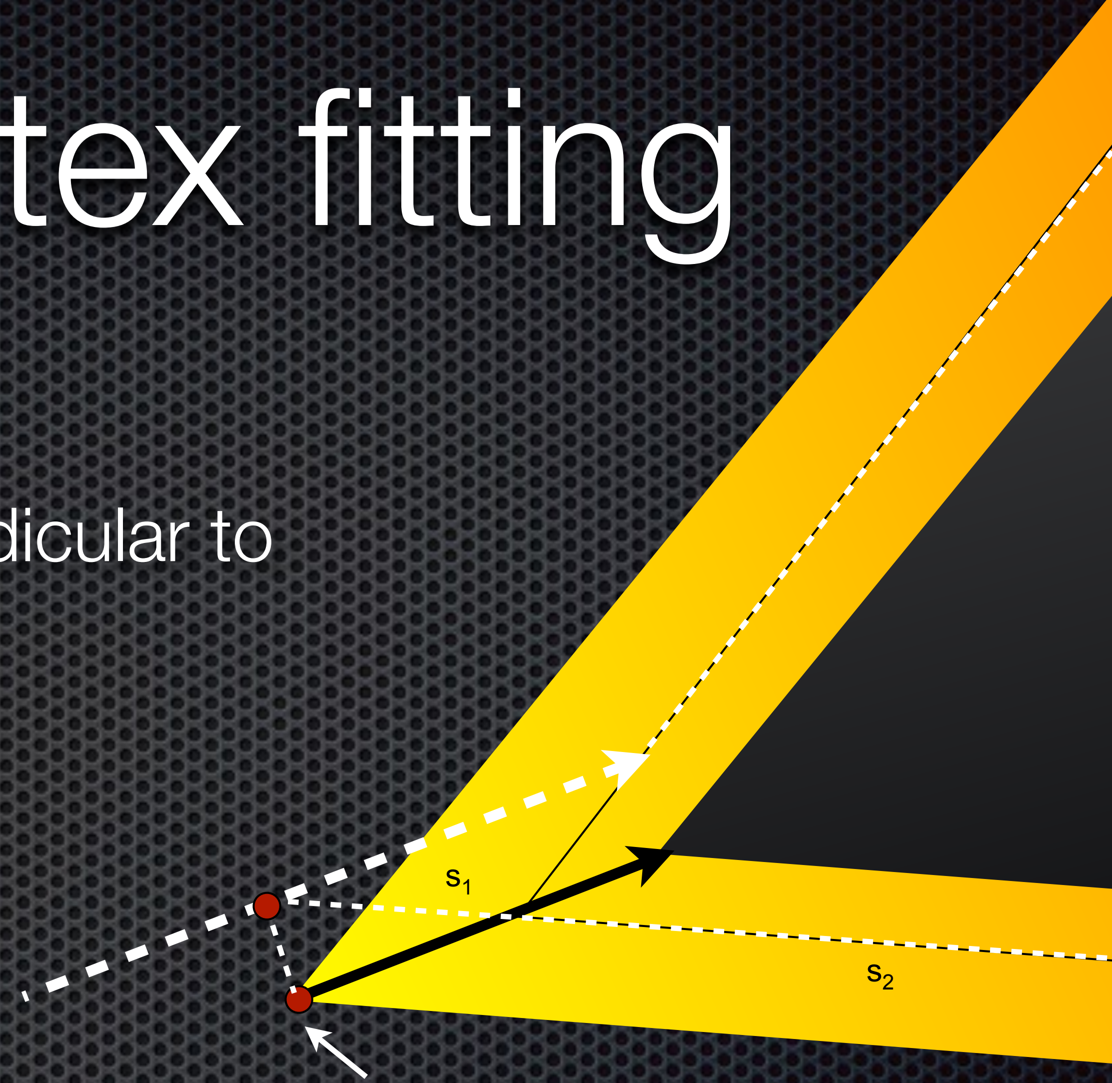
Based on pure timing, vertex position along the direction parallel to the track is unconstrained



Must use additional constraint: fit the “edge of the cone” (first light)

Timing-based vertex fitting

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

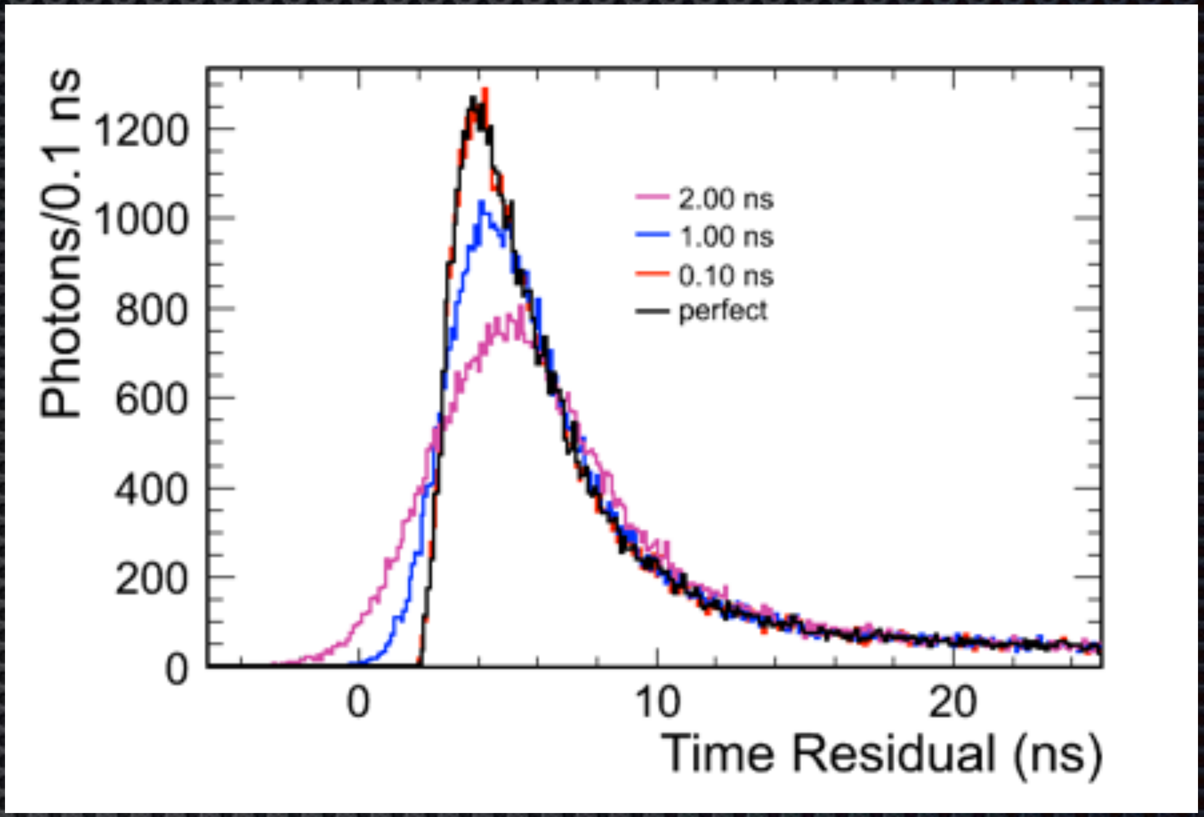


For single vertex fitting, we expect the transverse resolution to improve significantly with photosensor time-resolution!

100 picoseconds ~ 2.25 centimeters

Using Time Residuals

- Our studies show that beyond 100 psec there are no gains to be had when using time residual distributions in a 200kton detector.



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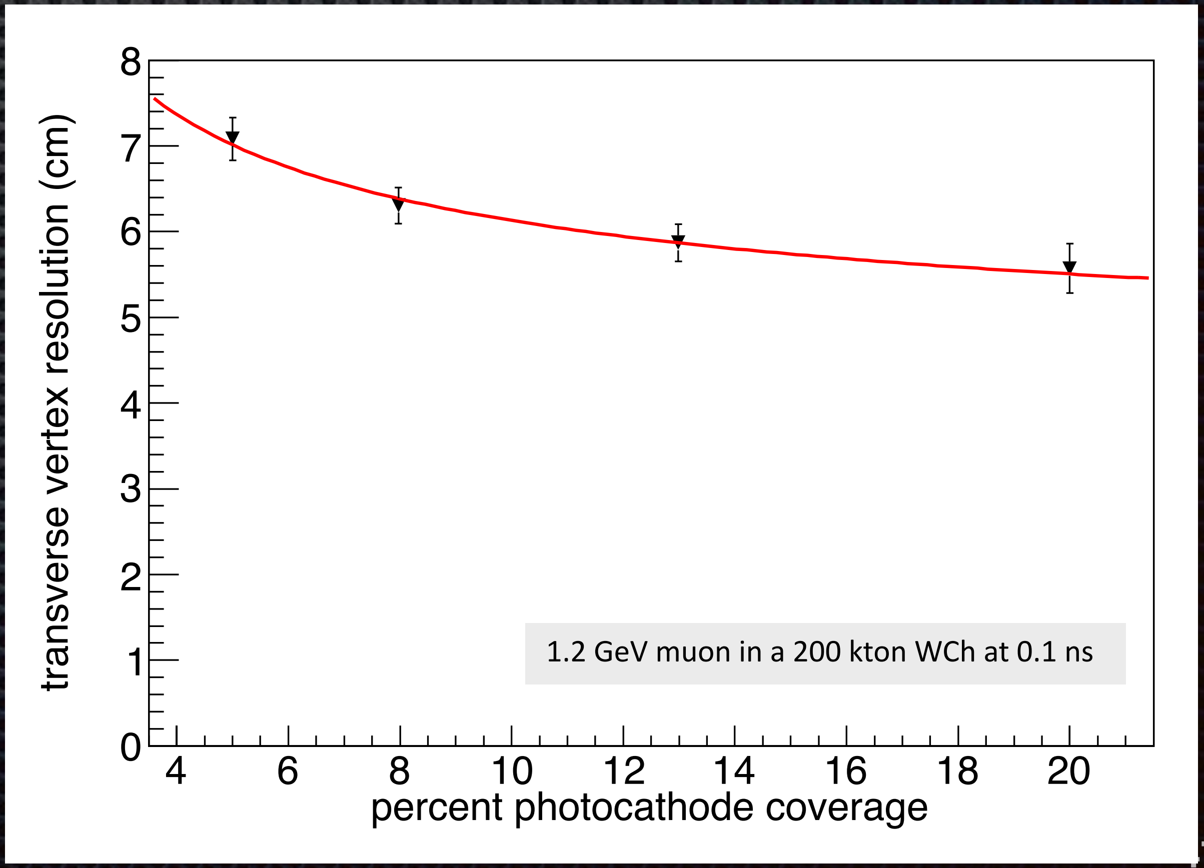
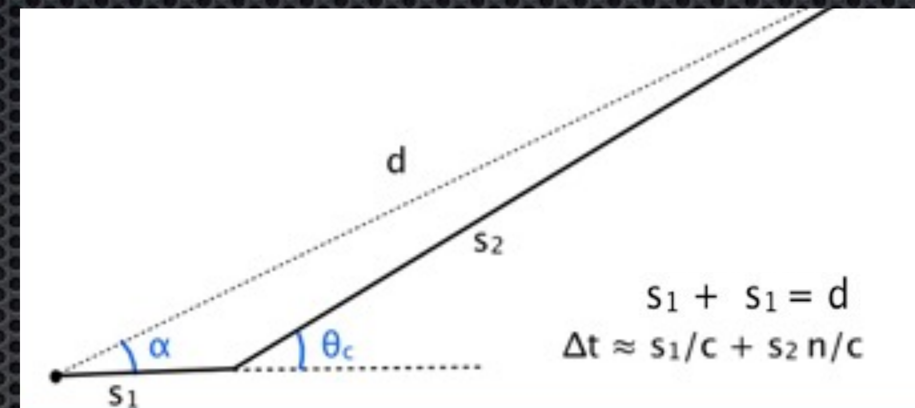
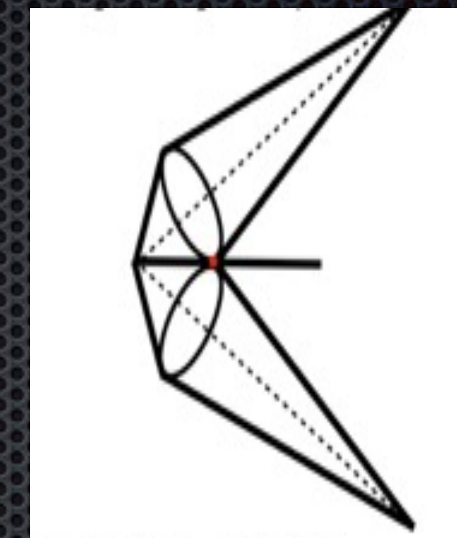


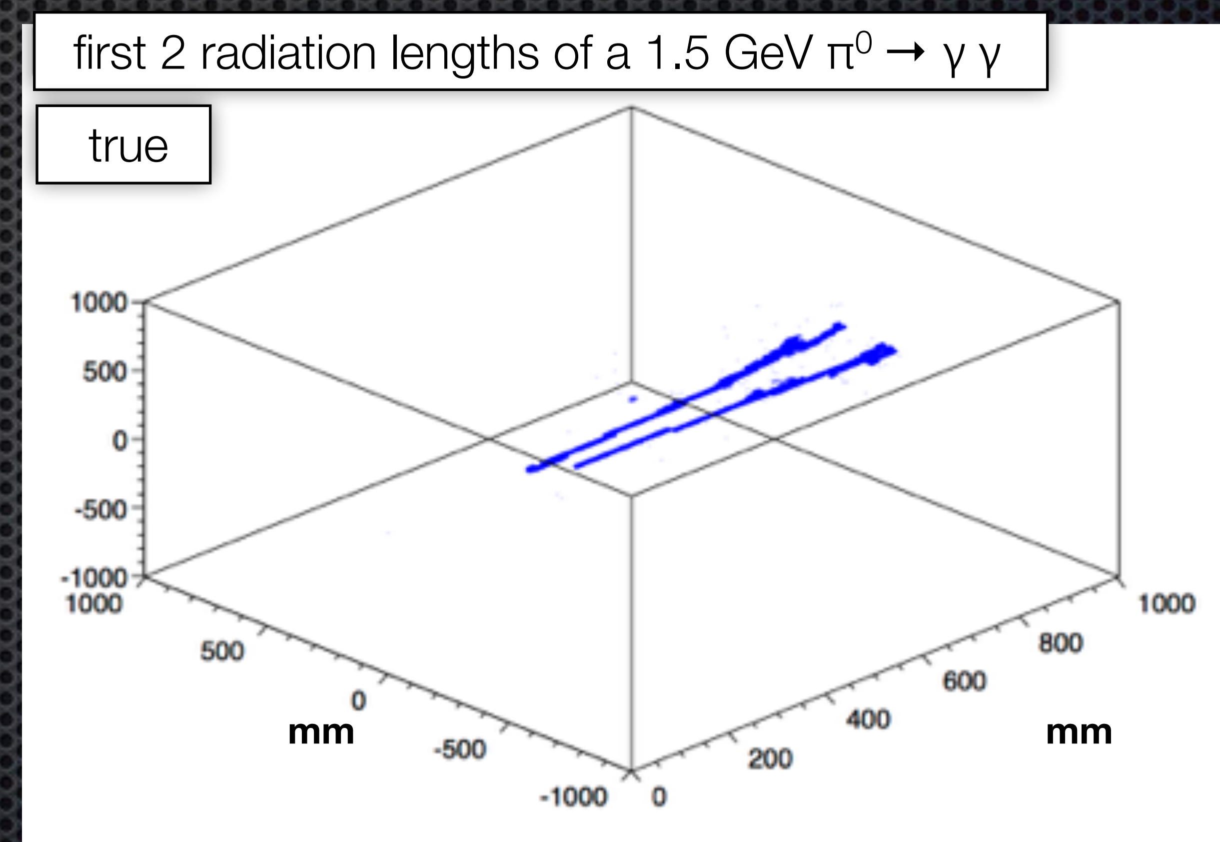
M. Sanchez (ISU/ANL), M. Wetstein (U Chicago/ANL),
I. Anghel (ISU), E. Catano-Mur (ISU), T. Xin (ISU)

Using the Isochron method

- The isochron transform is a **causal Hough transform**, that build tracks from a pattern of hits in time and space.
- This approach **requires a seed vertex**, but no prior assumption about number of tracks or event topology.
- It connects each hit to the vertex through a two segment path, one that of the charged particle, the other representing emitted light.
- The rotational ambiguity is easily resolved, since the same track will intersect maximally around their common emission point.



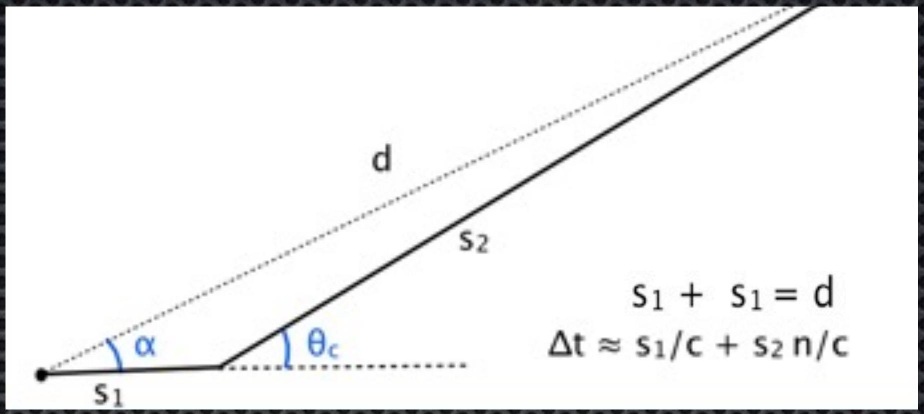


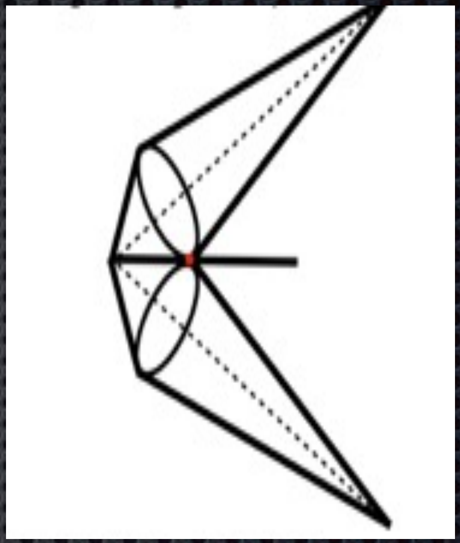


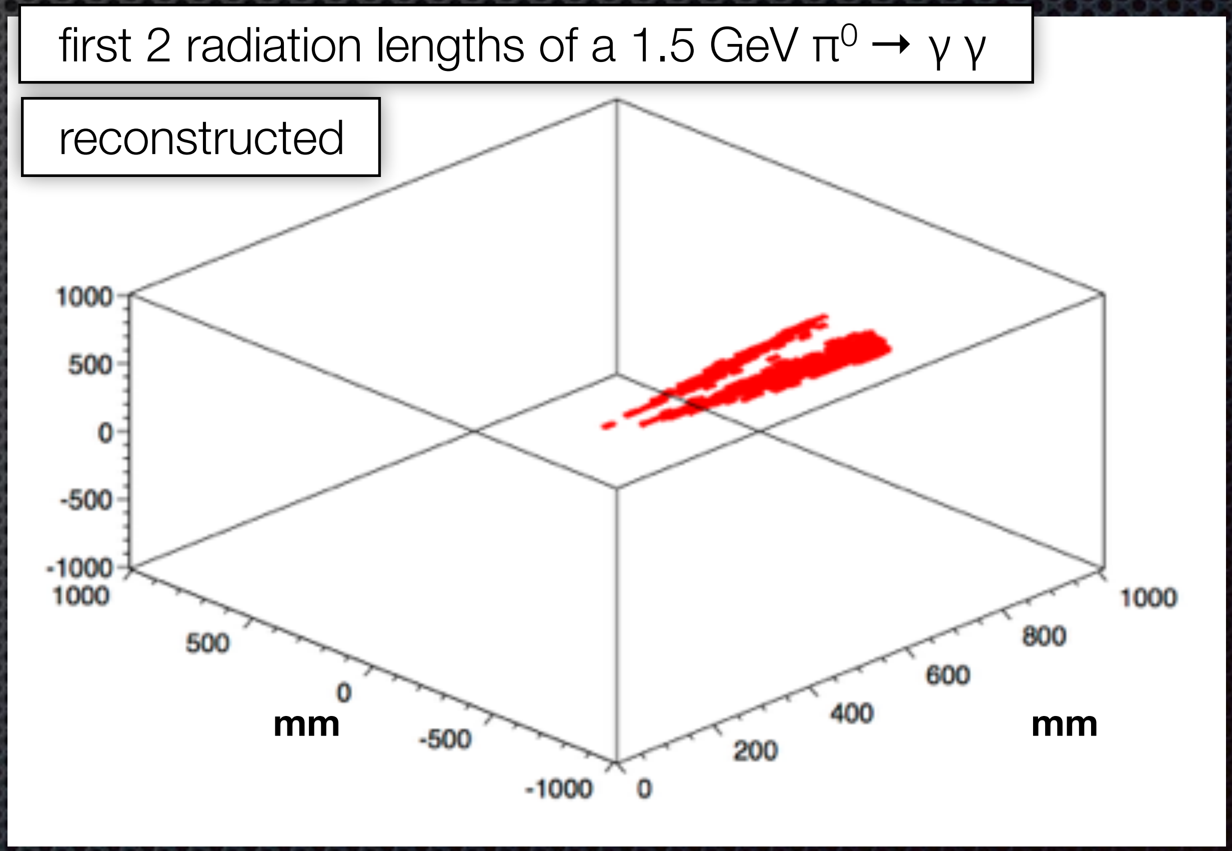
M. Wetstein

Using the Isochron method

- Track-like clusters emerge from density of intersections:
  - This density is sensitive to the position of the vertex hypothesis.
  - Image sharpness can be used as a figure of merit for fitting the vertex.
- Initial implementation tested on a 6m spherical detector with 100% coverage and perfect resolution.
- Full optical effects are applied
  - Not yet correcting for chromatic dispersion.
  - Not using any timing-based quality cuts.
- Challenges for realistic implementation: optimization for larger detectors, sparser coverage, less resolution.







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