University of Chicago

Argonne NATIONAL LABORATORY

ANNIE:

The Atmospheric Neutrino Neutron Interaction Experiment

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on behalf of the ANNIE Collaboration:

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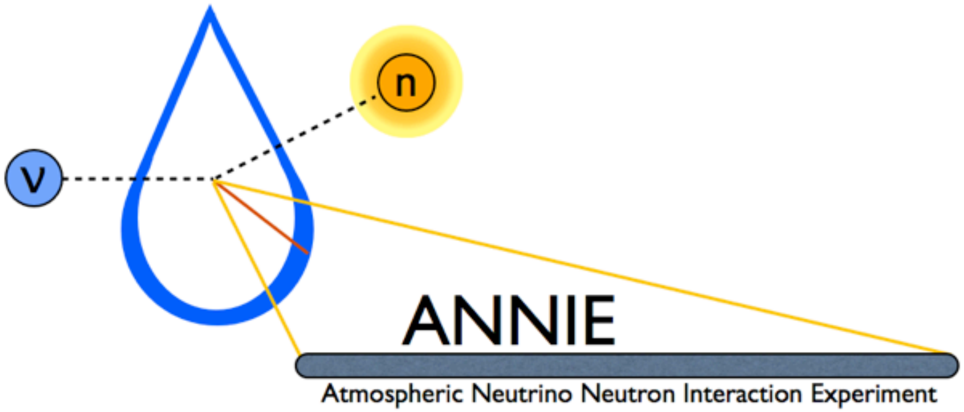
Fermilab, Intensity Frontier Seminar

Feb 20, 2014

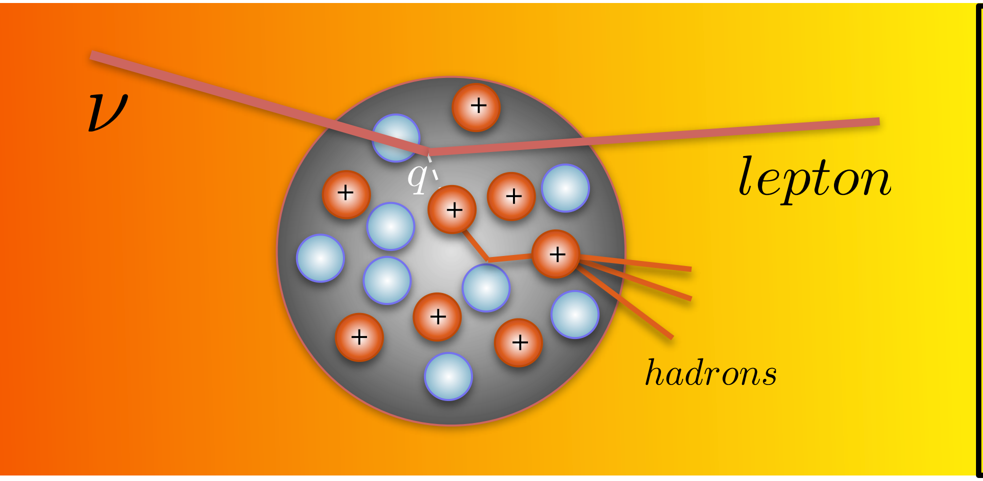
U.S. DEPARTMENT OF ENERGY

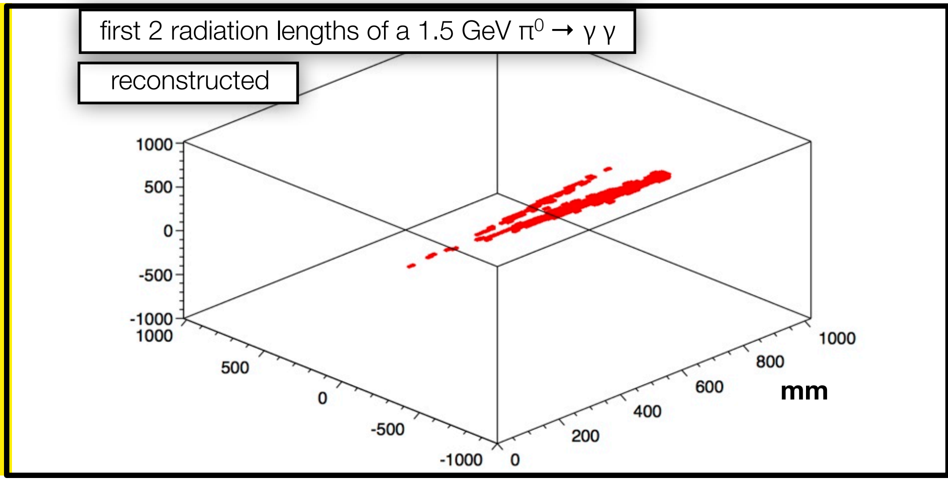
What is ANNIE?

- A measurement of the abundance of final state neutrons from neutrino interactions in water, as a function of energy.



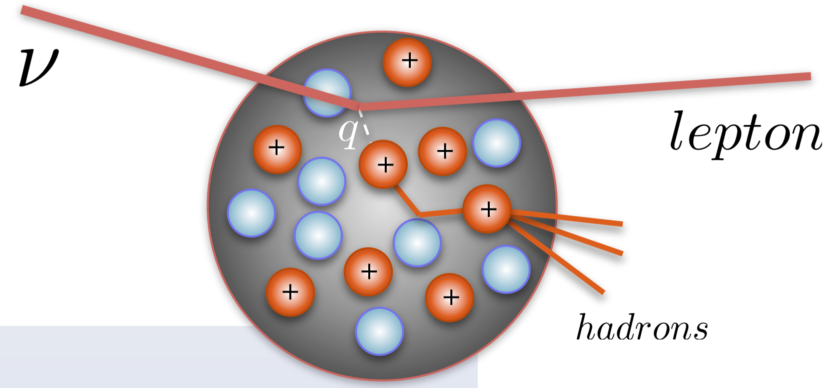
a key measurement for proton decay physics, supernova neutrino detection in water, and fundamental neutrino interaction physics

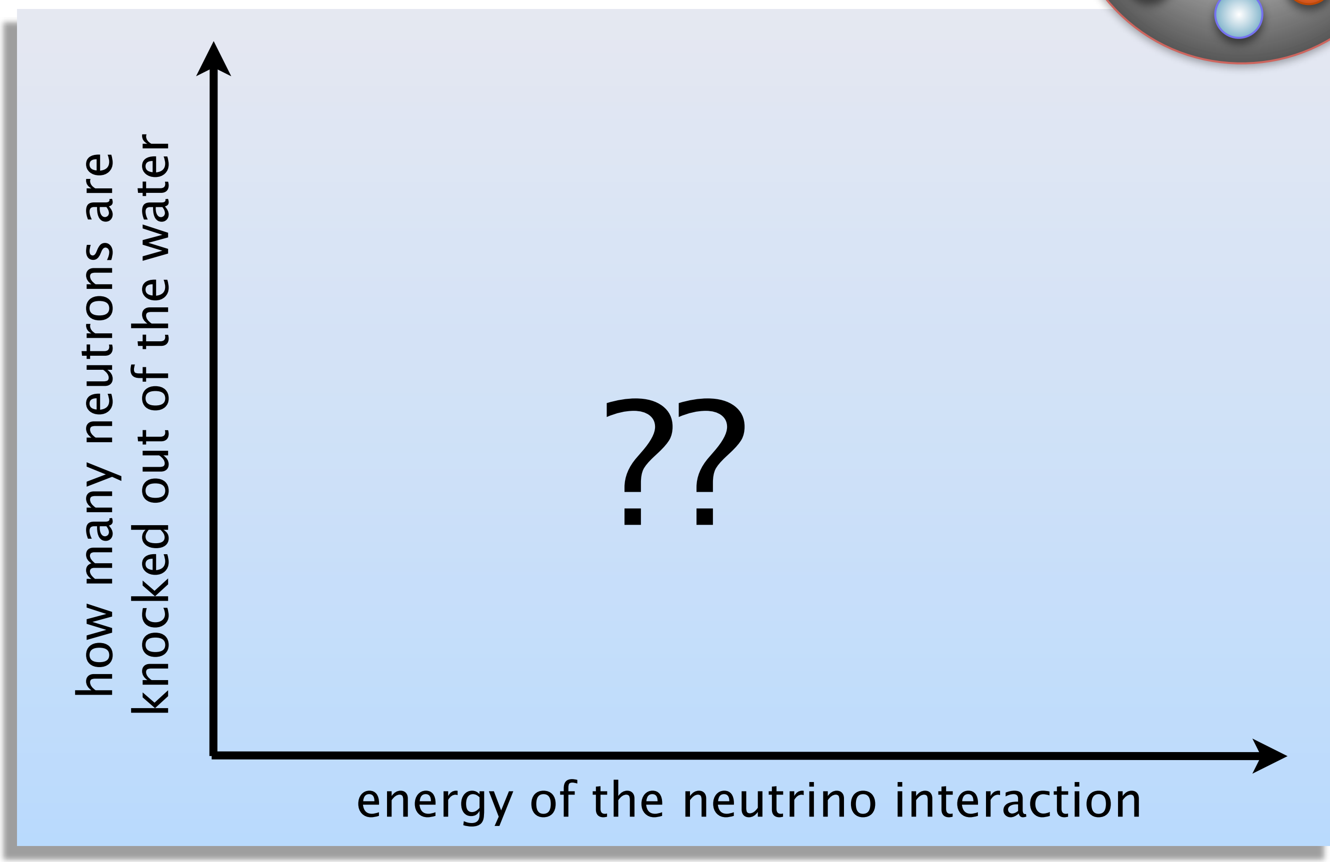




- Demonstration of a new approach to neutrino detection: *Optical Time Projection Chamber* using new photosensor technology.

The ANNIE Measurement (in a nutshell)





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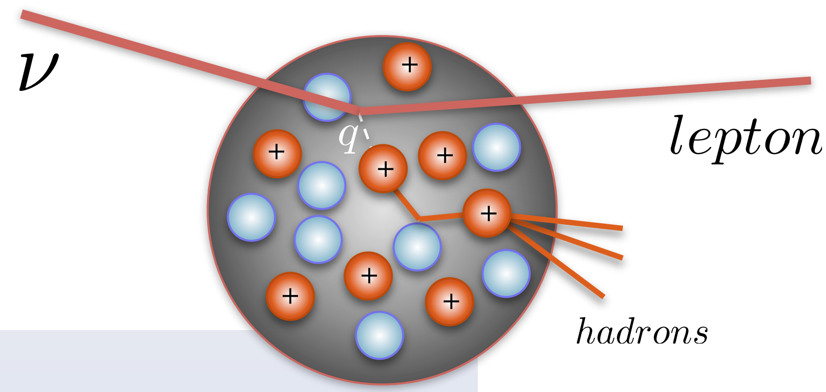
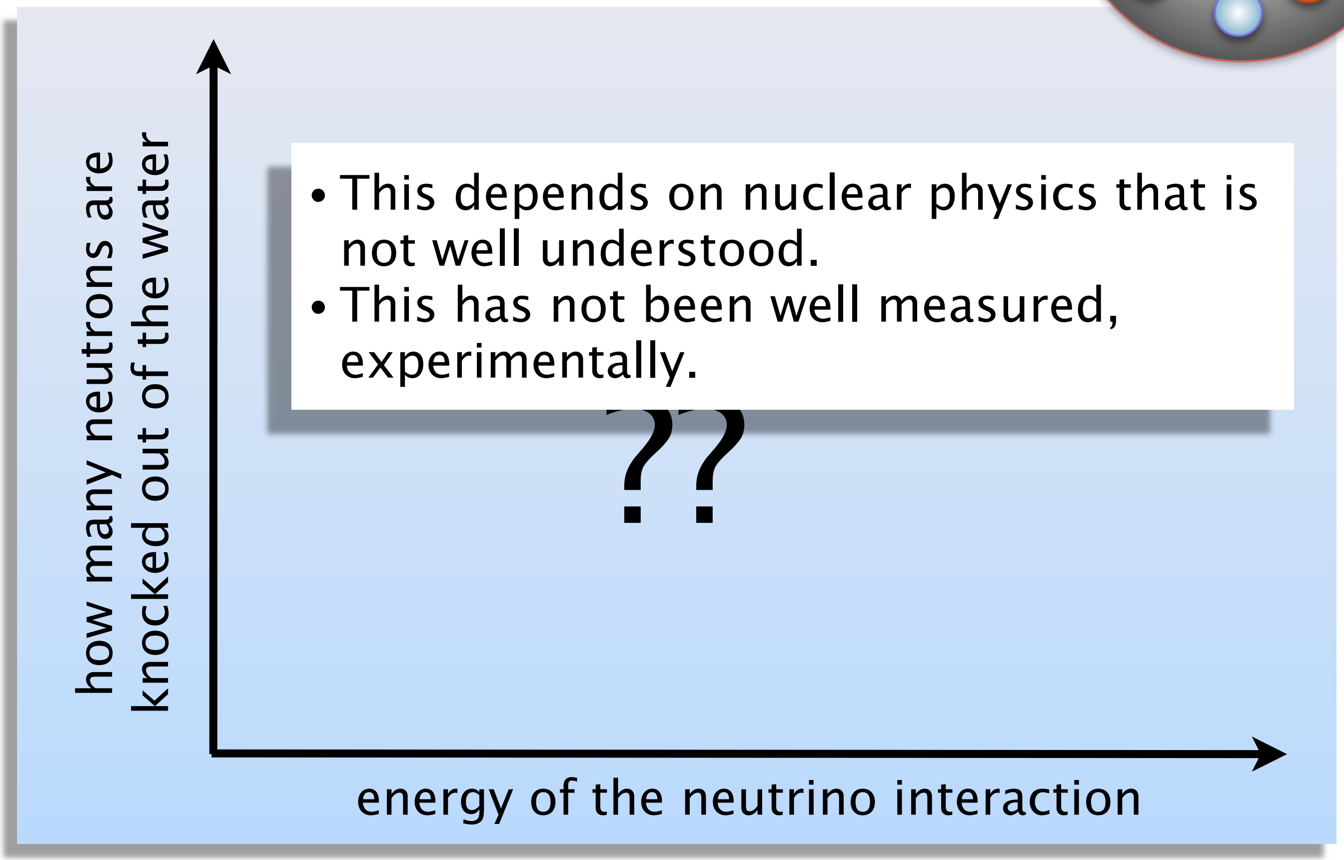
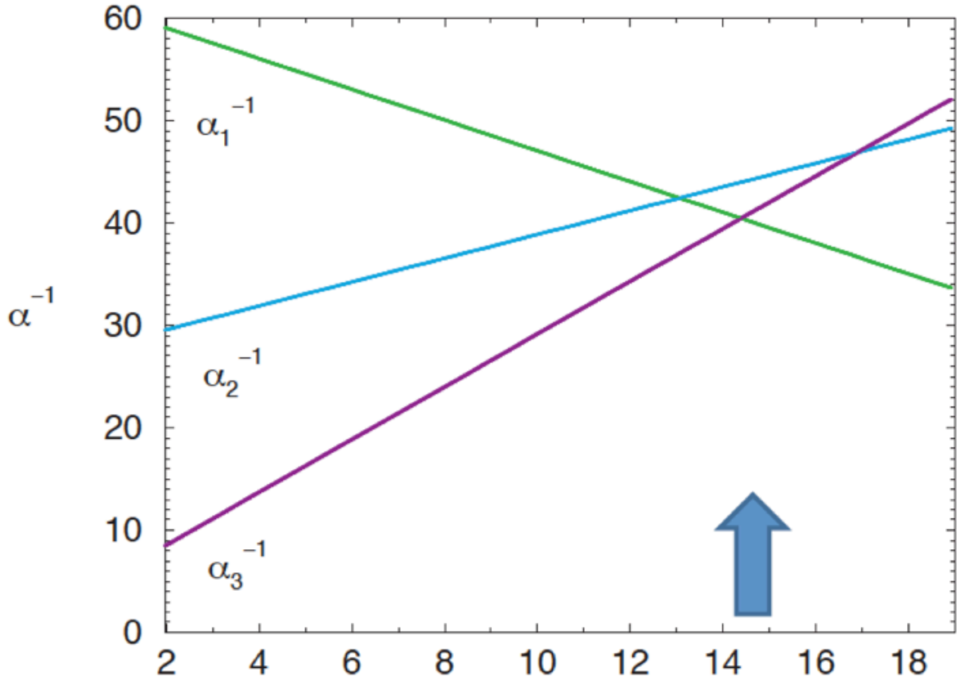




- This depends on nuclear physics that is not well understood.
- This has not been well measured, experimentally.

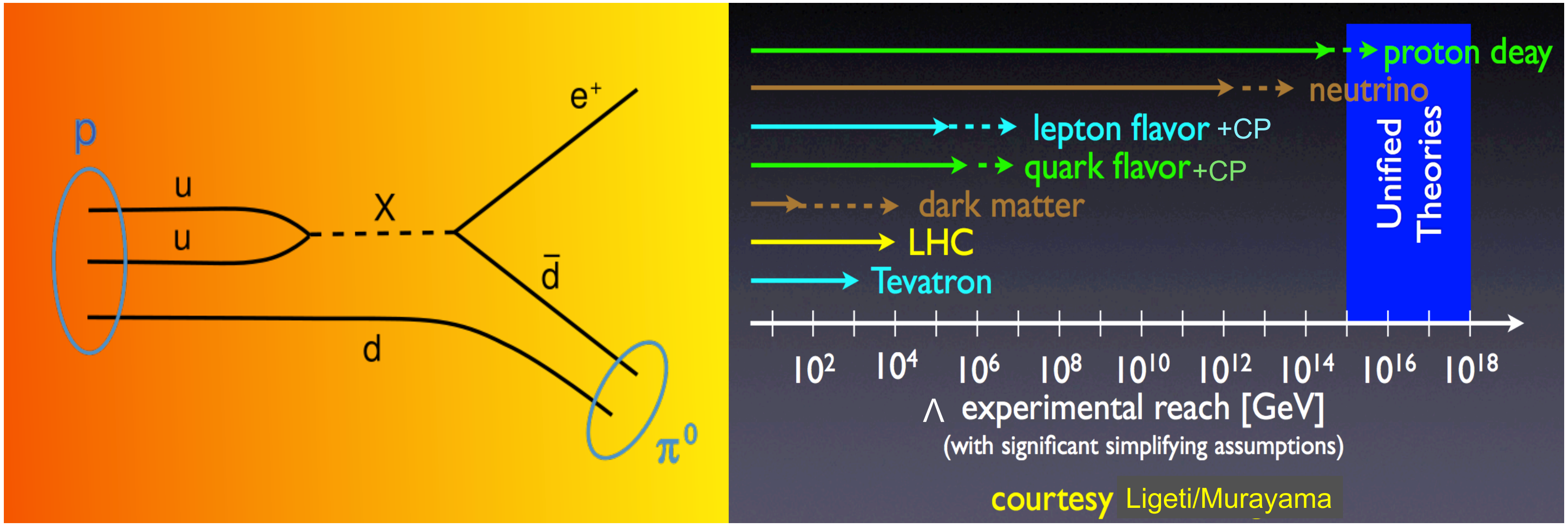
Proton Decay Searches Often Accompany Neutrino Experiments

- Proton decay searches often accompany neutrino experiments: similar signatures, detection techniques, and size scales
- One of the “Big Ideas” in particle physics is the notion that at higher energies, the laws of physics become increasingly symmetric and simple.
- A convergence of the coupling constants at a very high “unification energy” implies that there may be a single force that could connect quarks and leptons at that scale.



Proton Decay Searches Often Accompany Neutrino Experiments

- A consequence of this: baryon and lepton number are not conserved and protons can decay.
- We cannot probe these energies directly. At our energies proton decay is very rare.
- But, if we put enough protons in a detector and wait long enough, eventually we'll see one of these rare events.
- This would be a revolutionary discovery!



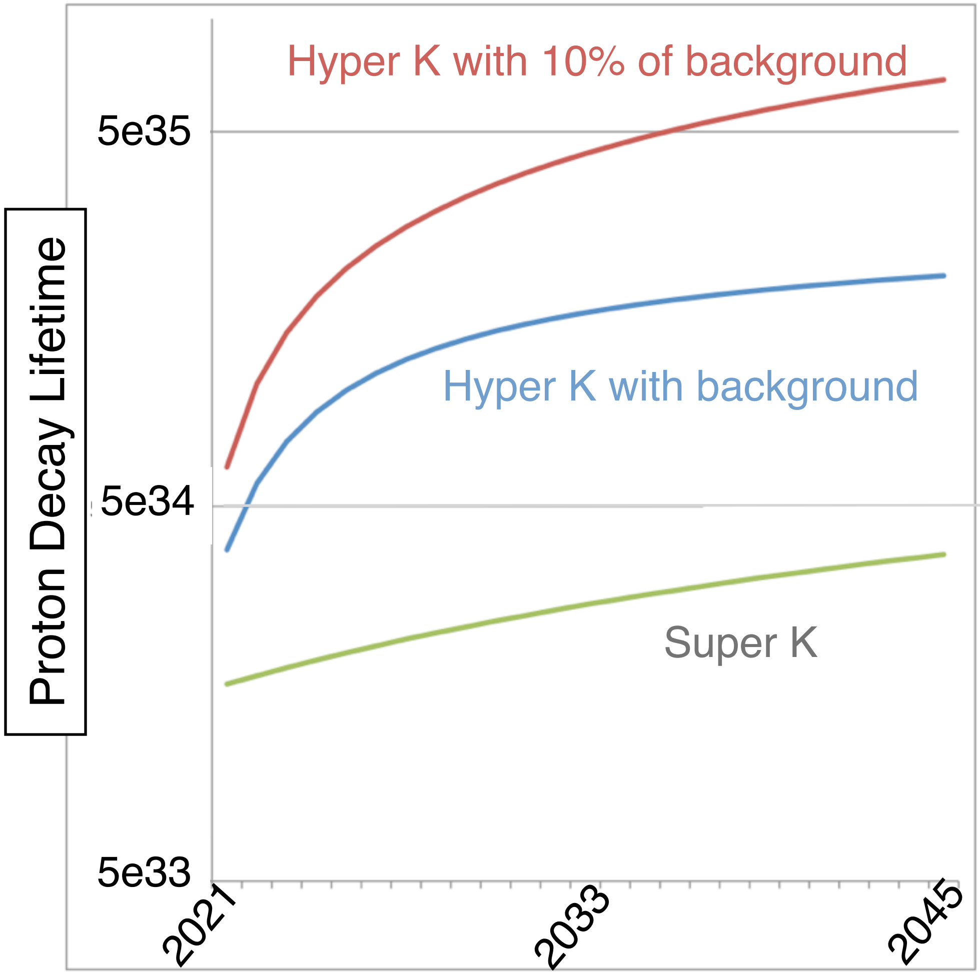
Motivation

Proton decay (PDK) searches in planned megaton-scale water Cherenkov detectors such as Hyper-K could achieve unprecedented sensitivity.

However, at such scales, previously negligible backgrounds from atmospheric neutrinos start to limit this sensitivity.

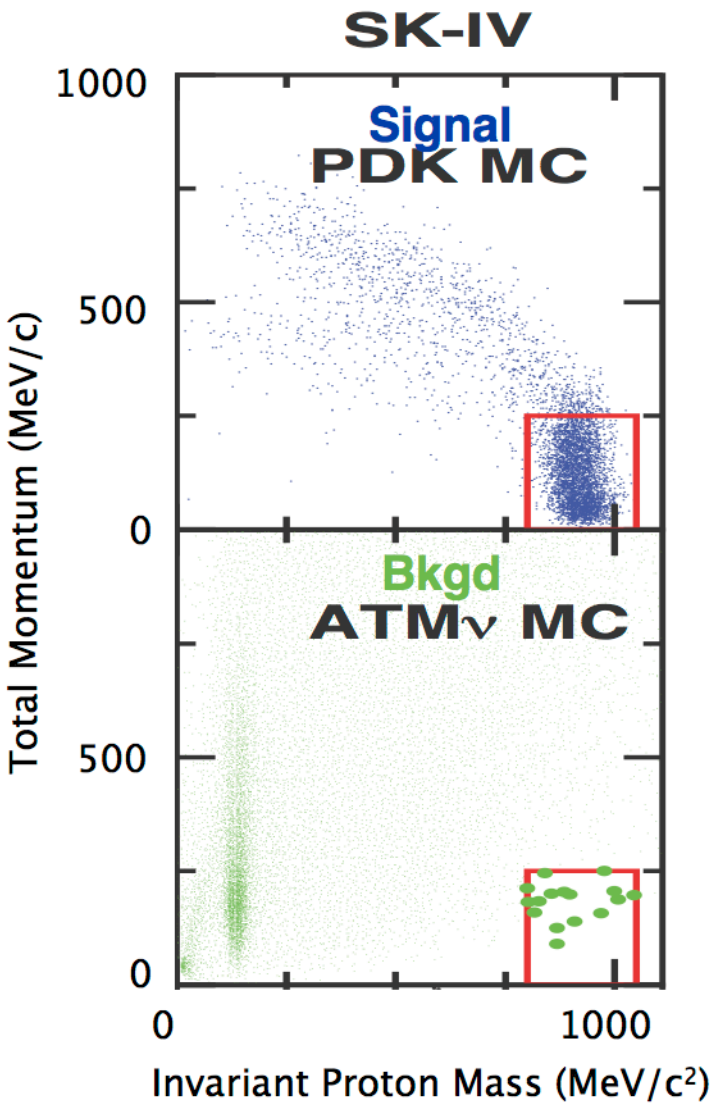
Techniques capable of reducing these backgrounds would have a large impact on the potential physics reach.

$p \rightarrow e^+ + \pi^0$



Motivation

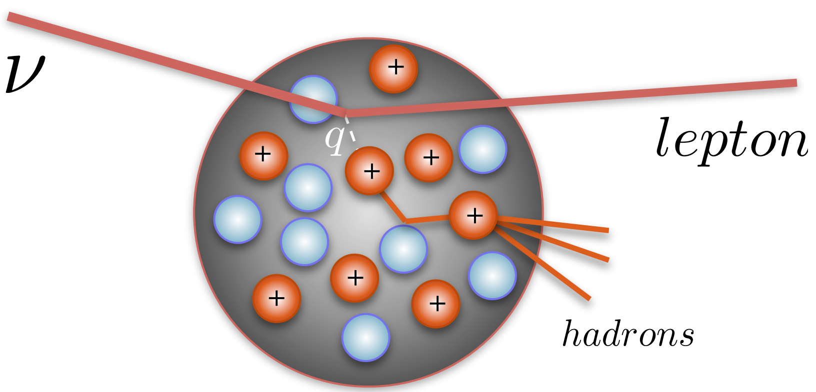
Backgrounds come almost exclusively from atmospheric neutrino interactions.

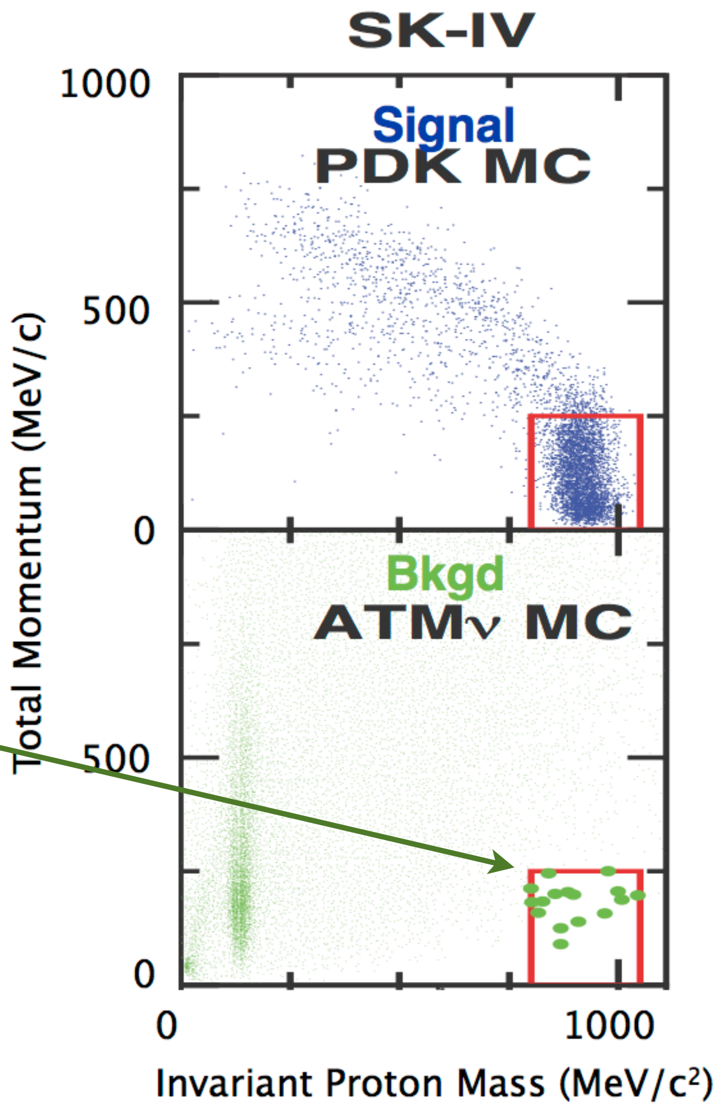


Motivation

Backgrounds come almost exclusively from atmospheric neutrino interactions

High energy neutrino interactions typically produce neutrons in the final state.



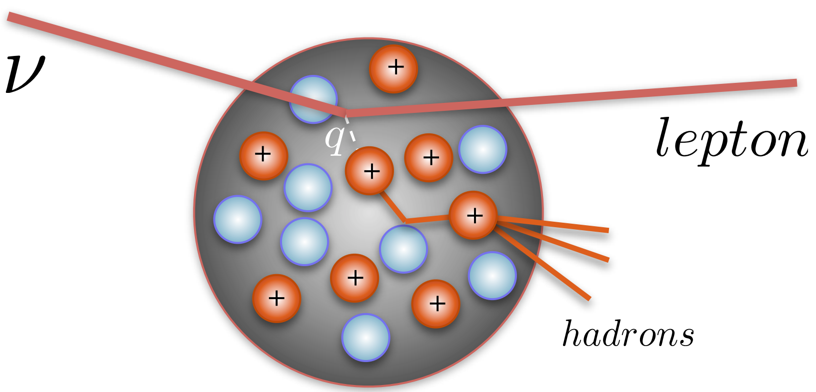


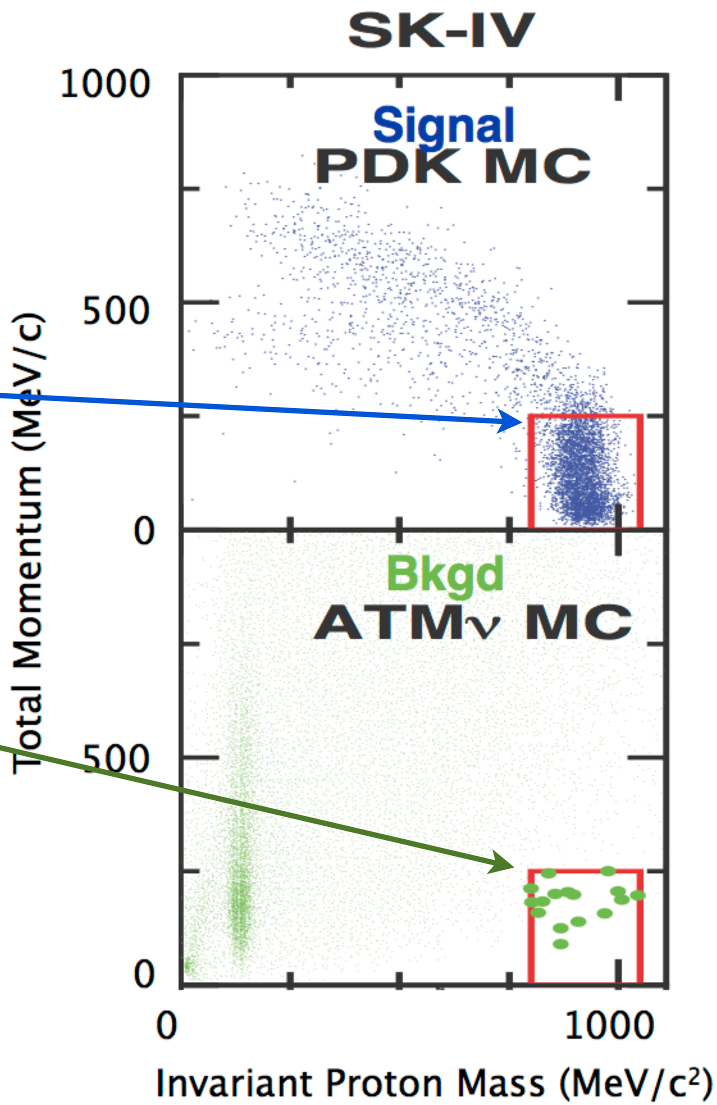
Motivation

Backgrounds come almost exclusively from atmospheric neutrino interactions

Proton decay events are expected to only rarely produce neutrons in the final state.

High energy neutrino interactions typically produce neutrons in the final state.





Motivation

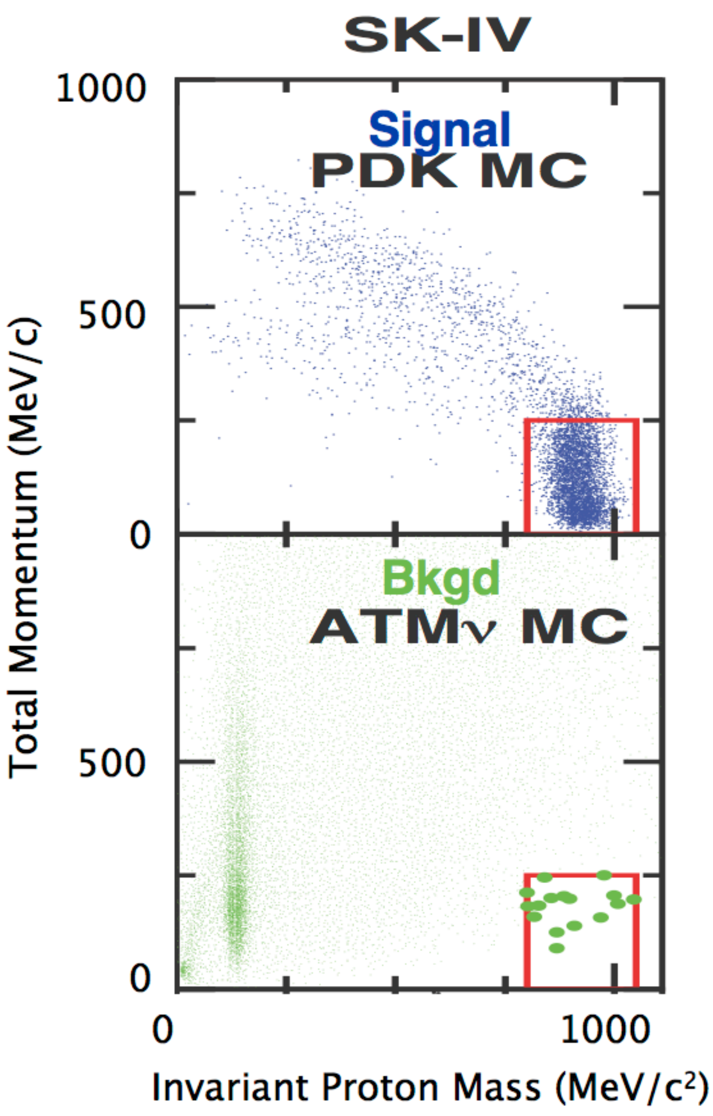
Backgrounds come almost exclusively from atmospheric neutrino interactions.

Proton decay events are expected to only rarely produce neutrons in the final state.

High energy neutrino interactions typically produce neutrons in the final state.

Thus, neutron-tagging in large Water Cherenkov detectors would provide a handle for separating between signal and background.

Efficient neutron-tagging can be achieved by dissolving Gadolinium salts in water. Gd has a high neutron capture cross-section and the captures release 8 MeV in gammas.



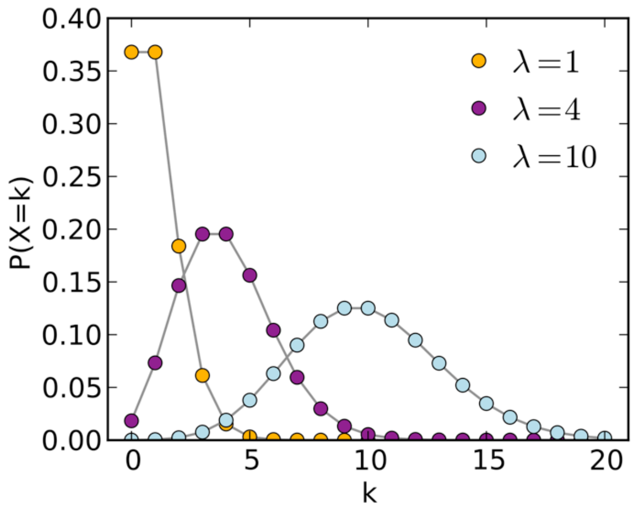
Why do I care "how many" neutrons are produced?

The presence of any neutrons can be used to confidently reject proton decay backgrounds.

But the absence of any neutrons is not necessarily a strong indicator of signal (could be detection inefficiency).

Attributing confidence to proton decay candidates without neutrons requires:

- knowledge of the neutron tagging efficiency, and
- **knowledge of how many neutrons are expected per background event**



Did we see zero neutrons, given an expectation of 1 or 10?
What is the number of expected neutrons? The spread?

It is not enough merely to identify the presence or absence of neutrons

The presence of any neutrons can be used to confidently reject PDK backgrounds (with little signal loss)

However the absence of any neutrons is not necessarily a strong indicator of signal (could be detection inefficiency).

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Some physics analyses require discrimination between different types of neutrino interactions (eg, CC vs NC) with different average neutron abundances.

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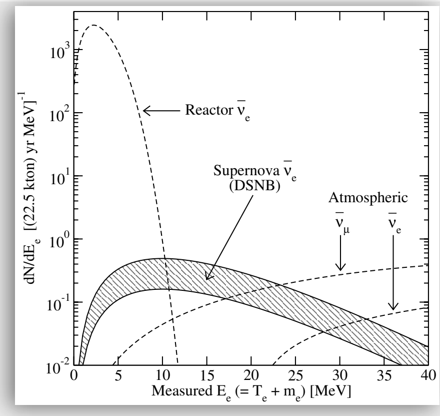
- **knowledge of how many neutrons are expected per background event**

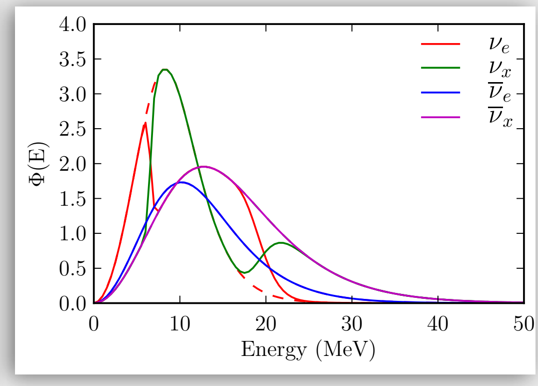
Some physics analyses require discrimination between different types of neutrino interactions (eg, CC vs NC) with different average neutron abundances.

This requires detailed understanding of the number of final-state neutrons:

The theoretical underpinnings of this observable are not well known
FS neutron abundances have not been well measured

Neutron Tagging May Have a Large Impact on Many Other Topics

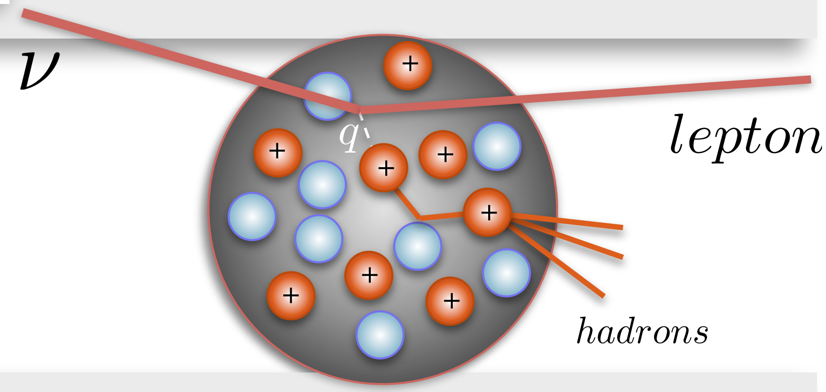




SN neutrino detection

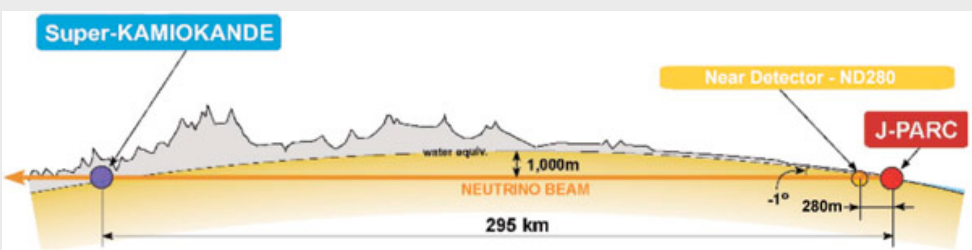
Help to separate diffuse cosmic SN neutrinos from various backgrounds

Help to disentangle the various fluxes from core collapse SN



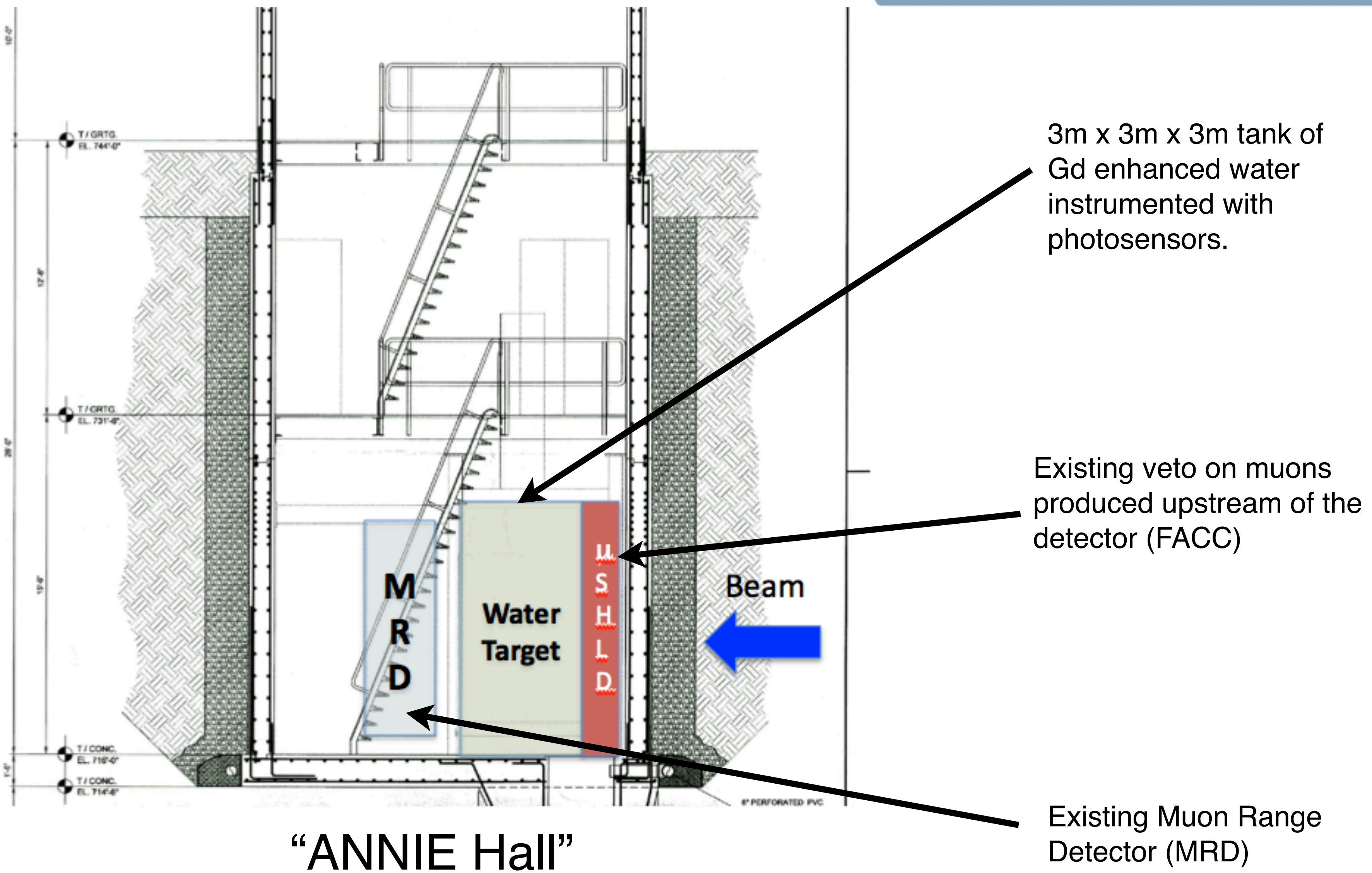
Neutrino interaction Physics

Help to constrain and distinguish between various models of neutrino nucleon interactions



Precision Neutrino Oscillation Measurement

help reduce uncertainties on neutrino cross-sections (largest systematic in T2K)



“ANNIE Hall”

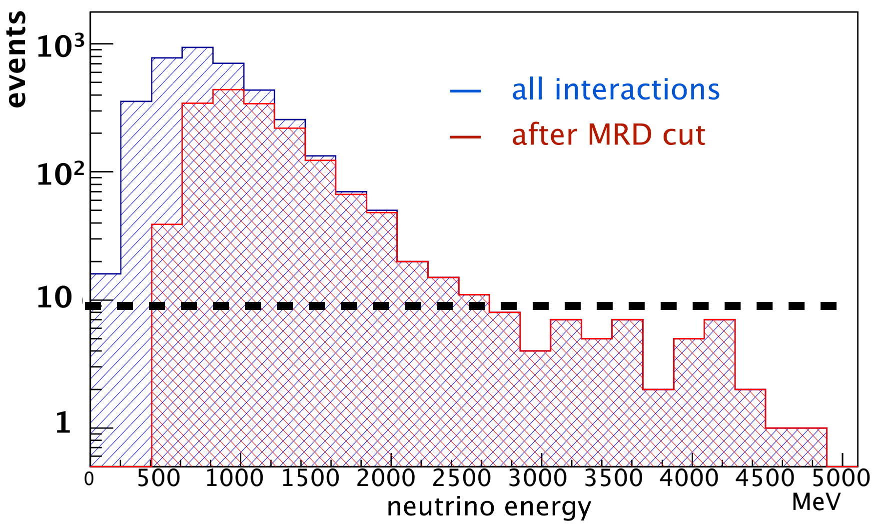
(formerly the SciBooNE pit)

The Booster Neutrino Beam Delivers The Needed Flux

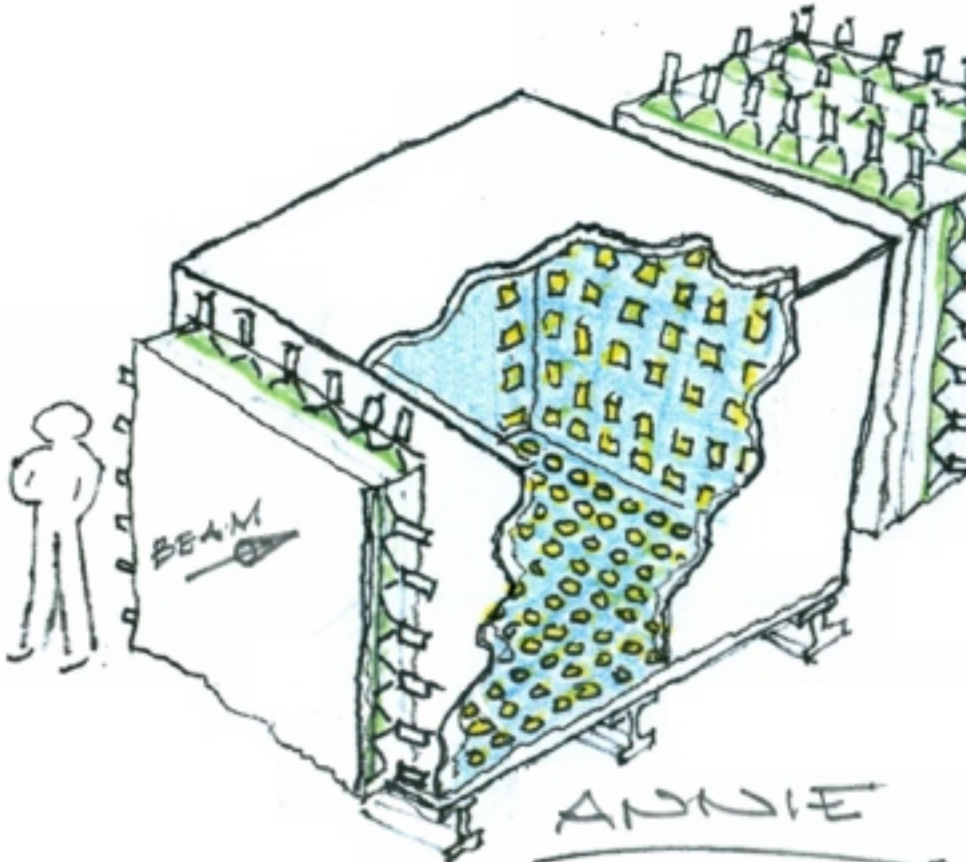
- Expected proton decay backgrounds typically come from interactions from around 1-5 GeV.
- The Booster Neutrino Beam provides an energy spectrum peaked near 1 GeV.
- We will see several hundreds of ν_μ CC interactions per 10^{20} POT per ton in the relevant window, and several tens of events at the highest energies.

Expected Event Rates in Booster Neutrino Beam

Nevts / 10^{20} POT / 200 MeV



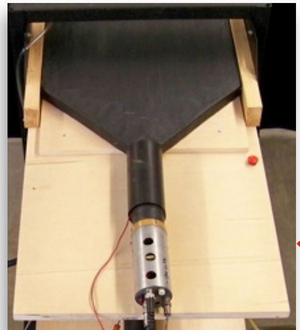
The ANNIE Detector System



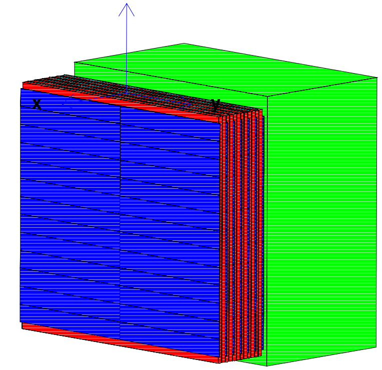
R. Northrop

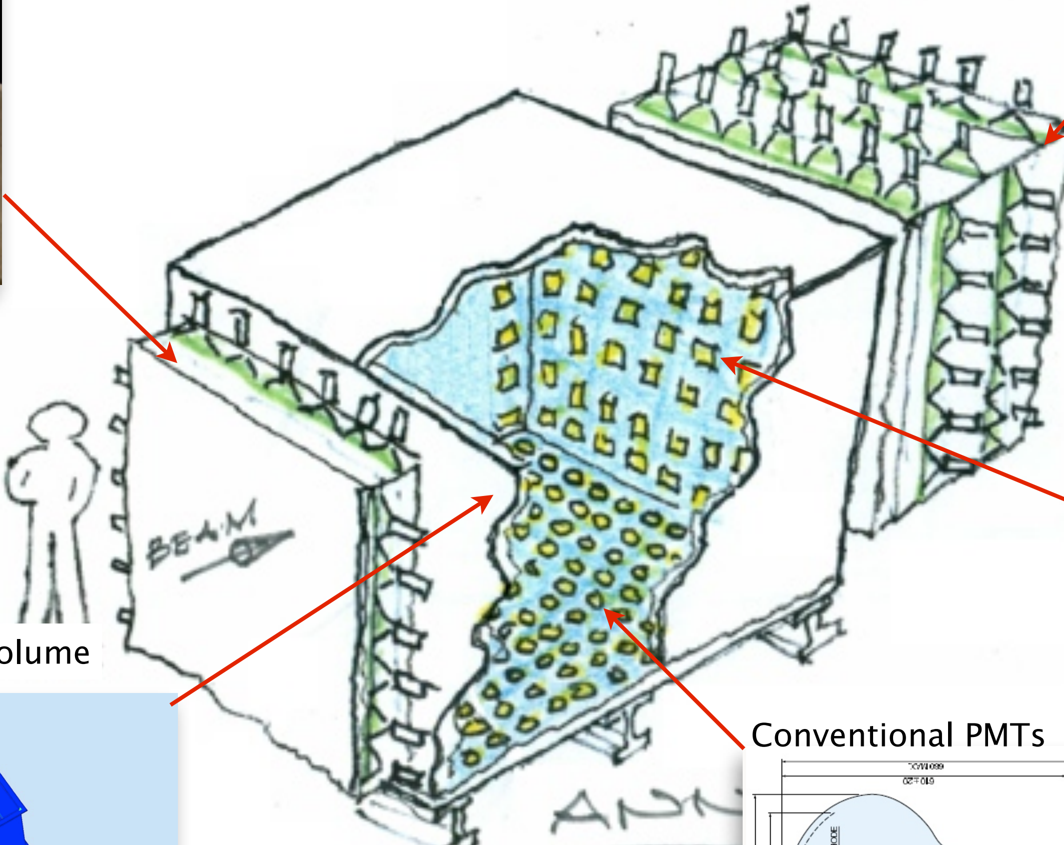
The ANNIE Detector System

Front Anti-Coincidence Counter



Muon Range Detector

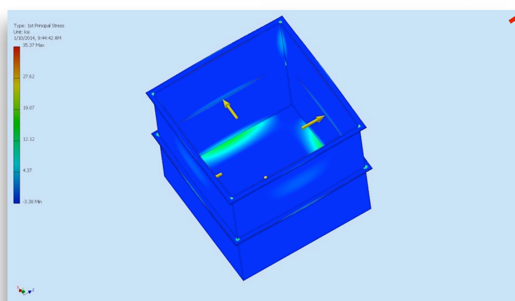




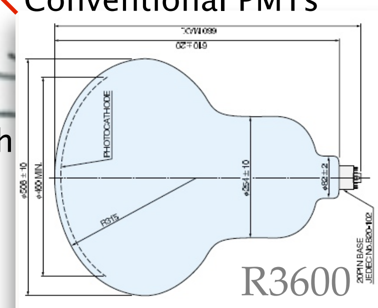
R. North

LAPPDs

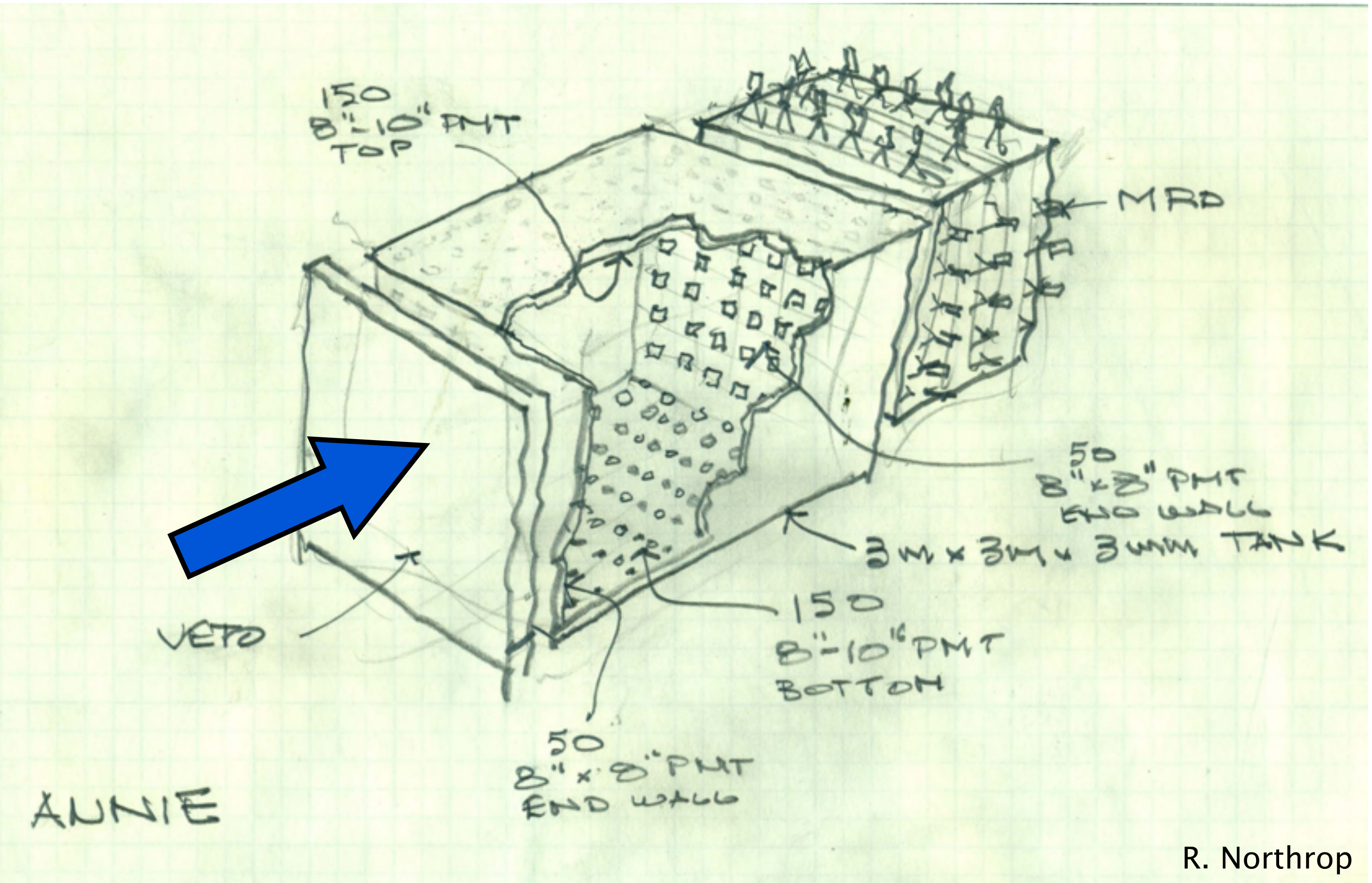
Gd-loaded water volume



Conventional PMTs



ANNIE – basic concept



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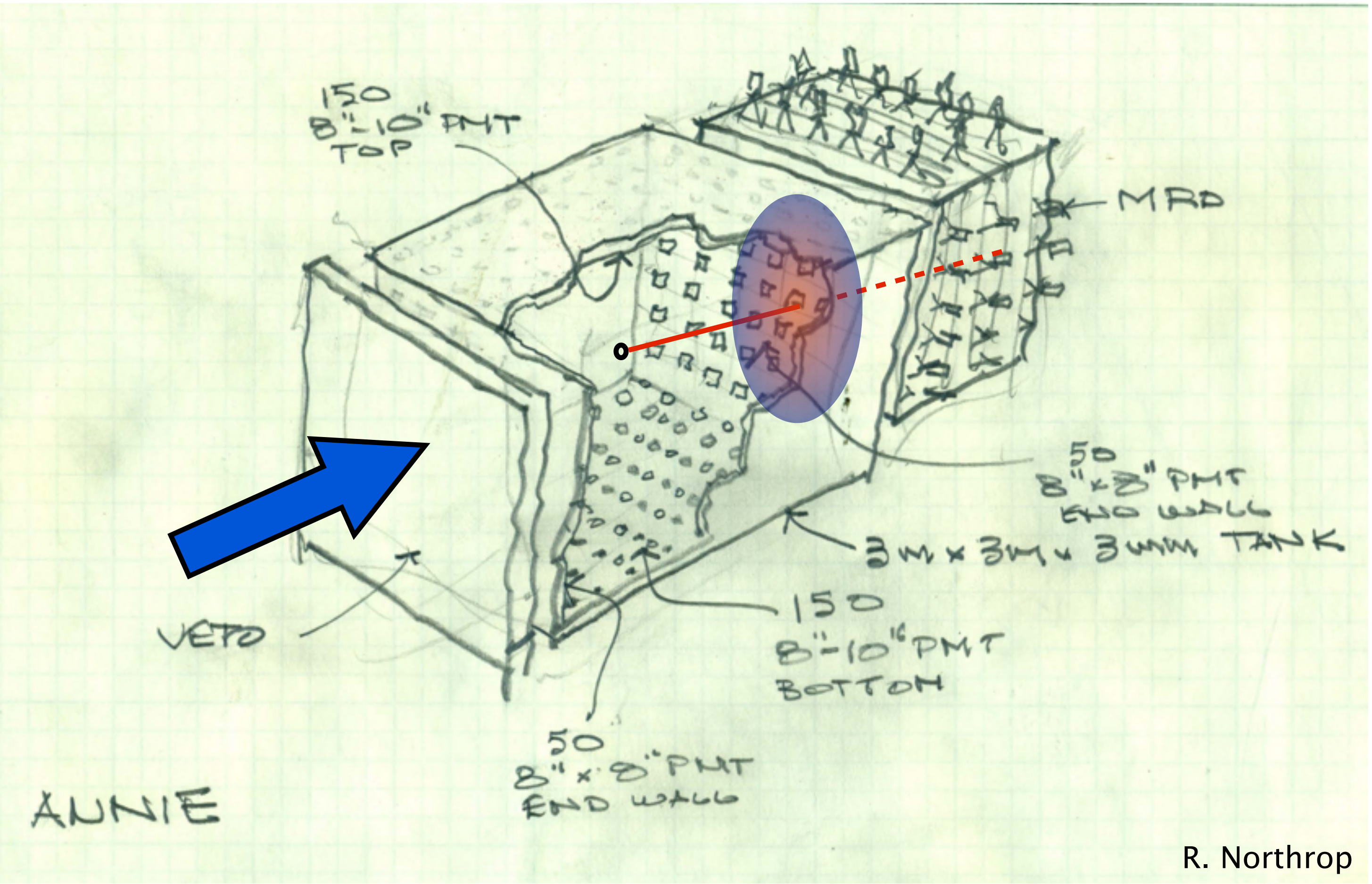
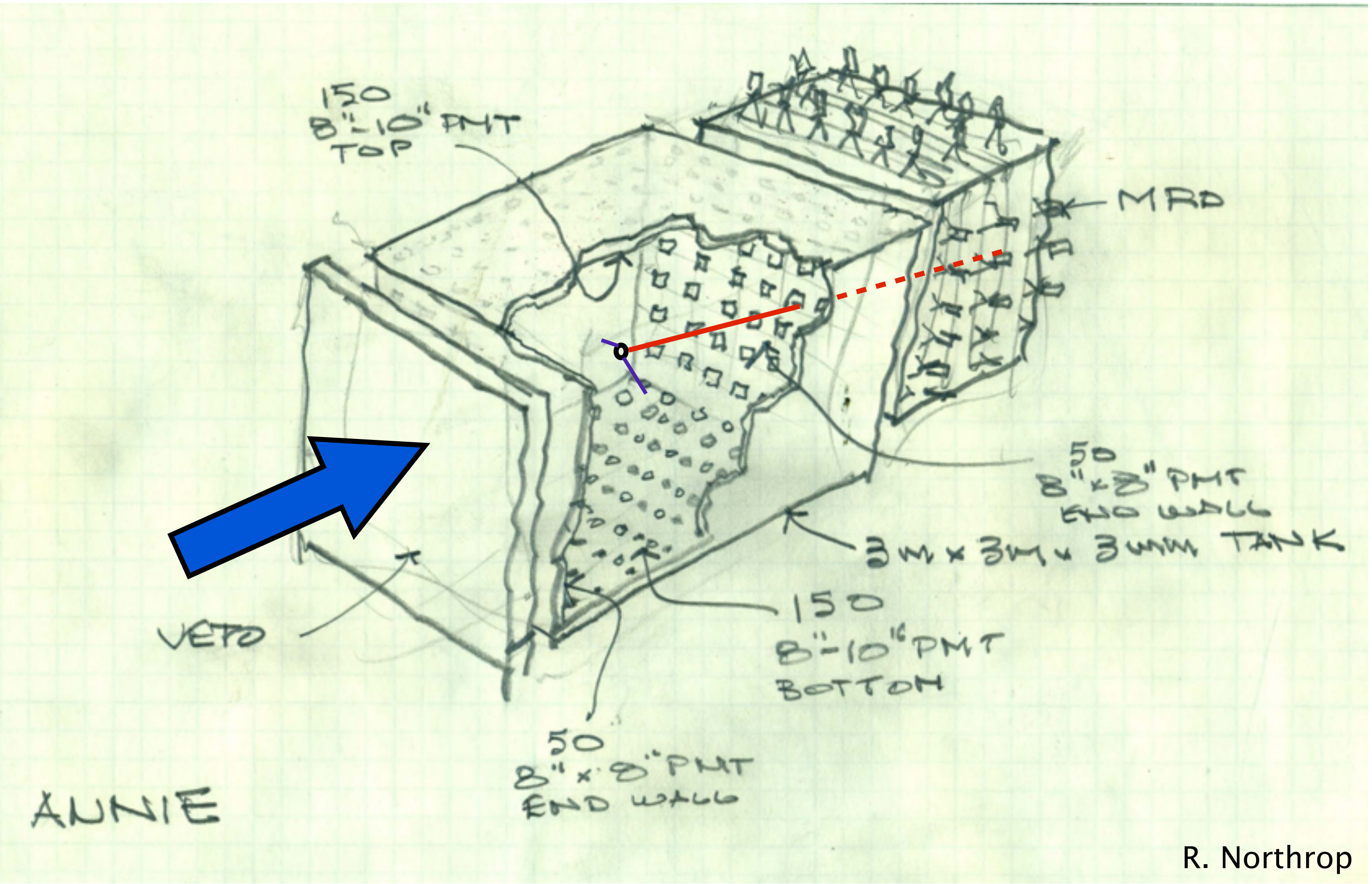


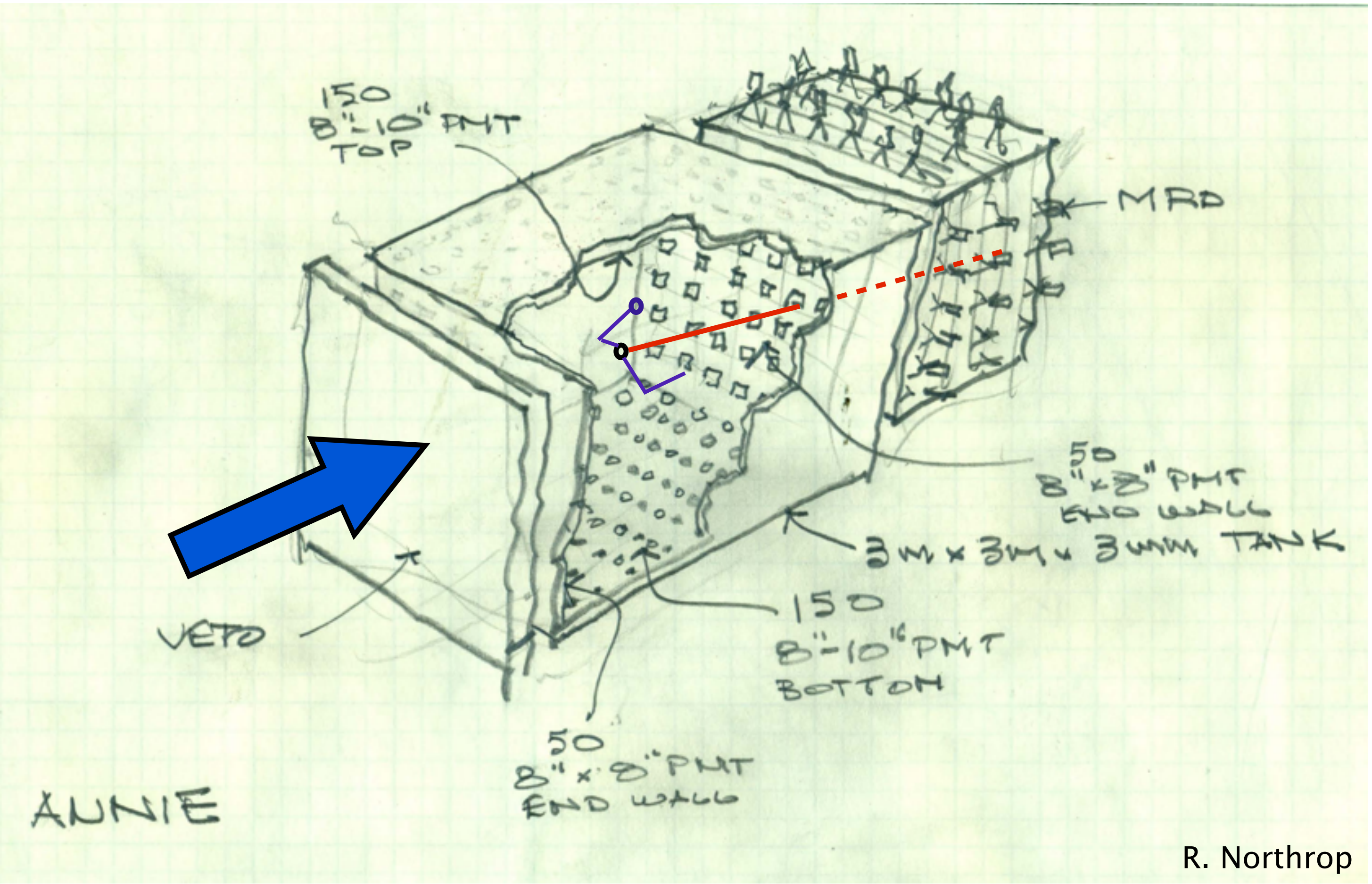
- A muon is produced and detected in the MRD.
- LAPPDs used to reconstruct vertex position based on arrival of Cherenkov light.

ANNIE – basic concept



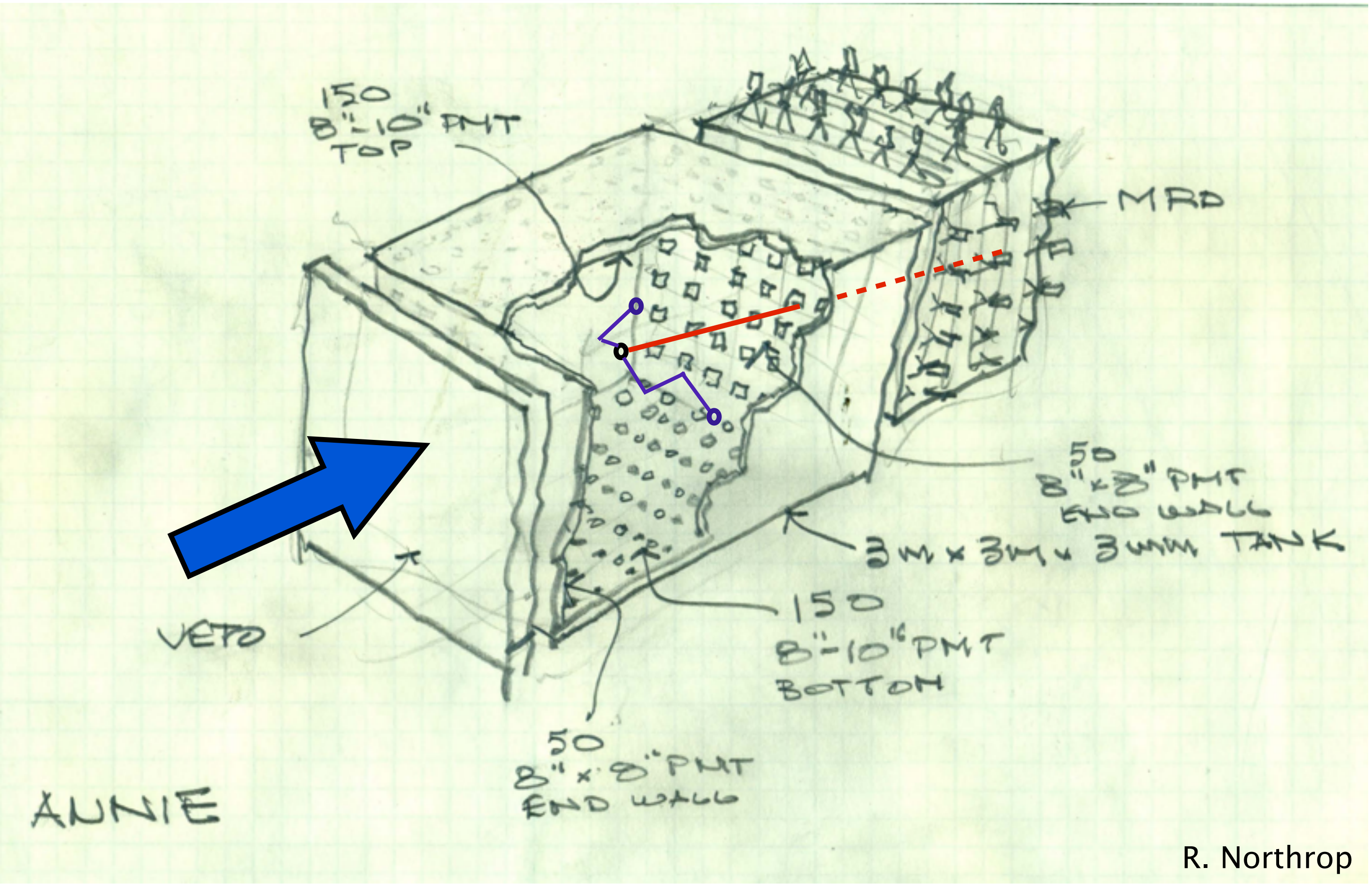
- A muon is produced and detected in the MRD.
- LAPPDs used to reconstruct vertex position based on arrival of Cherenkov light.
- Neutrons thermalize

ANNIE – basic concept



- A muon is produced and detected in the MRD.
- LAPPDs used to reconstruct vertex position based on arrival of Cherenkov light.
- Neutrons thermalize and stop.

ANNIE – basic concept



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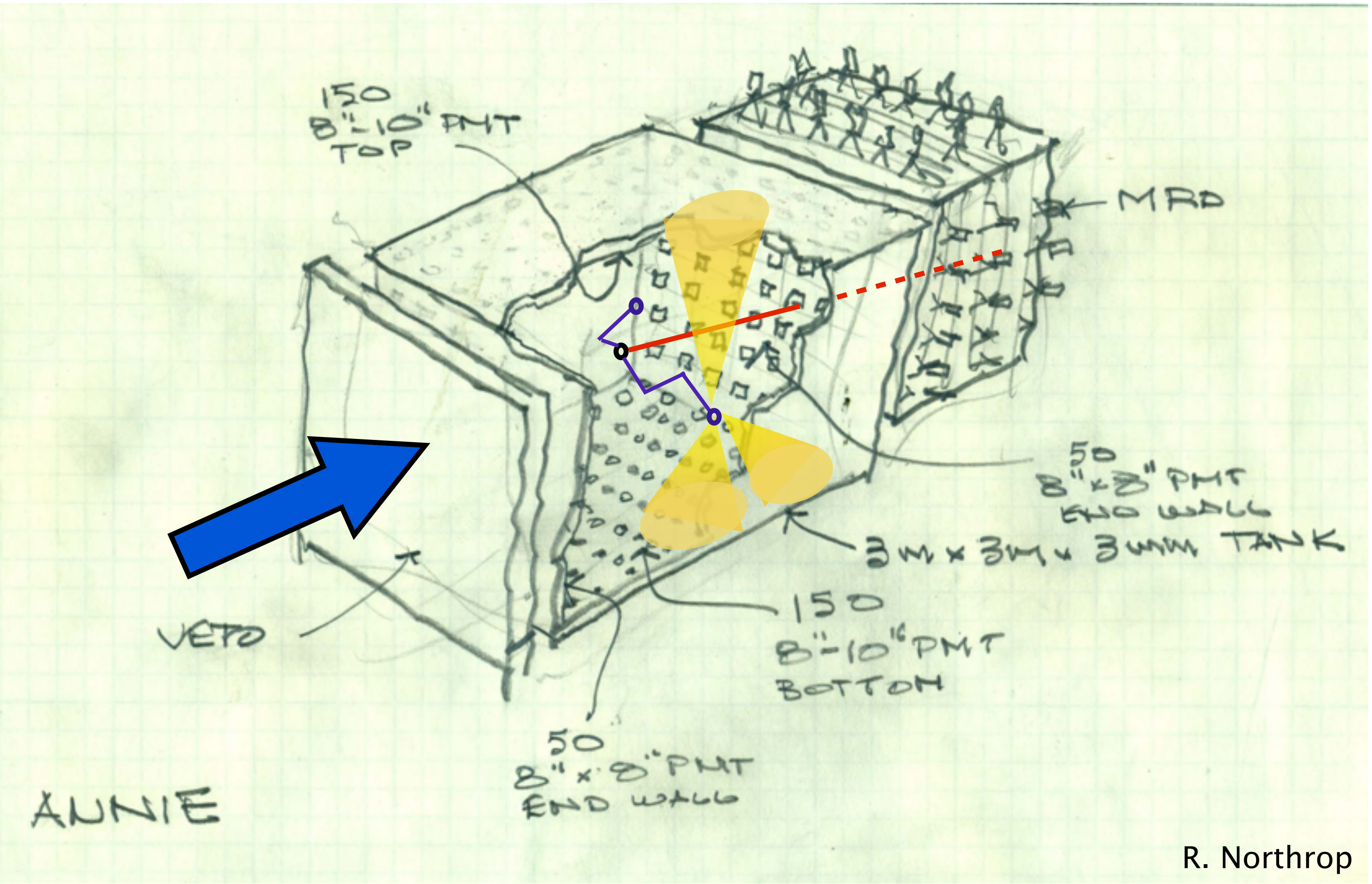

R. Northrop

- A muon is produced and detected in the MRD.
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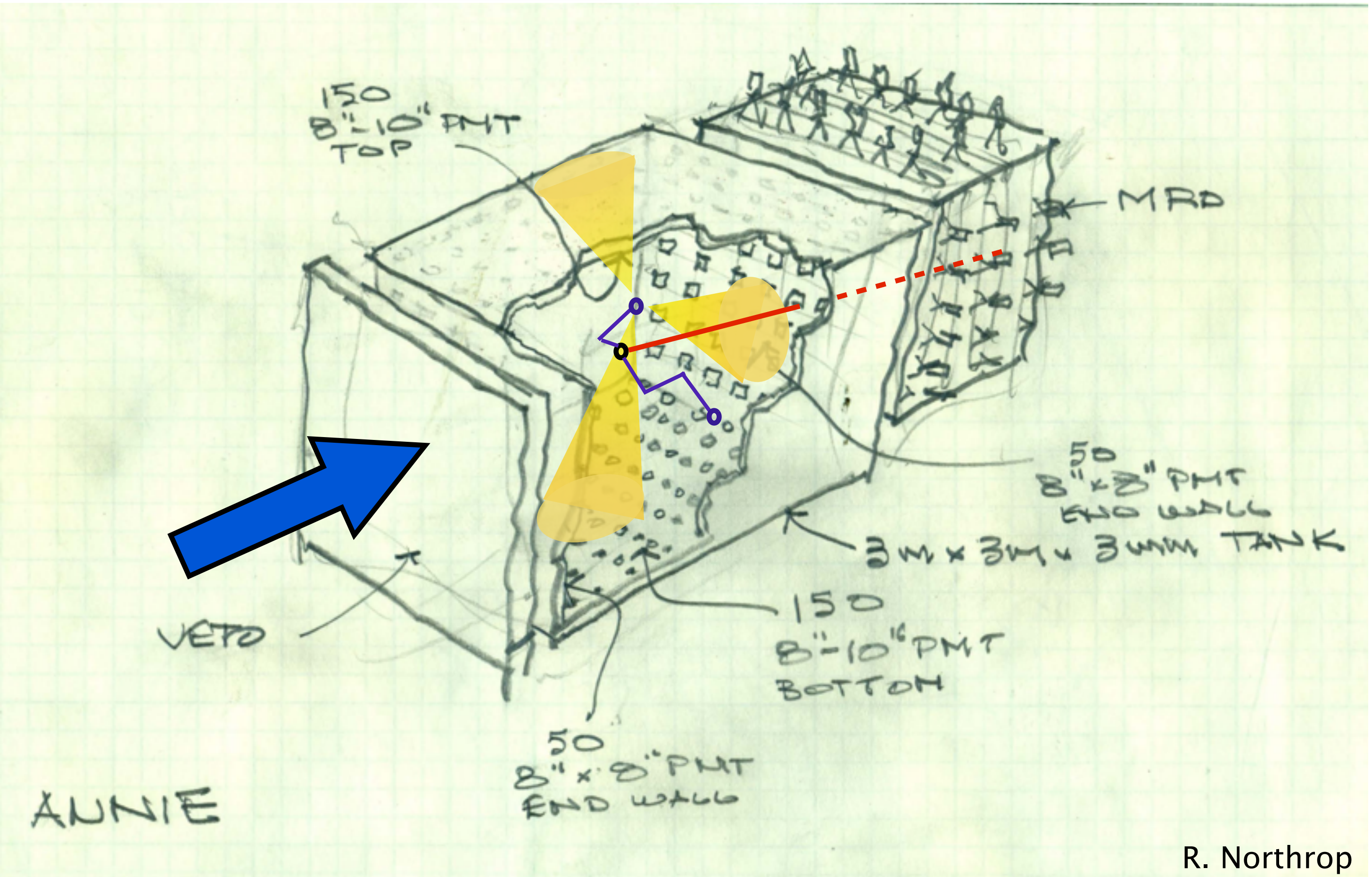
- Several tens of microseconds later, the neutrons are captured and produce somewhat isotropic flashes of light from typically 3 gamma showers (8 MeV).

ANNIE – basic concept



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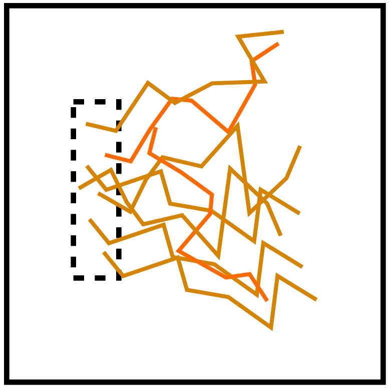
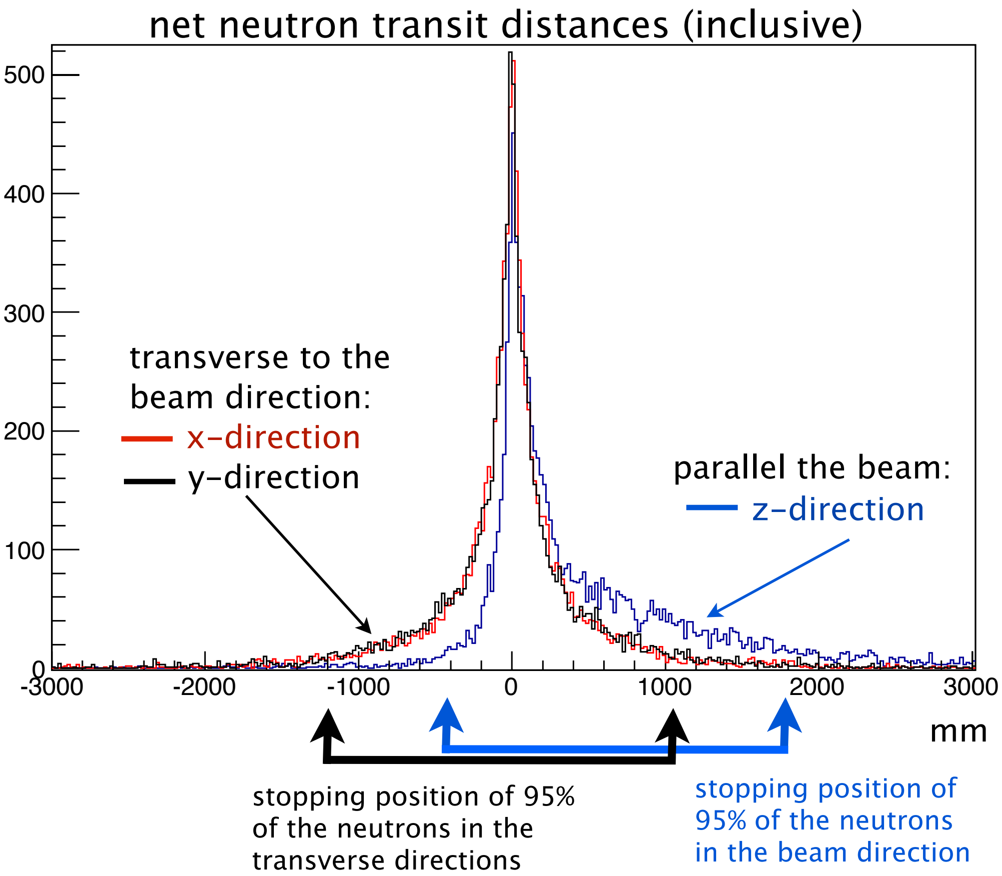
Timing-based vertex reconstruction is essential

Neutrons in ANNIE will typically drift over a 2 meter distance.

In order to get a clean sample of neutrons, this analysis must be restricted to a small ~1 ton fiducial volume situated sufficiently far from the walls of the tank to stop the neutrons.





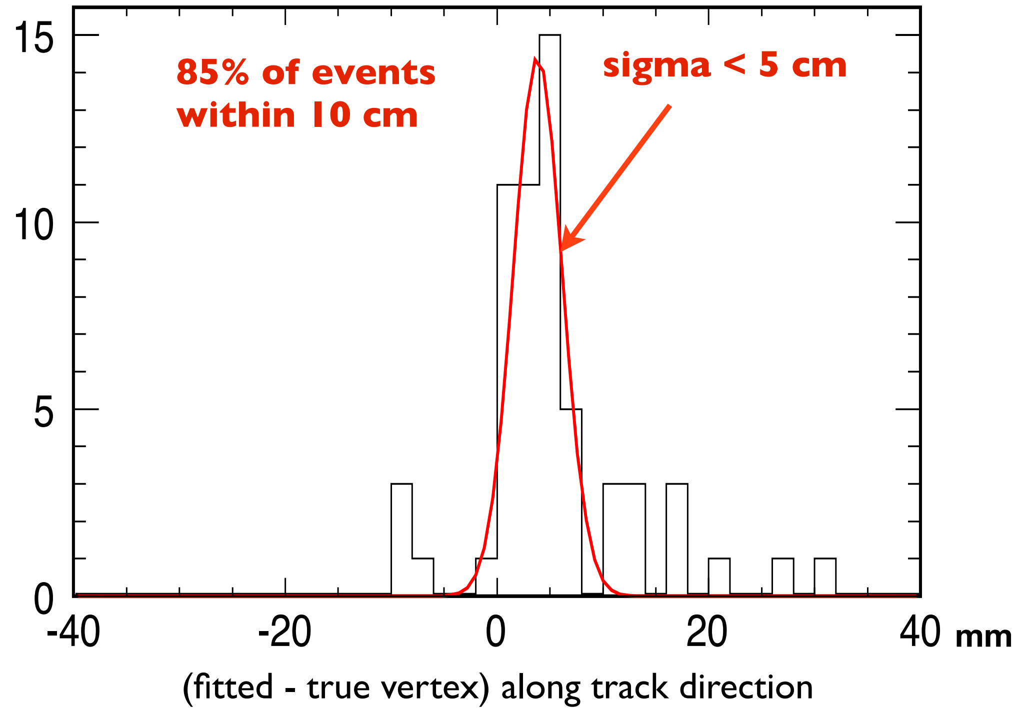
In order to identify events in this fiducial volume, we need to reconstruct the interaction vertex to better than 10 cm. Accurate timing based reconstruction from the Cherenkov light is essential.

Timing-based vertex reconstruction is essential

New technologies often require new reconstruction strategies.

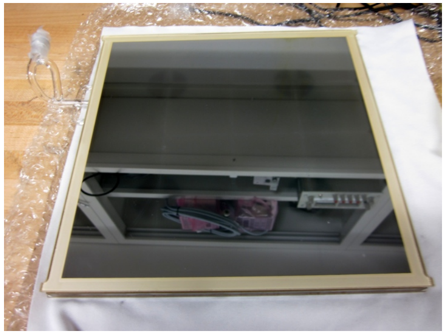
Groups at U Chicago, Iowa State, and Argonne have done considerable work on the application of LAPPDs to W Ch detectors.

Preliminary work, specifically for ANNIE shows promise: a very simple starting algorithm gives resolutions close to our target.



These techniques need to be further developed and optimized for the ANNIE detector. We also need these results to guide optimization of the detector design.

LAPPD Collaboration
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

Key Elements of the LAPPD Detector

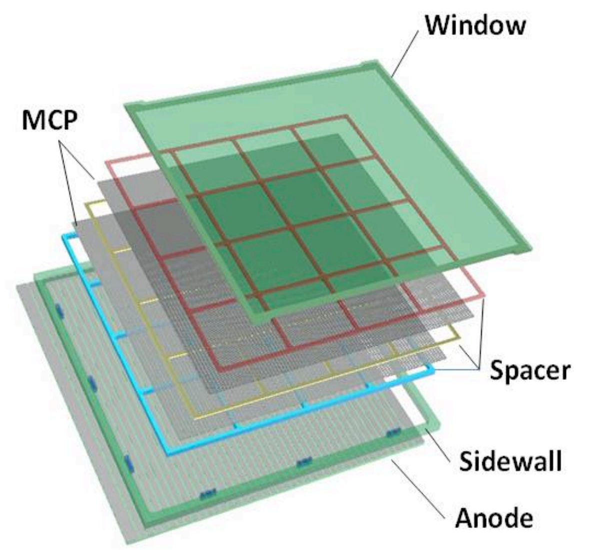
Glass body, minimal feedthroughs

MCPs made using atomic layer deposition (ALD).

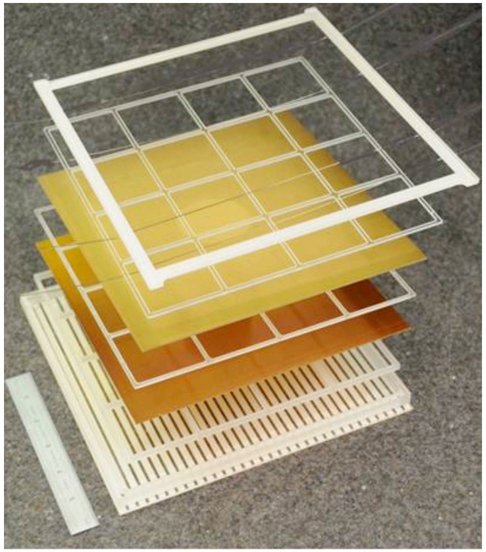
transmission line anode

fast and economical front-end electronics

large area, flat panel photocathodes



Design Drawing - September 2010



Actual Glass Parts - April 2012

LAPPD – Testing

We were published in Review of Scientific Instrumentation as the cover article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Collaboration between varied organizations develops larger, more precise photodetectors for the market

BY CHELSEA LEU • NOVEMBER 5, 2013

Like 56 Tweet 8 Share Email Print

Scientific particle detectors, medical imaging devices and cargo scanners with higher resolutions and cheaper price tags could become a reality, thanks to a three-way collaboration between industry, universities and U.S. national laboratories.

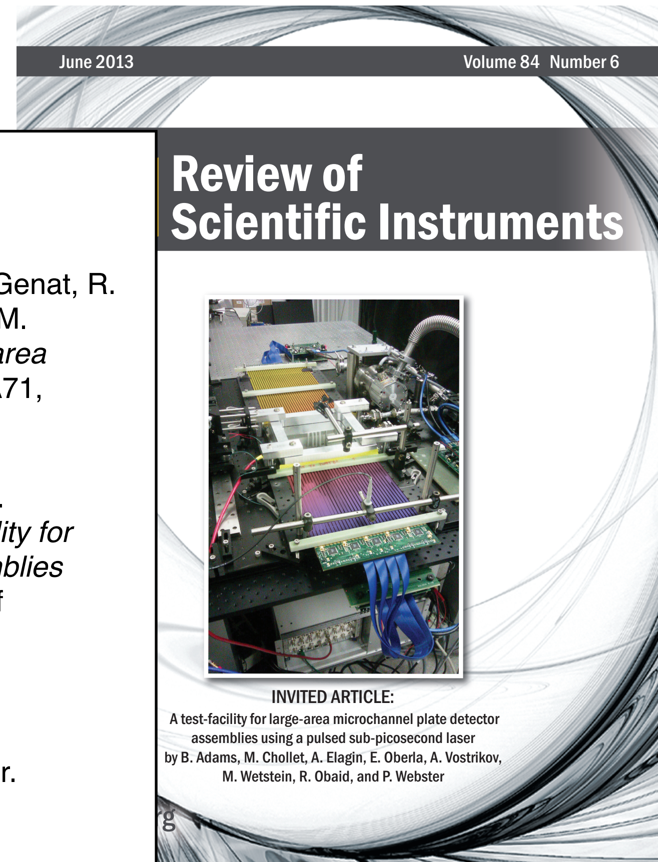
Pulling together expertise from a variety of scientific disciplines, a team of scientists has designed a photodetector system that detects the arrival

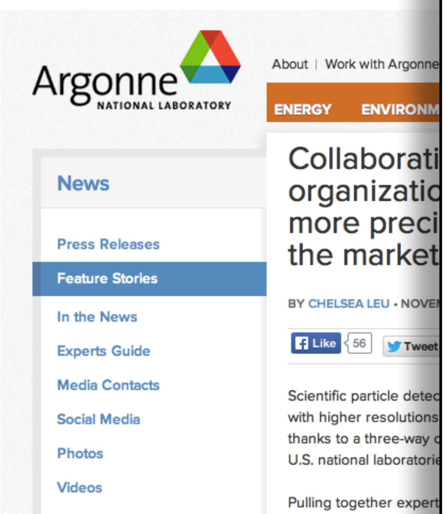
Andrey Elagin (left), postdoctoral scholar at the Enrico Fermi Institute at the University of Chicago, and Matthew Wetstein, the Grainger Postdoctoral Fellow at the Enrico Fermi Institute at the University of Chicago, adjust the optics in the Large Area Picosecond Photodetector testing facility. The facility uses extremely short laser pulses to precisely measure the time resolution of the photodetectors. Click to enlarge.

Enjoyed a short lived status as "rock stars"

LAPPD – Testing

We were pub
Scientific Ins
the cover art





a few key LAPPD papers

H. Grabas, R. Obaid, E. Oberla, H. Frisch J.-F. Genat, R. Northrop, F. Tang, D. McGinnis, B. Adams, and M. Wetstein; *RF Strip-line Anodes for Psec Large-area MCP-based Photodetectors*, Nucl. Instr. Meth. A71, pp124-131, May 2013

B. Adams, M. Chollet, A. Elagin A. Vostrikov, M. Wetstein, R. Obaid, and P. Webster; *A Test-facility for Large-Area Microchannel Plate Detector Assemblies using a Pulse Sub-picosecond Laser;* Review of Scientific Instruments 84, 061301 (2013)

E. Oberla, J.-F. Genat, H. Grabas, H. Frisch, K. Nishimura, and G Varner; A 15 GSa/s, 1.5 GHz *Bandwidth Waveform Digitizing ASIC*; Nucl. Instr. Meth. A735, 21 Jan., 2014, 452; http://dx.doi.org/10.1016/j.nima.2013.09.042; arxiv:http://arxiv.org/abs/1309.4397

O.H.W. Siegmund,*, J.B. McPhate, J.V. Vallerga, A.S. Tremsin, H. Frisch, J. Elam, A. Mane, and R. Wagner; *Large Area Event Counting Detectors with High Spatial and Temporal Resolution;* submitted to JINST; Dec, 2013

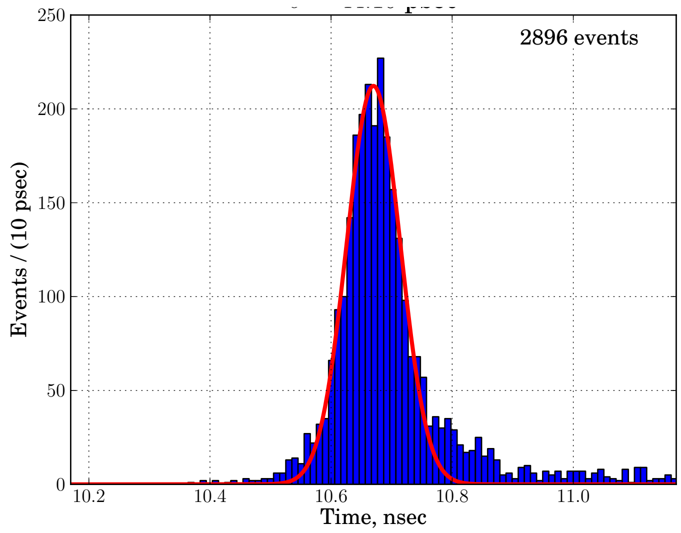
See http://psec.uchicago.edu for more references

d a short lived status as
tars”

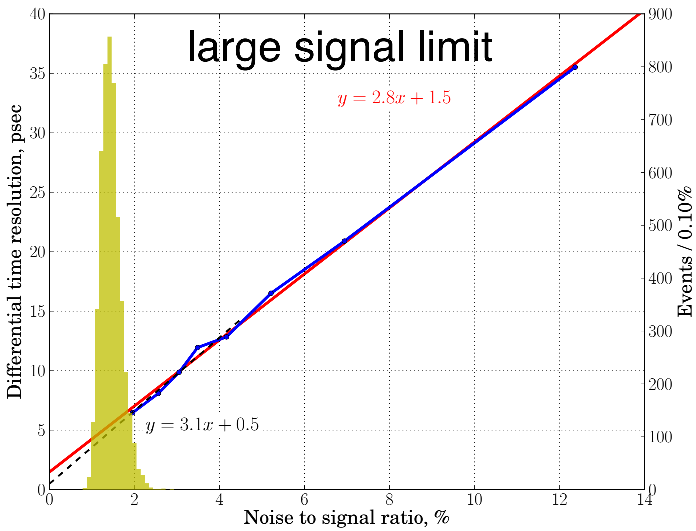
LAPPD – Testing

We measured typical single photoelectron (PE) time resolutions below 50 picoseconds.

single PE: σ ~ 44 psec

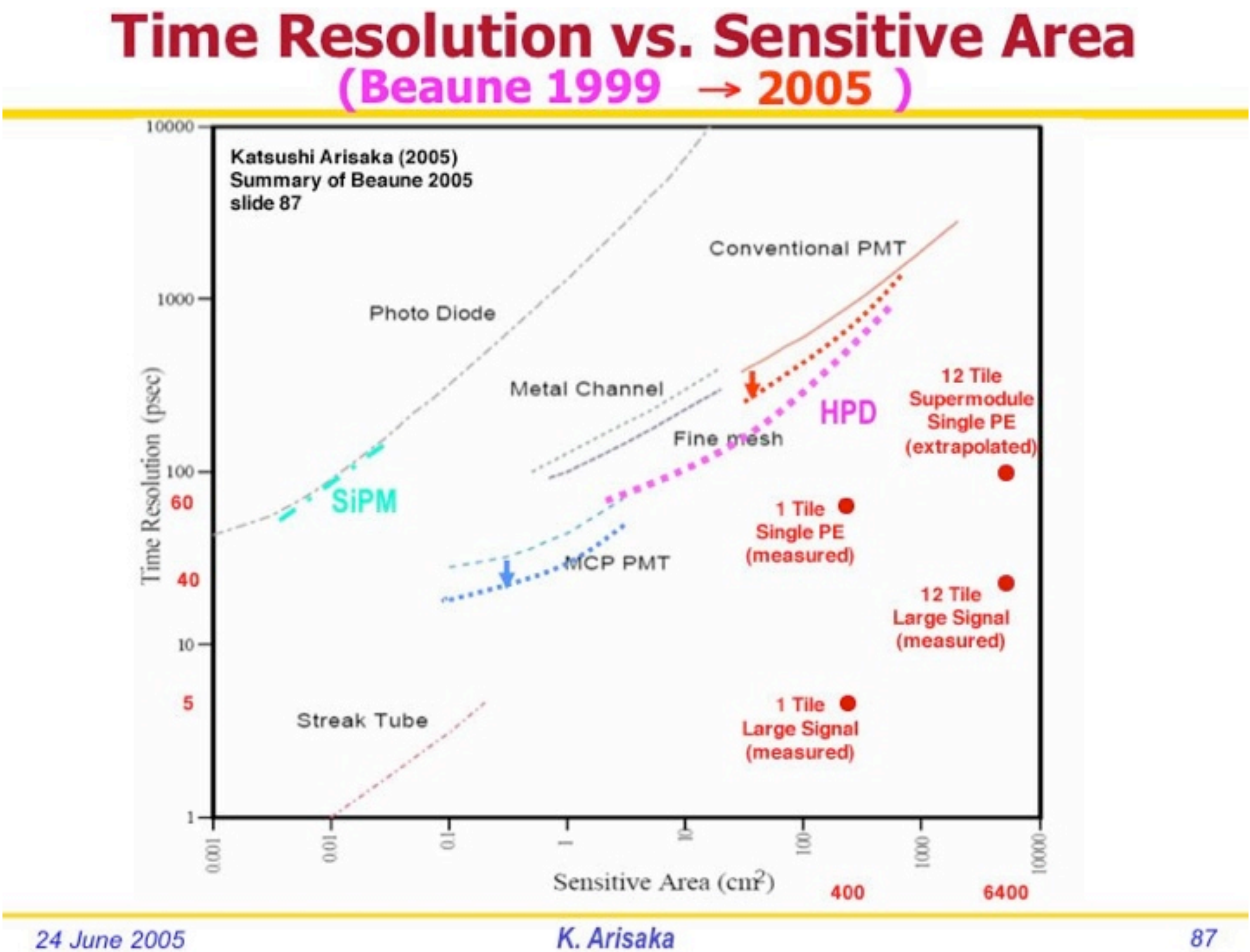


large signal limit



We measured the large signals (multi-PE) down to σ ~ 7 psec with the limit extrapolating to ~ 1 psec.

LAPPD – Testing



This puts us in new territory....

LAPPD2 – What's Next

LAPPDs are now in the commercialization phase. Incom, Inc has submitted a Phase II TTR application ($3M).

Work in support of that effort is important.

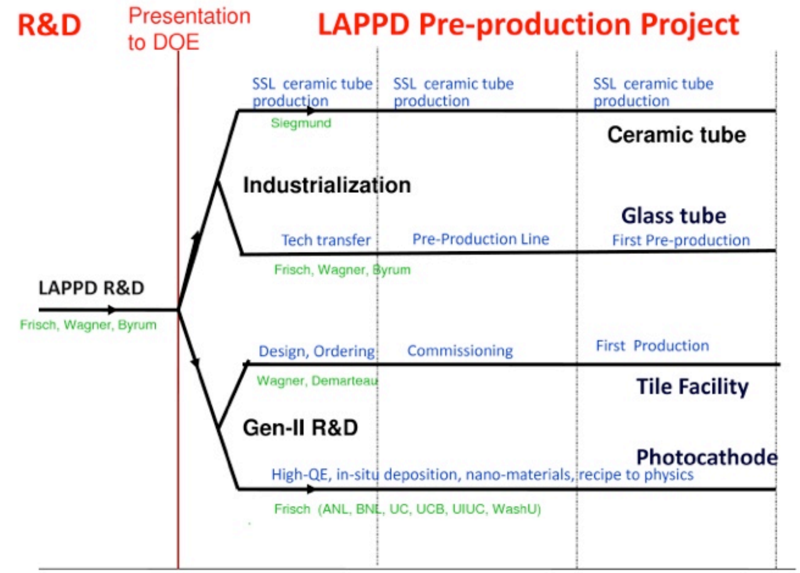
This also presents an opportunity to pursue new ideas:

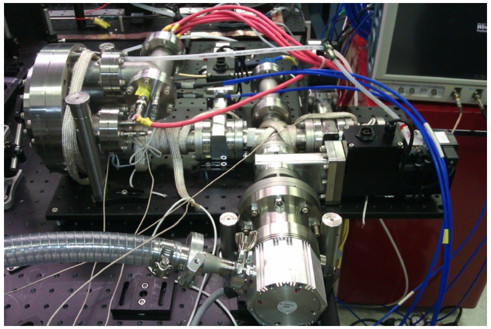
- further improve performance
- further reduce cost of manufacture

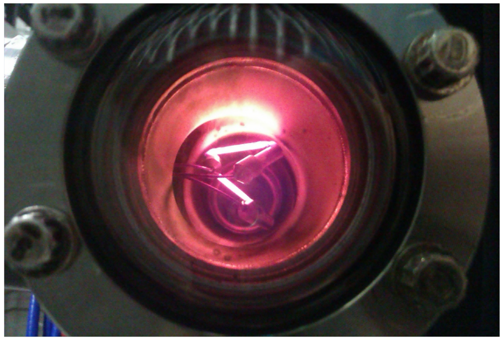
One fruitful effort is on the development of better photocathodes.

A major remaining cost in the manufacture of LAPPDs is the necessity of a "transfer photocathode" which requires large and expensive vacuum infrastructure.

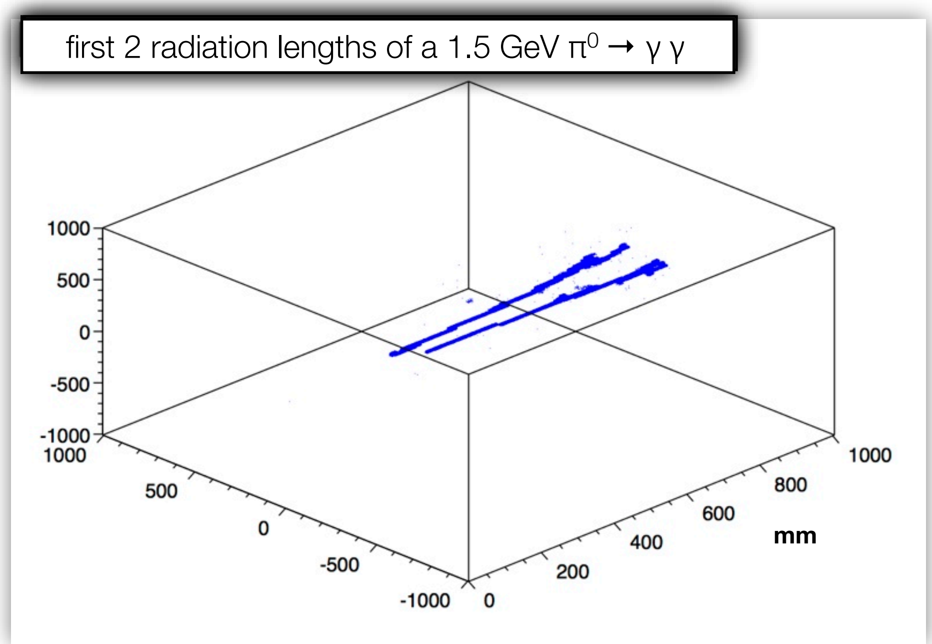
If it were possible to deposit or activate photocathodes through a glass tube into an already sealed tile, this would be a game changer.

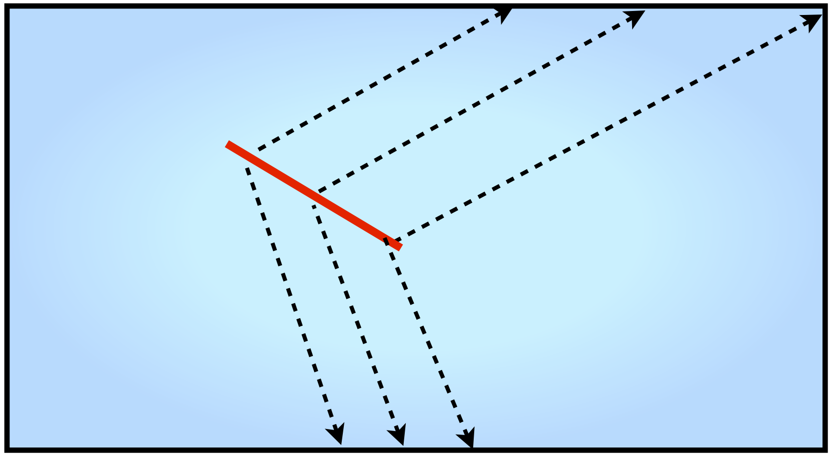






Full Track Reconstruction: A TPC Using Optical Light?





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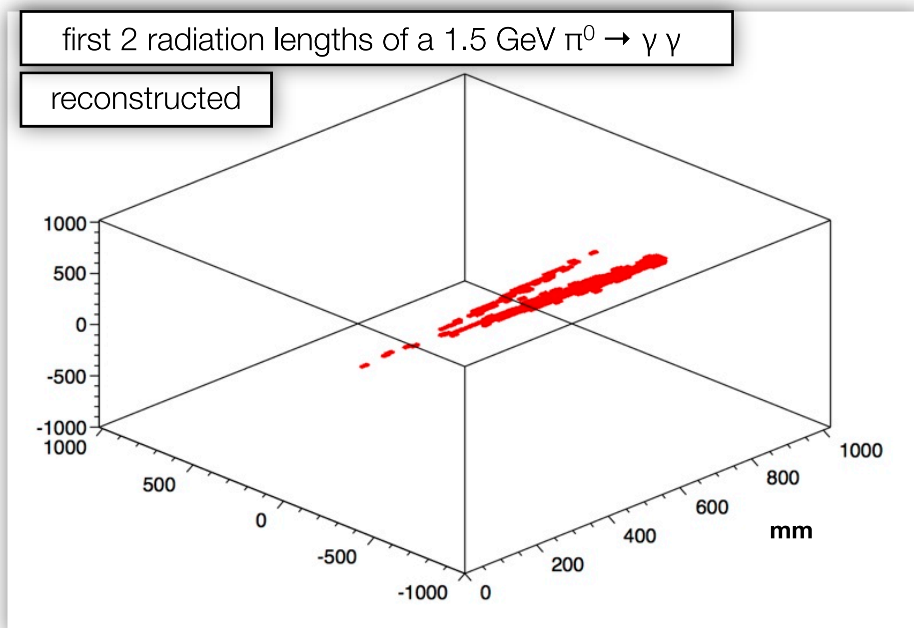
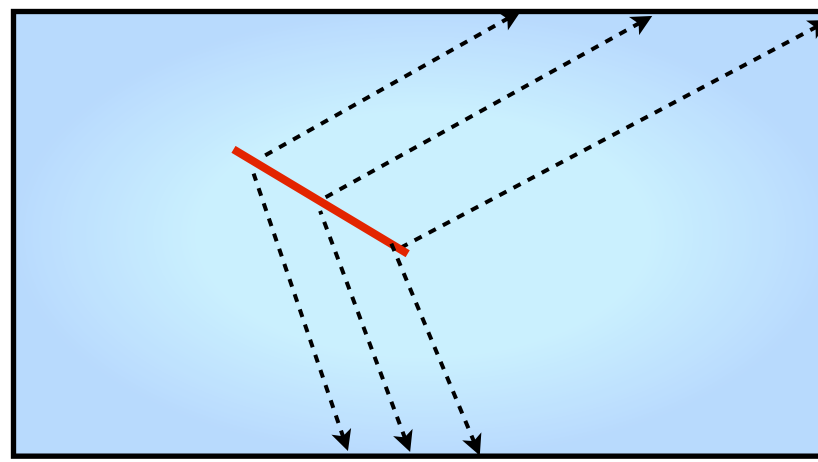


Image reconstruction, using a causal "Hough Transform" (isochron method)



Full Track Reconstruction: A TPC Using Optical Light?

1. Signal per unit length (before attenuation)

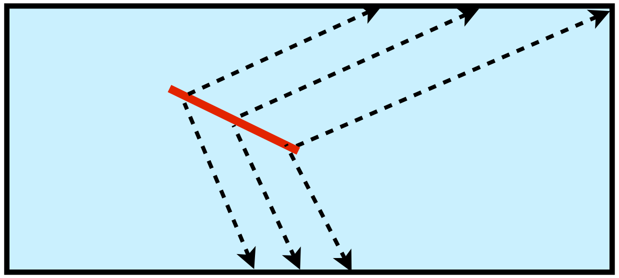
   ~20 photons/mm (Cherenkov)

2. “Drift time” (photon transit time)

   ~225,000mm/microsecond

3. Topology

   drift distances depend
   on track parameters



4. Optical Transport of light in water

Full Track Reconstruction: A TPC Using Optical Light?

1. Signal per unit length (before attenuation)

~20 photons/mm (Cherenkov)

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

2. "Drift time" (photon transit time)

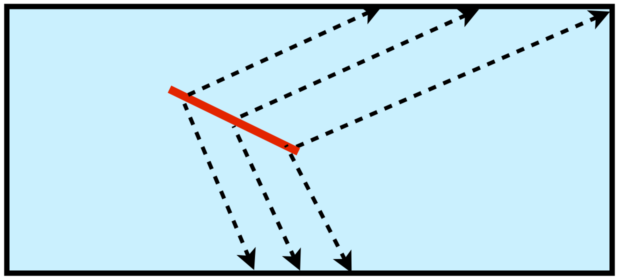
~225,000mm/microsecond

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.



4. Optical Transport of light in water

Appropriate reconstruction techniques are needed.

Timeline

Preparation

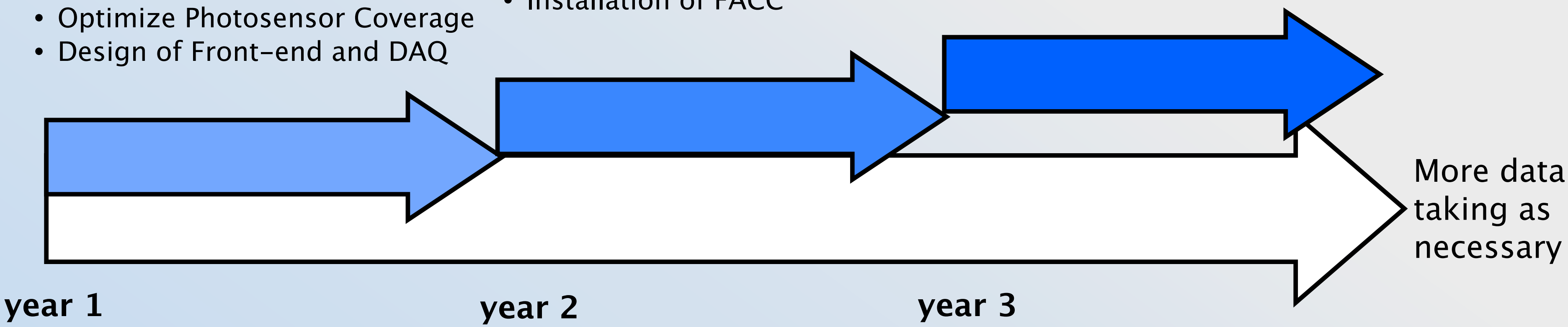
- Monte Carlo Studies
- Optimize Tank Design
- Optimize Photosensor Coverage
- Design of Front-end and DAQ

Commissioning

- Single LAPPD Beam-Tests
- Construction of Tank
- Installation of PMTs
- Installation of FACC

First Data

- Final Commissioning
- Systems Integration
- Staged LAPPD Installation
- First Data Runs



Timeline

First Incom LAPPD prototypes, expected to be available sometime around here

Preparation

- Monte Carlo Studies
- Optimize Tank Design
- Optimize Photosensor Coverage
- Design of Font-end and DAQ

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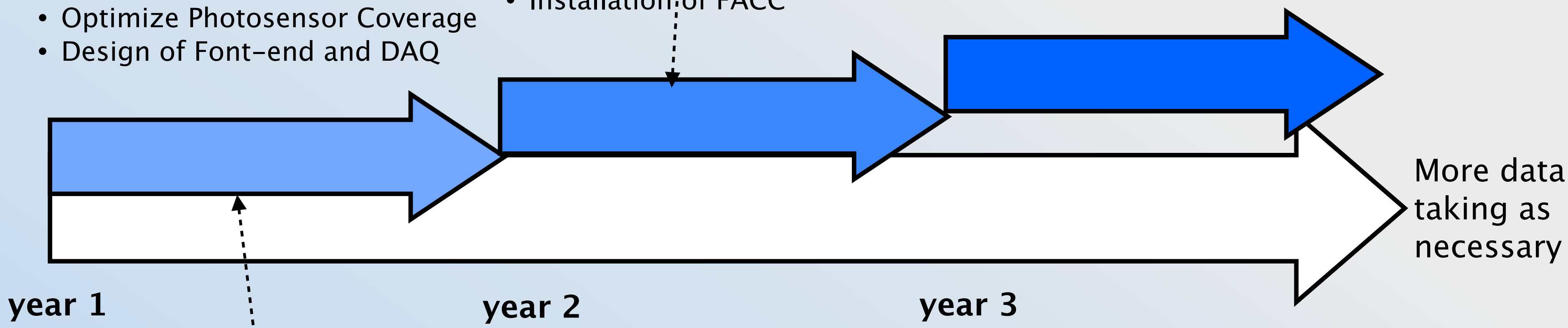


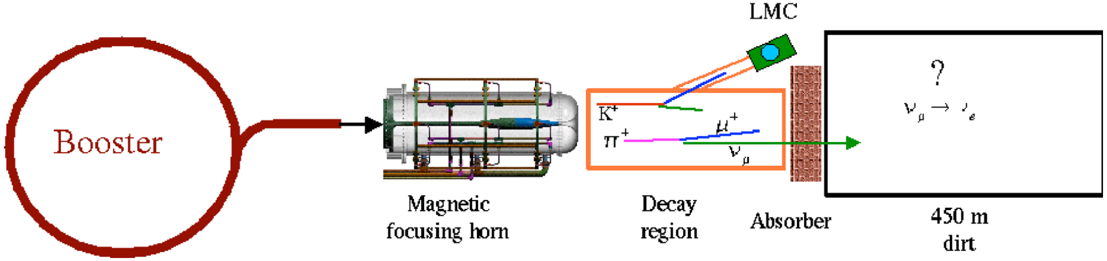
Submit full proposal

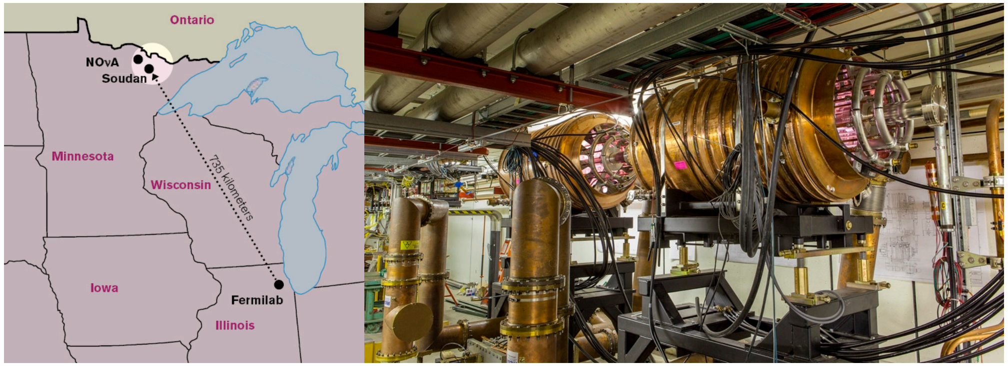
Preparatory work is already under way and moving quickly

Beyond ANNIE?

Fermilab has the most intense neutrino beams in the world

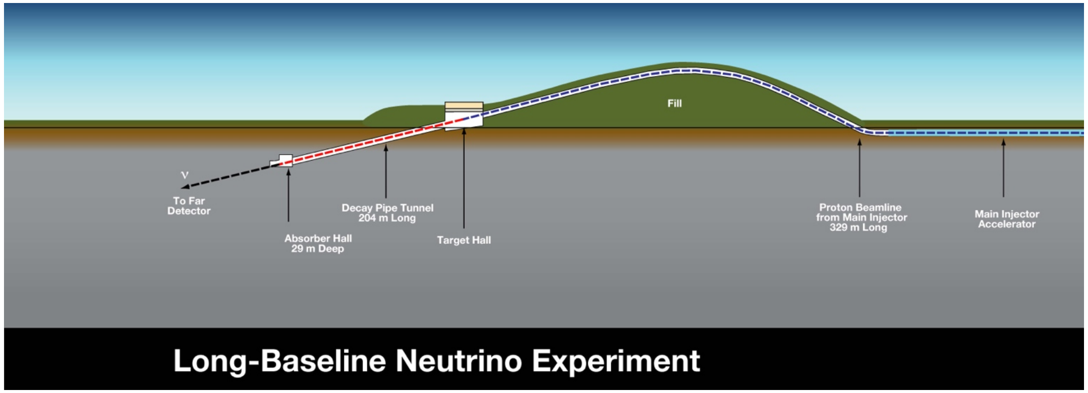
Booster Neutrino beamline





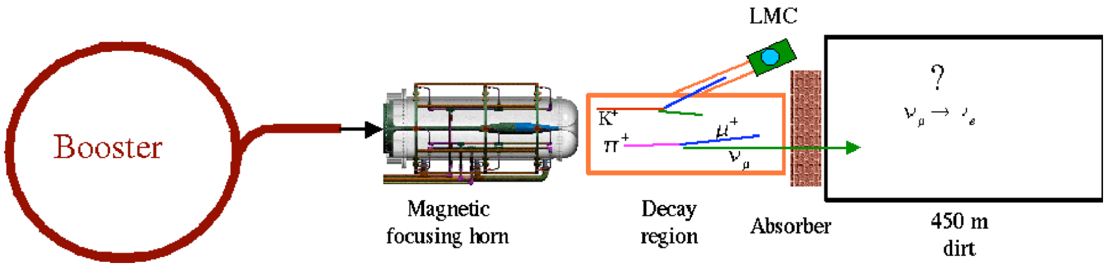
NuMI beamline

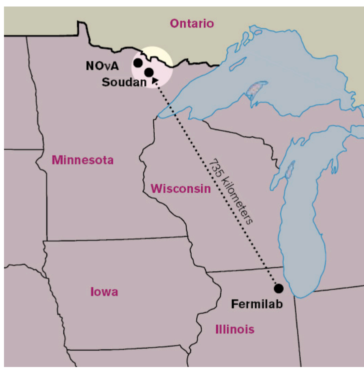
LBNE beamline

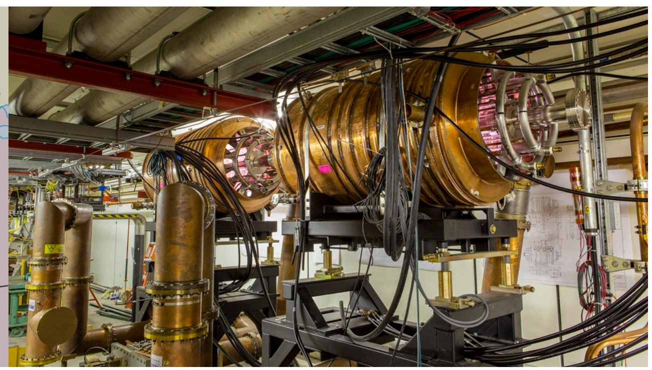


How can we maximize this great resource?

Booster Neutrino beamline

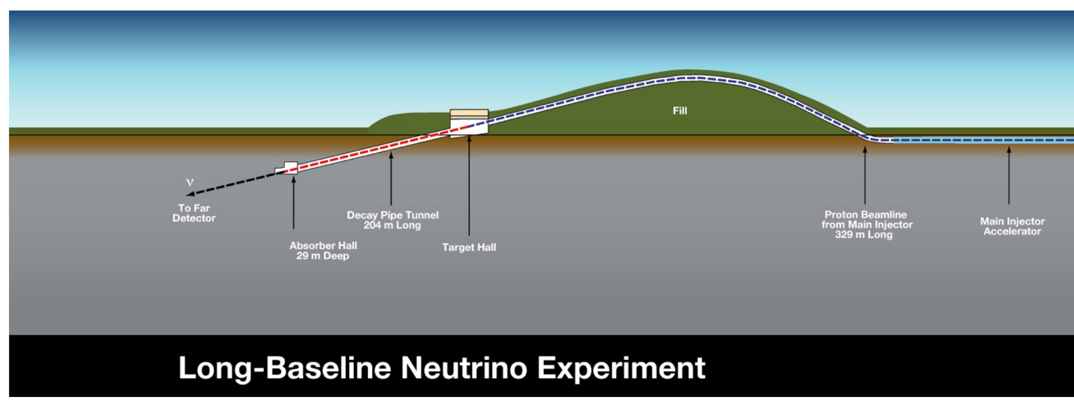






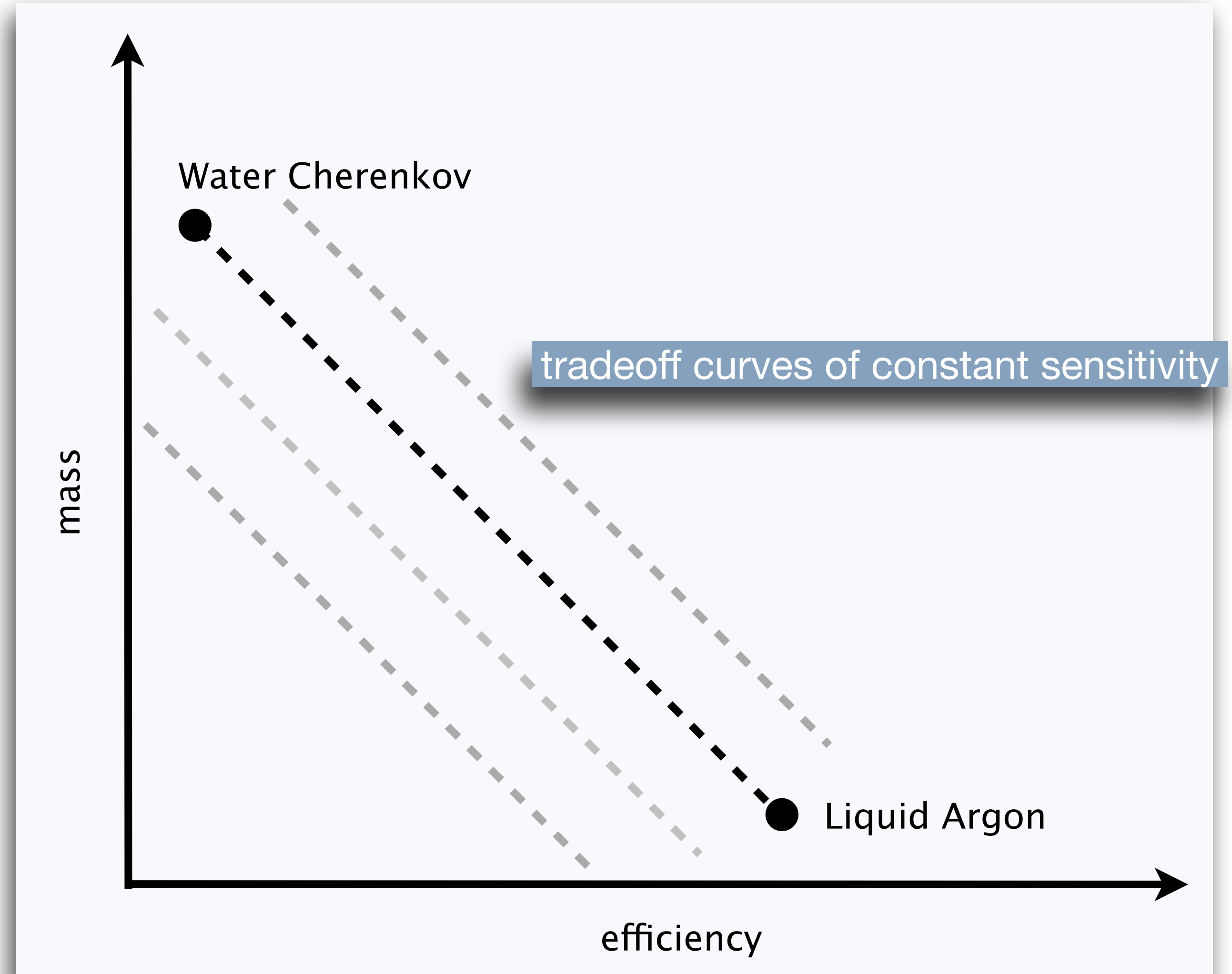
NuMI beamline

LBNE beamline



The Challenge: We Are Technologically Limited

Neutrino experiments often face tough choices.



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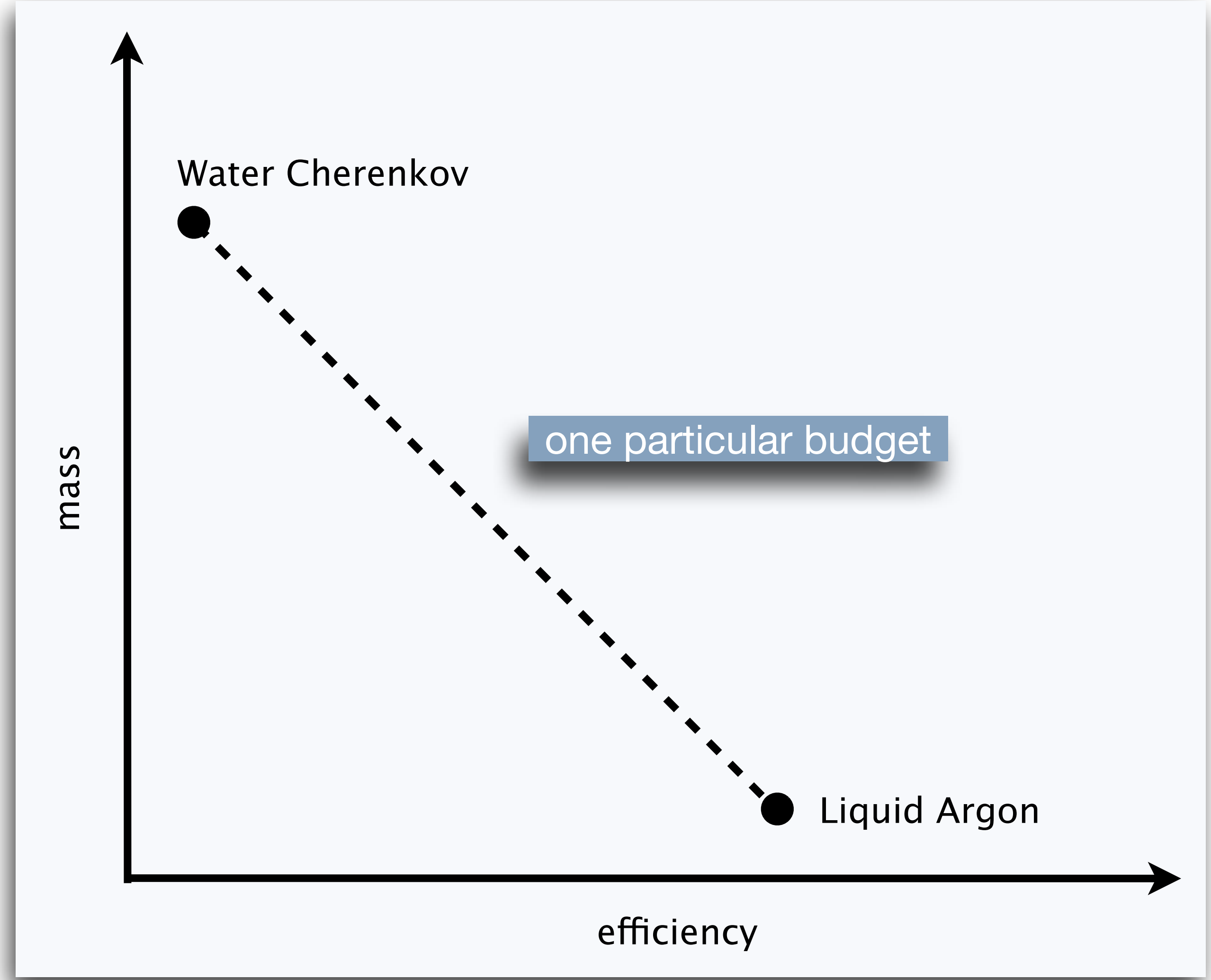
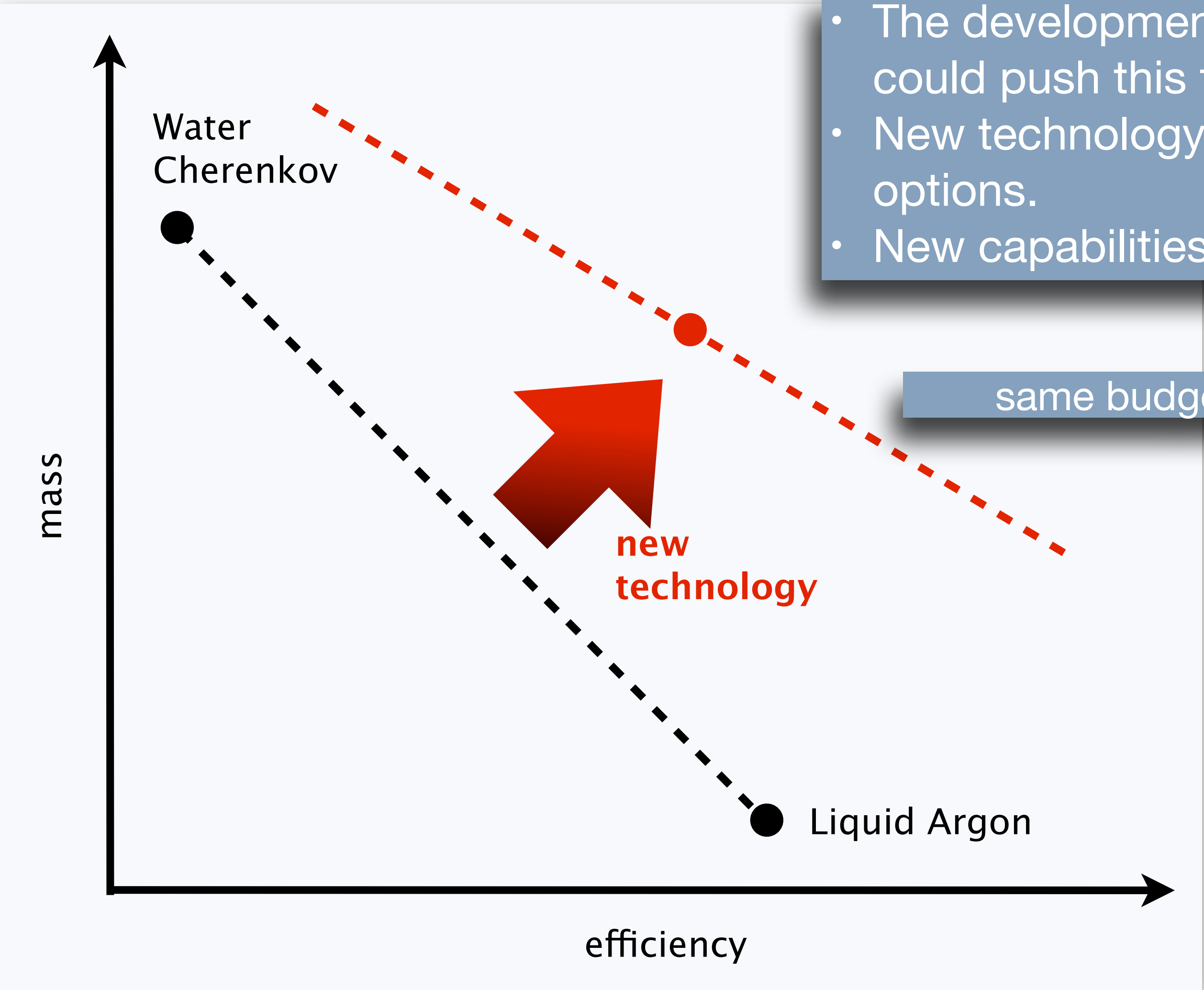


New Technology Can Have a Transformative Impact on Physics Sensitivity

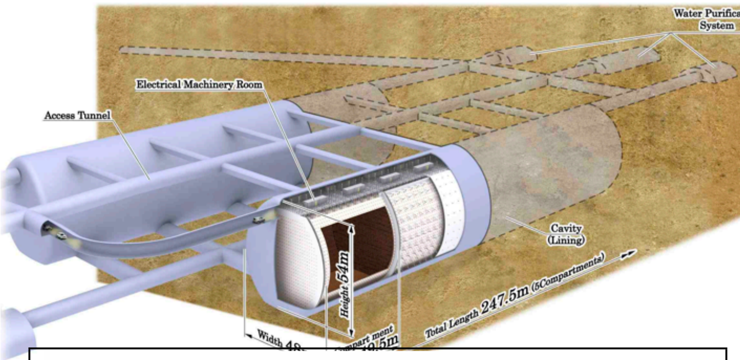


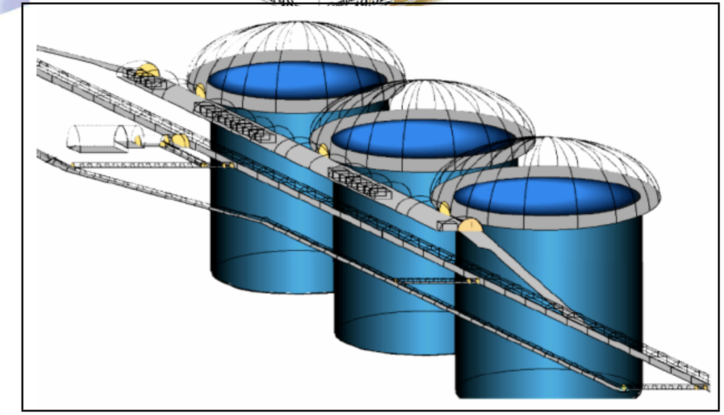
- The development of new technology could push this frontier forward.
- New technology can create intermediate options.
- New capabilities drive new physics.

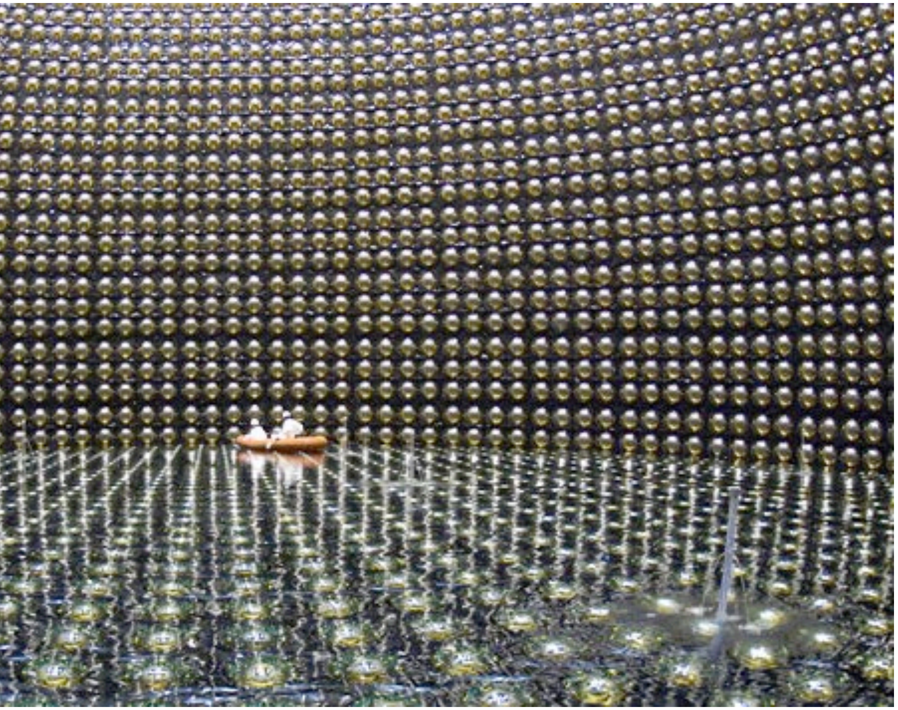
same budget

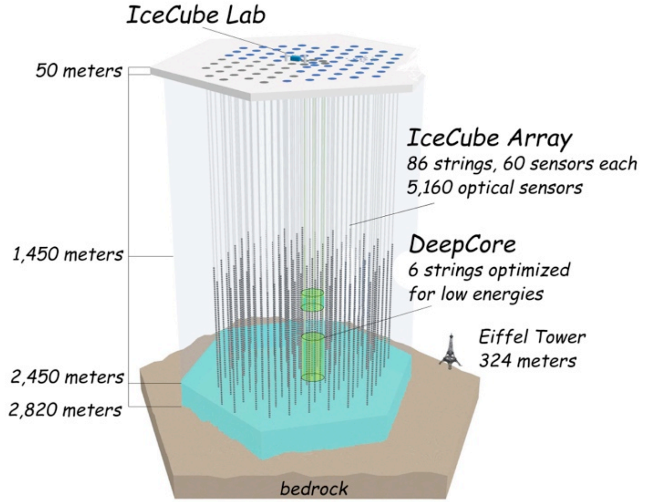
Could the Optical TPC Scale Up?

Are the tools and techniques developed for ANNIE scalable to >100 kton sizes?









Do These Approaches Scale Up?

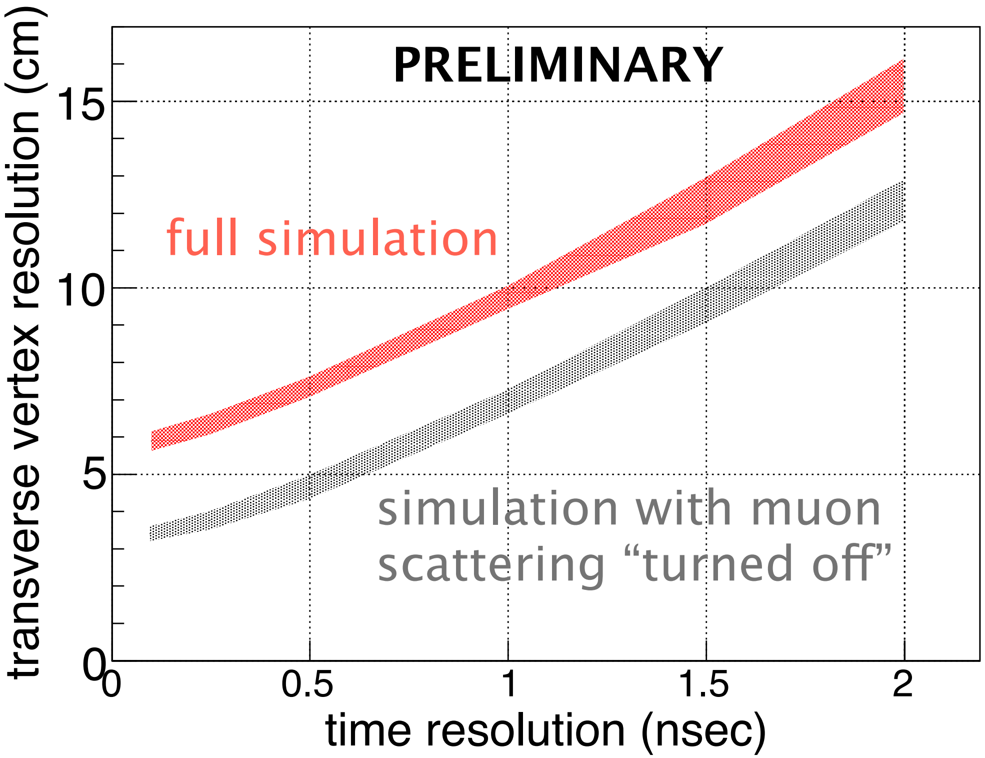
Yes!

Over large distances, transit times of light are strongly affected by

- chromatic dispersion - different colors travel at different speeds
- optical scattering

These effects are stochastic and can be accounted for in the analysis.

- a 200 kton water Cherenkov detector is likely capable of resolving features at around 5 cm or better!
- improvements in photosensor timing translate directly into better differential vertex resolution, with diminishing returns not setting in until ~200 picoseconds.

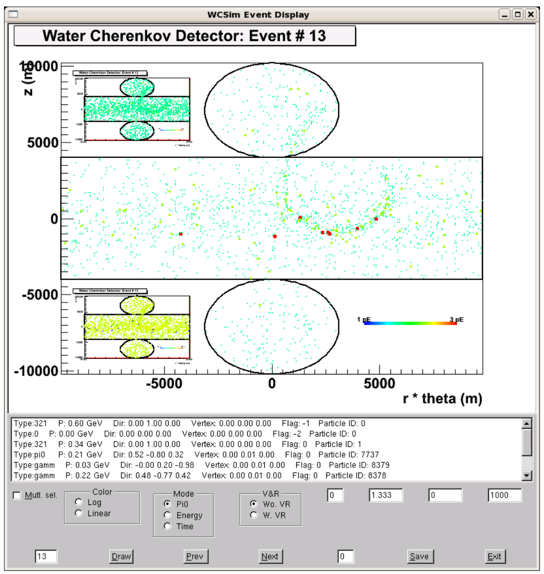


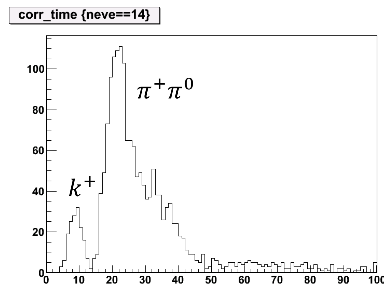
I. Anghel, E. Cantos, G. Davies, M. Sanchez, M. Wetstein, T. Xin

What about low energy and heavy particles that don't make Cherenkov?

Liquid scintillators, especially water soluble LAB, provide many advantages

- Sensitivity to charged particles below Cherenkov threshold
  - proton recoils
  - $p \rightarrow K^{+}\nu$
- Much improved lepton energy resolution





- Very clear Cerenkov ring even without cut

	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \rightarrow e^{+}\pi^{0}$	45%	0.2	45% ?	0.1
$p \rightarrow \nu K^{+}$	14%	0.6	97%	0.1
$p \rightarrow \mu^{+}K^{0}$	8%	0.8	47%	0.2
n-nbar	10%	21	?	?

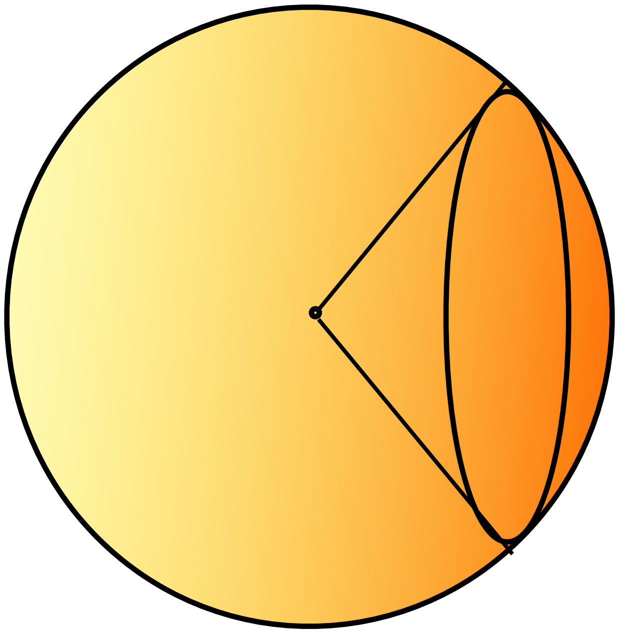
However, they also come with disavantages

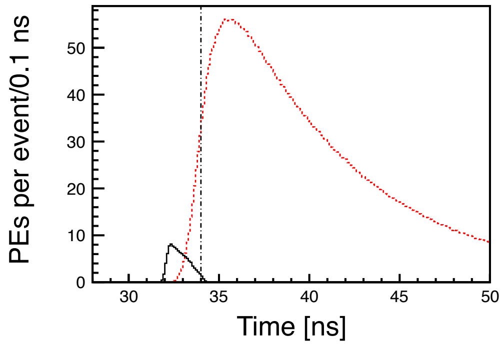
- loss of fast timing response
- loss of the directional information contained in Cherenkov light

Scintillation and Cherenkov

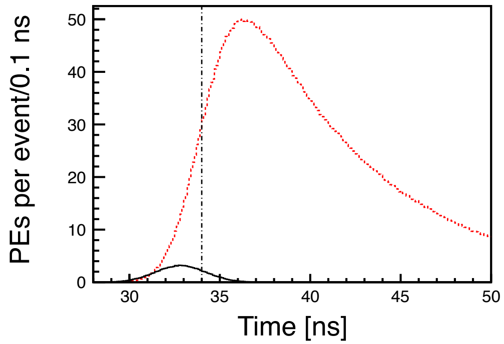
It may be possible to use timing to separate between Cherenkov and scintillation light in liquid scintillator volumes, capitalizing of the advantages of each separately.

One can use the scintillation light for low E sensitivity.
And the Cherenkov light for directionality.





(a) Default simulation.

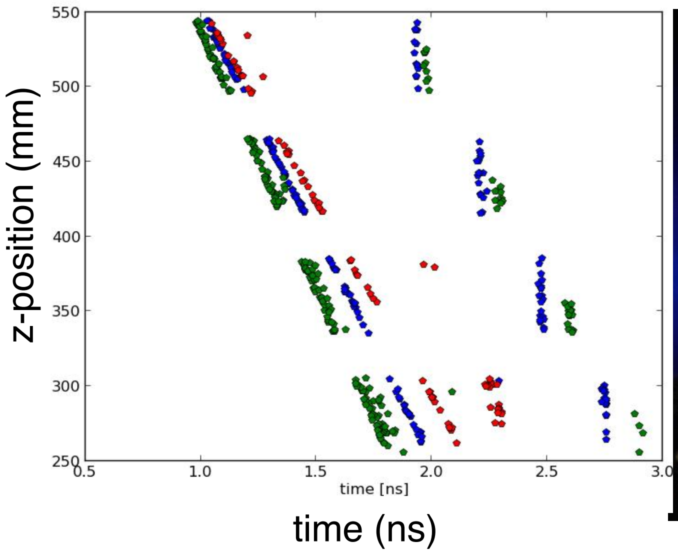


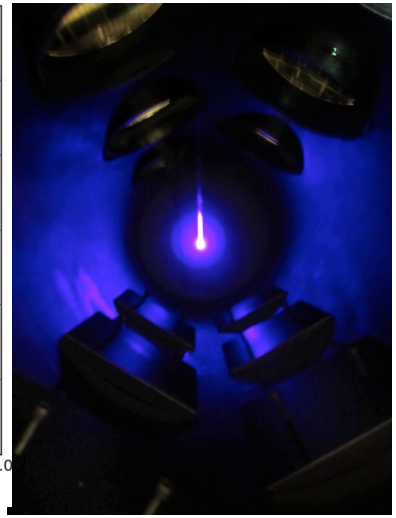
(b) Increased TTS (1.28 ns).

C. Aberle, A. Elagin, H.J. Frisch, M. Wetstein, L. Winslow. Submitted to JINST, Nov. 2013. e-Print: arXiv:1307.5813

Imaging/Reflective Geometries to Improve Light Collection

It may be possible to increase light collection through imaging optics, mapping the light onto a smaller surface.





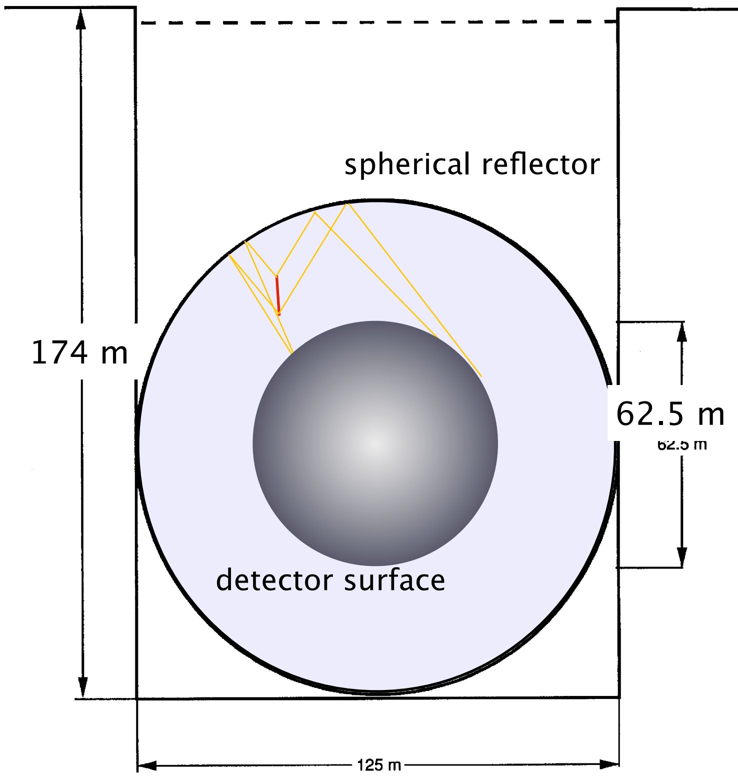
“Optical TPC”

E. Oberla, H. Frisch, R. Northrop

A long, tubular geometry with mirrors reflecting Cherenkov light back at MCPs.

Aqua-RICH

Nuclear Instruments and Methods in Physics Research A 433 (1999) 104}120



Closing Thoughts

Conclusions: Let's Get Digging

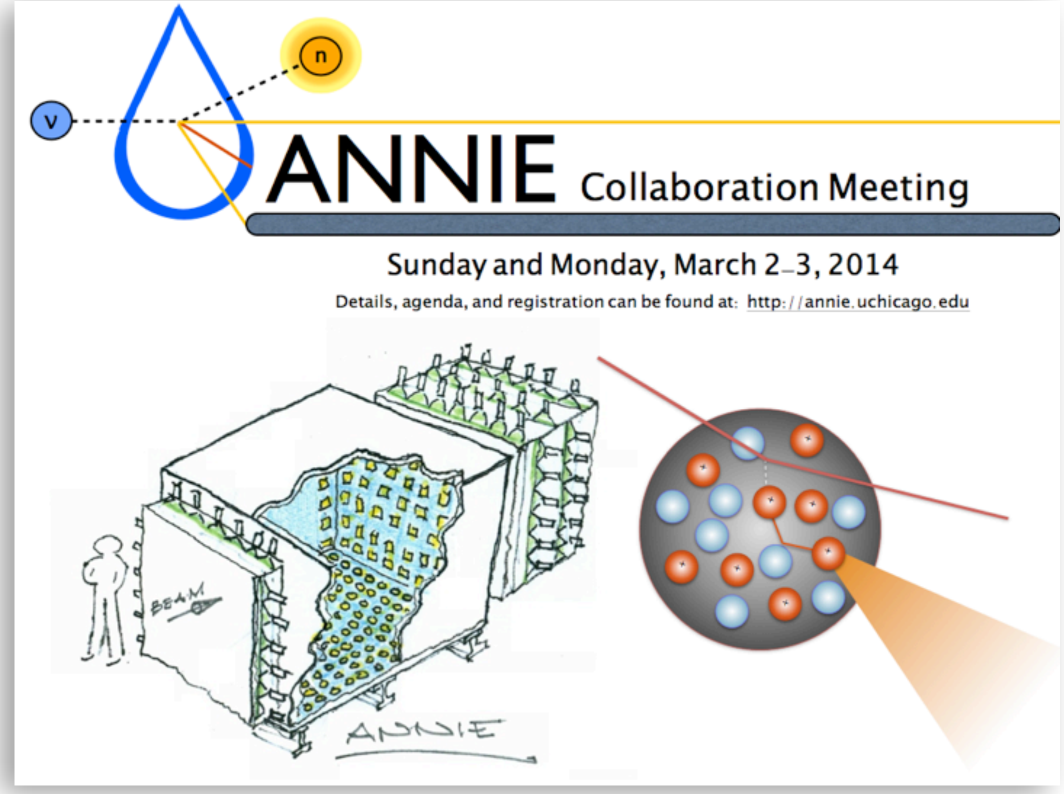
- ANNIE measures an important aspect of neutrino-nuclear interactions with high impact on a variety of physics analyses. This includes a major handle on the limiting backgrounds for proton decay.
- Also represents a working demonstration of new neutrino detection methods, such as a first demonstration of LAPPDs in an optical TPC.
- Capitalizes on largely existing beams and infrastructure and fits in well with the Fermilab Intensity Frontier program.
- The main technical tasks build on a large body of existing work.
- This sort of effort is a great context for training a new generation of well-rounded physicists.
- With Fermilab positioning itself as the world leader in high intensity neutrino beams, there are many exciting opportunities for neutrino and PDK physics.

Get Involved!

For more information: annie.uchicago.edu (ANNIE collaboration)

psec.uchicago.edu (LAPPD collaboration)

Upcoming collaboration meeting: Sunday and Monday, March 2 and 3



Thank You

Thanks also to all of my ANNIE, LAPPD, and “fast timing” neutrino colleagues for all of the work presented in this talk

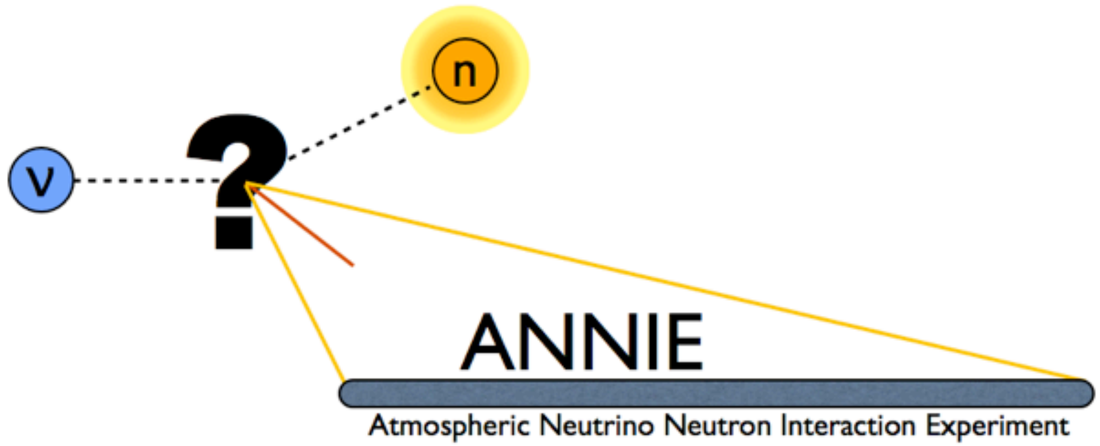
Any Questions?

Backup Slides

Why Water ?

Especially for the $p \rightarrow e^{+} \pi^{0}$ channel, the most sensitive planned experiments are very large WCh detectors such as Hyperkamiokande.

Nuclear effects are not well understood enough to extrapolate the neutron abundances in water from other target materials.



Also, this is not a conventional WCh detector. It is an optical, tracking detector.

Doesn't a tighter momentum cut reduce the backgrounds enough?

Tighter momentum cuts to select only free proton decays do succeed in reducing backgrounds from a few events per Mton per year to 0.15 events per Mton per year (roughly a factor of 10 reduction).

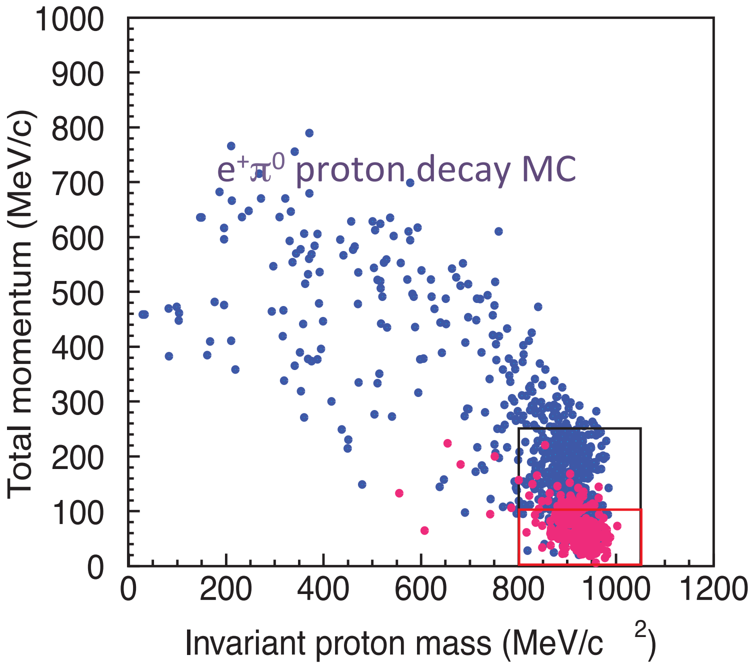
However, they also reduce the efficiency by a factor of 2

Still good, but could use further improvements.

One would still like smaller backgrounds with less inefficiency.

More importantly :

In the case of an observed candidate, one would still like an unambiguous signature. Neutron tagging will greatly help, in this regard.



Some example neutrino-neutron production mechanisms

- direct interaction of an anti-neutrino on a proton, converting it into a neutron
- secondary (p,n) scattering of struck nucleons within the nucleus
- charge exchange reactions of energetic hadrons in the nucleus (e.g., $\pi^- + p \rightarrow n + \pi^0$)
- de-excitation by neutron emission of the excited daughter nucleus
- capture of π^- events by protons in the water, or by oxygen nuclei, followed by nuclear breakup
- secondary neutron production by proton scattering in water

Neutron production in proton decay events?

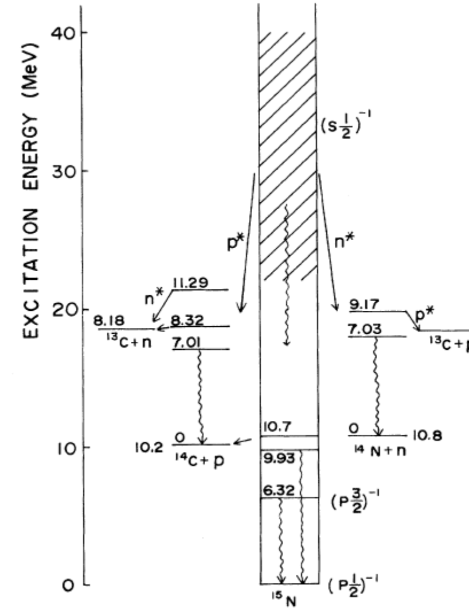
- For water, 20% of all protons are essentially free. If these decay, there is no neutron produced as the π^0 would decay before scattering in the water, and 400 MeV electrons rarely make hadronic showers that result in free neutrons.
- Oxygen is a doubly-magic light nucleus, and hence one can use a shell model description with some degree of confidence. Since two protons are therefore in the $p_{1/2}$ valence shell, if they decay to ^{15}N, the resultant nucleus is bound and no neutron emission occurs except by any final state interactions (FSI) inside the nucleus.
- Similarly, if one of the four protons in the $p_{3/2}$ state decays, a proton drops down from the $p_{1/2}$ state emitting a 6 MeV gamma ray, but the nucleus does not break up except by FSI.
- Finally, if one of the two $s_{1/2}$ protons decays, there is a chance that the nucleus will de-excite by emission of a neutron from one of the higher shells.
- 8% x 80% = 6% proton decays with neutrons (Ejiri)

Hole	Residual	States	(k)	E_γ	E_p	E_n	$B(k)$
$(p_{1/2})_p^{-1}$	g.s.	$\frac{1}{2}^-$	^{15}N	0	0	0	0.25
$(p_{3/2})_p^{-1}$	6.32	$\frac{3}{2}^-$	^{15}N	6.32	0	0	0.41
	9.93	$\frac{3}{2}^-$	^{15}N	9.93	0	0	0.03
	10.70	$\frac{3}{2}^-$	^{15}N	0	0.5	0	0.03
$(s_{1/2})_p^{-1}$	g.s.	1^+	^{14}N	0	0	~ 20	0.02
	7.03	2^+	^{14}N	7.03	0	~ 13	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	1.6	~ 11	0.01
	g.s.	0^+	^{14}C	0	~ 21	0	0.02
	7.01	2^+	^{14}C	7.01	~ 14	0	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	~ 11	~ 2	0.03
$(j)_p^{-1}$	others		many states	≤ 3–4			0.16

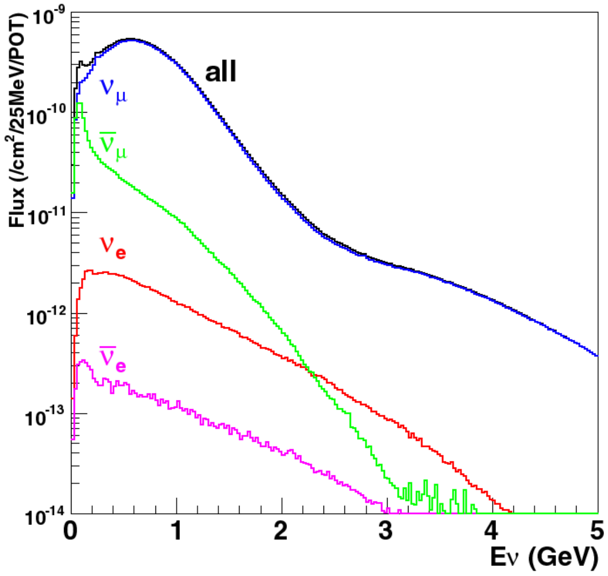
some gammas

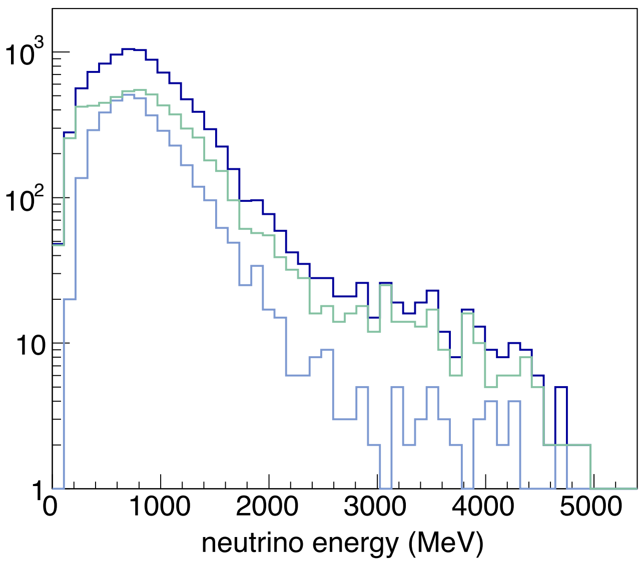
few neutrons

H. Ejiri Phys. Rev. C48 (1993)



More Details on the Booster Neutrino Beam





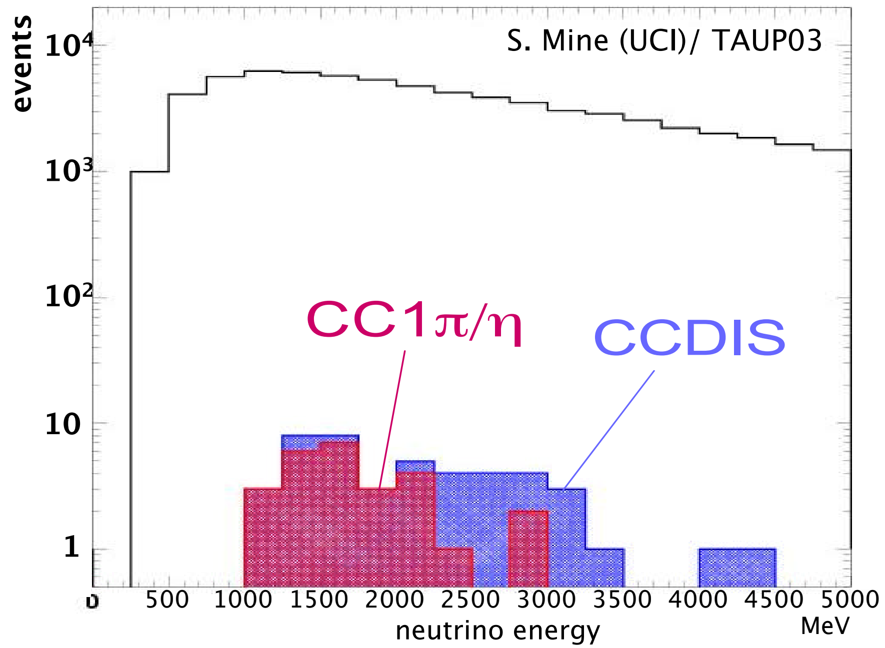
ν-type	Total Interactions	Charged Current	Neutral Current
ν_μ	10210	7265	2945
$\bar{\nu}_\mu$	133	88	45
ν_e	70	52	20
$\bar{\nu}_e$	4.4	3	1.4

Table 1: Rates expected in 1 ton of water with 1x10^{20} POT exposure at ANNIE Hall.

More Details on the Booster Neutrino Beam

- Expected proton decay backgrounds typically come from interactions between 1-5 GeV.
- The Booster neutrino beam line provides an energy spectrum peaked near 1 GeV.
- We will see several hundreds of ν_μ CC interactions per 10^{20} POT per ton in the relevant window, and several tens of events at the highest energies.

proton decay background energies
as measured by Super-K*



* note: this measurement did not include detection of final-state neutrons.

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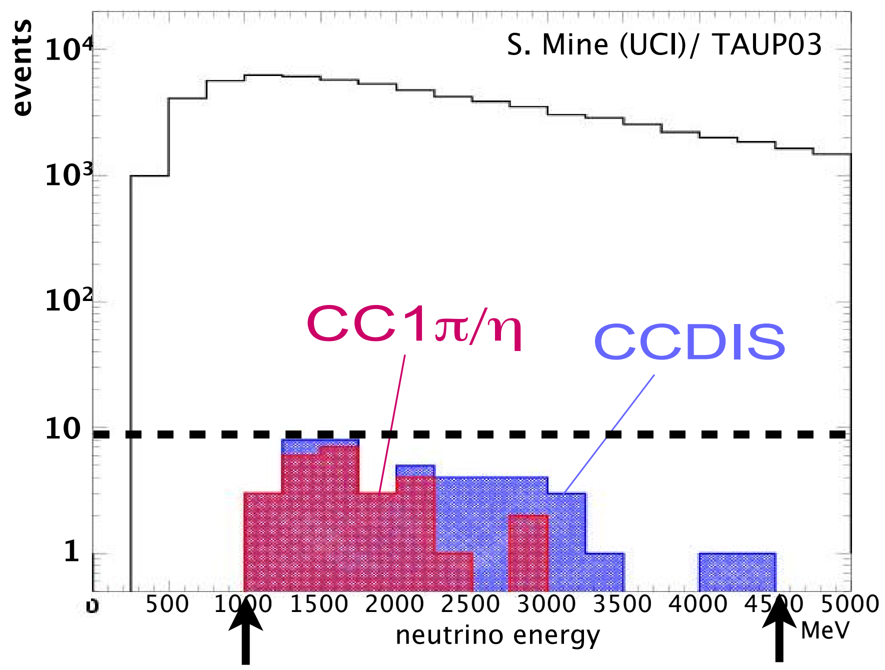

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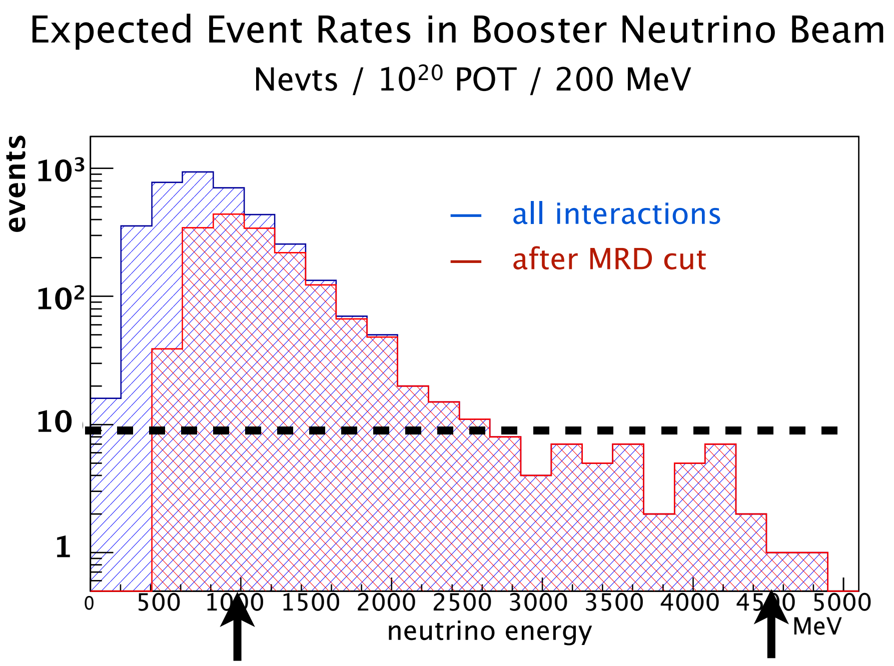
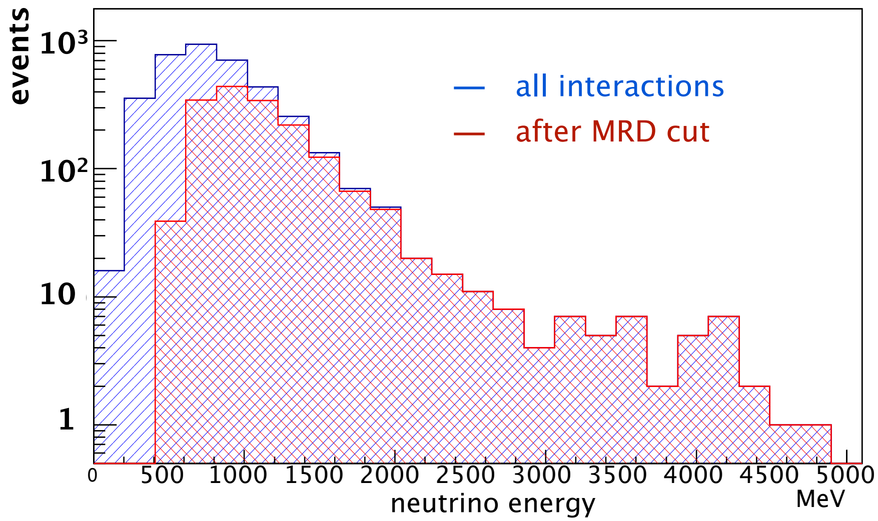


More Details on the Booster Neutrino Beam

This expected rate plot is for Oxygen only (not water) but it gives a handle on the difference in rates between the SciBooNE pit and the NDOS

Expected Event Rates in Booster Neutrino Beam

Nevts / 10^{20} POT / ton water/ 200 MeV

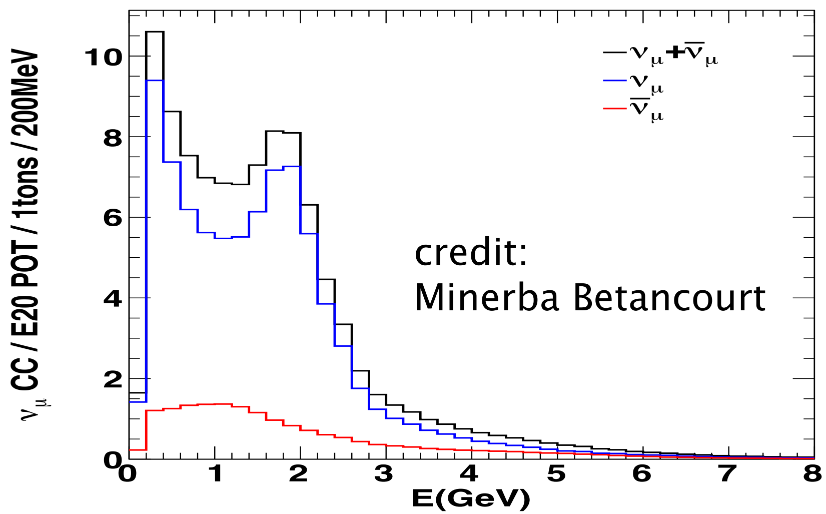


~500 events per ton/1e20 POT/200 MeV at 1 GeV

~8 events per ton/1e20 POT/200 MeV at 3 GeV

Expected Event Rates at the NDOS (NuMI)

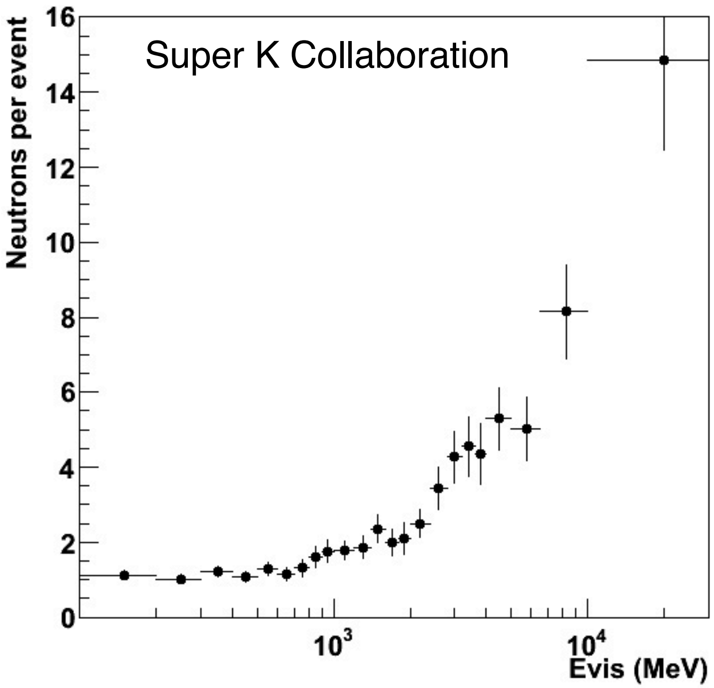
Nevts / 10^{20} POT / ton Oxygen/ 200 MeV



8 events per ton/1e20 POT/200 MeV at 1 GeV

~2 events per ton/1e20 POT/200 MeV at 3 GeV

Did Super Kamiokande Make This Measurement?

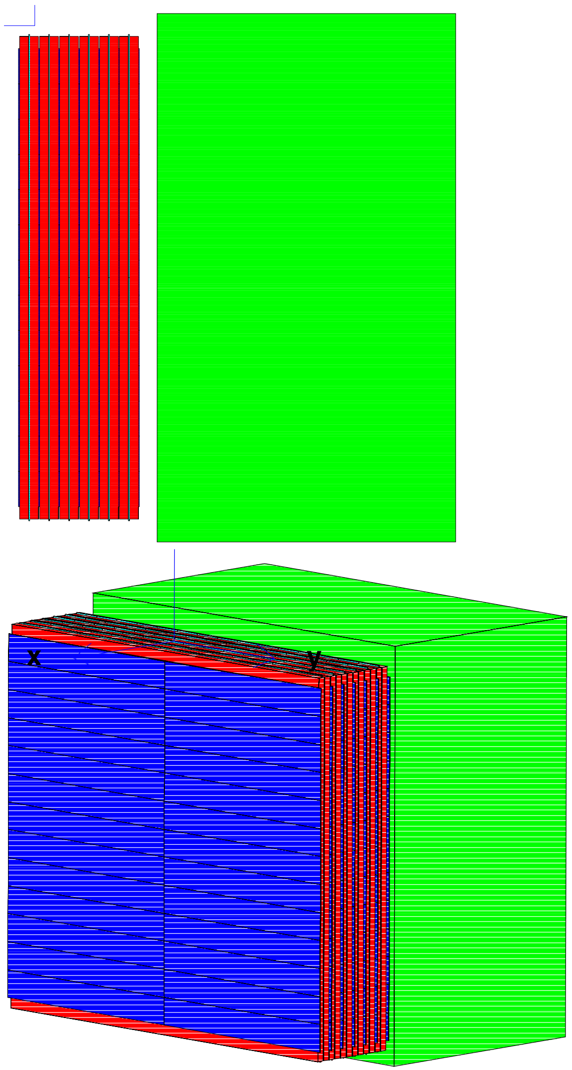


Yes, but not to an extent that they felt publishable:

- inefficient neutron capture on pure water (no Gd)
- uncertainties in flux
- difficulty reconstructing the energy

Nonetheless, this result is promising and strongly motivates a dedicated measurement.

More on the MRD



- 12 planes of 2 inch iron plates, and 13 planes of scintillator strips
- vertical scintillator strips are 0.6x138x20, with 13 strips in two sections, for a total of 182 vertical strips in 7 planes
- horizontal strips are 0.6x155x20, with 15 strips in two sections, for a total of 180 vertical strips in 6 planes

Will LAPPDs Be Ready?

- Phase II request for $3M for commercialization has been submitted by Incom, Inc
- We'll have much more clarity on this question in time for the LOI/proposal.
- Incom has been involved in the LAPPD collaboration from the beginning (they make the channel plate substrates) and are very serious.

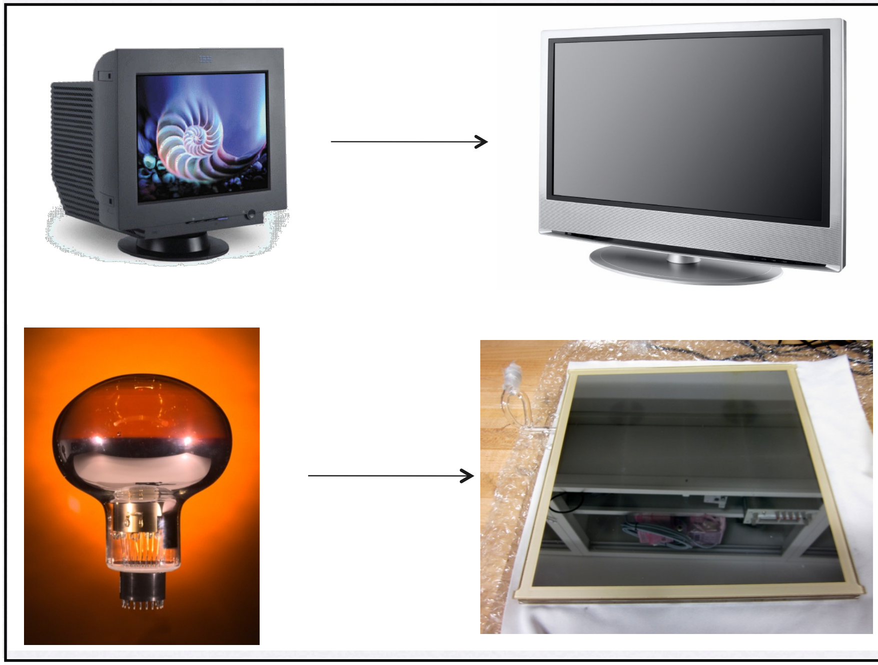
Price and availability?

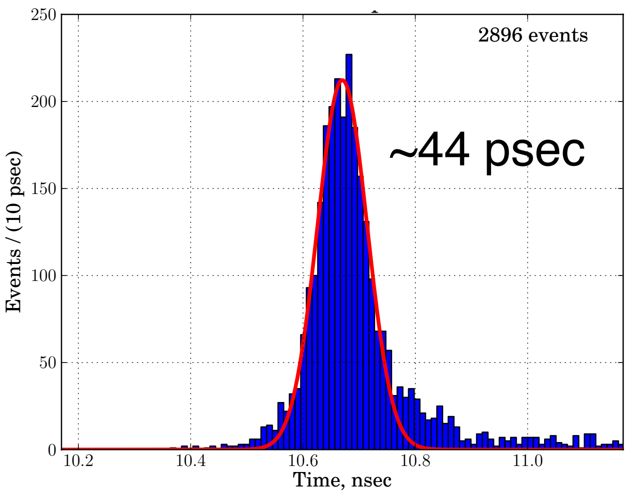
- Without a large market or economy of scale, we do not expect the first LAPPDs to be sold at what we hope the asymptotic price will be.
- Nonetheless, we expect them to be significantly cheaper per-unit-area than commercial MCPs
- We also hope, as early adopters, that Incom will be able to negotiate a fair price in order to get their product out to the community
- Members of the ANNIE collaboration have been involved with LAPPD since the beginning. Incom is enthusiastic about ANNIE (see "Letter of Support" from Michael Minot).

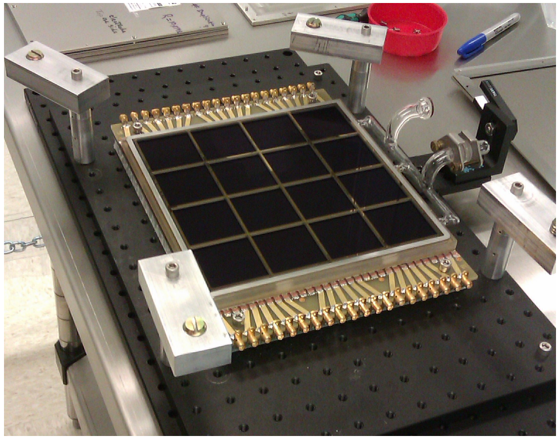
Adapting LAPPDs for Water Cherenkov Detectors

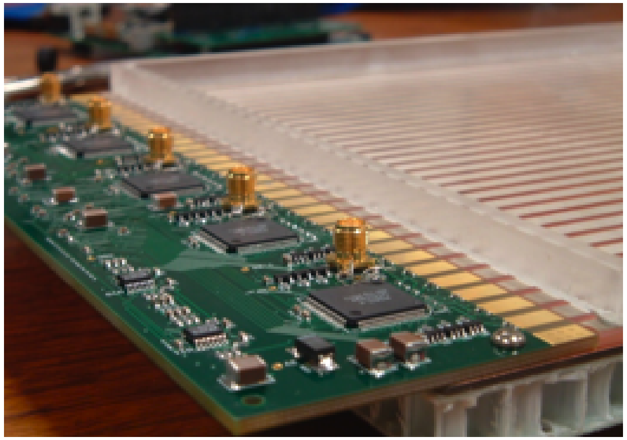
Subtasks:

- Further adapt readout system to our experimental needs (precision, buffer depth, acquisition rates). ANNIE events cover two very different time-scales: tens of picoseconds and 10 of microseconds.
- Work out techniques for hi-potting in water
- Operational testing on a small scale

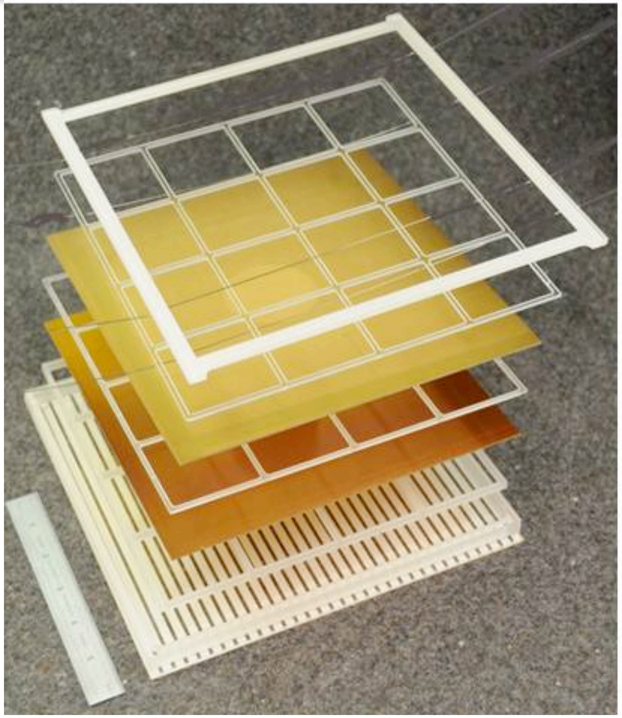


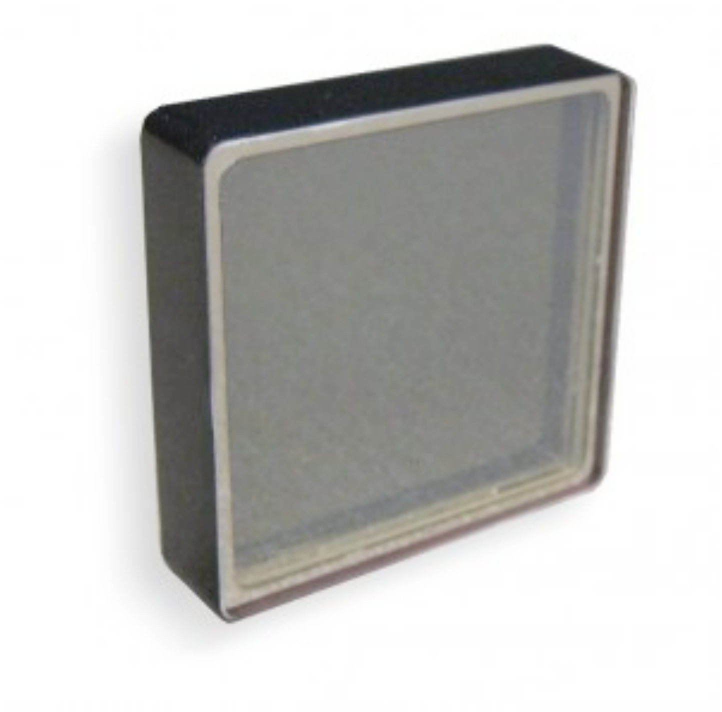






More on LAPPDs





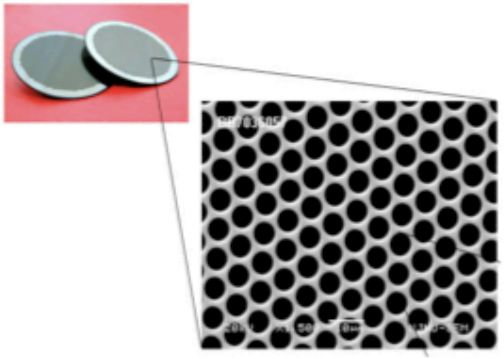
LAPPD detectors:

- 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

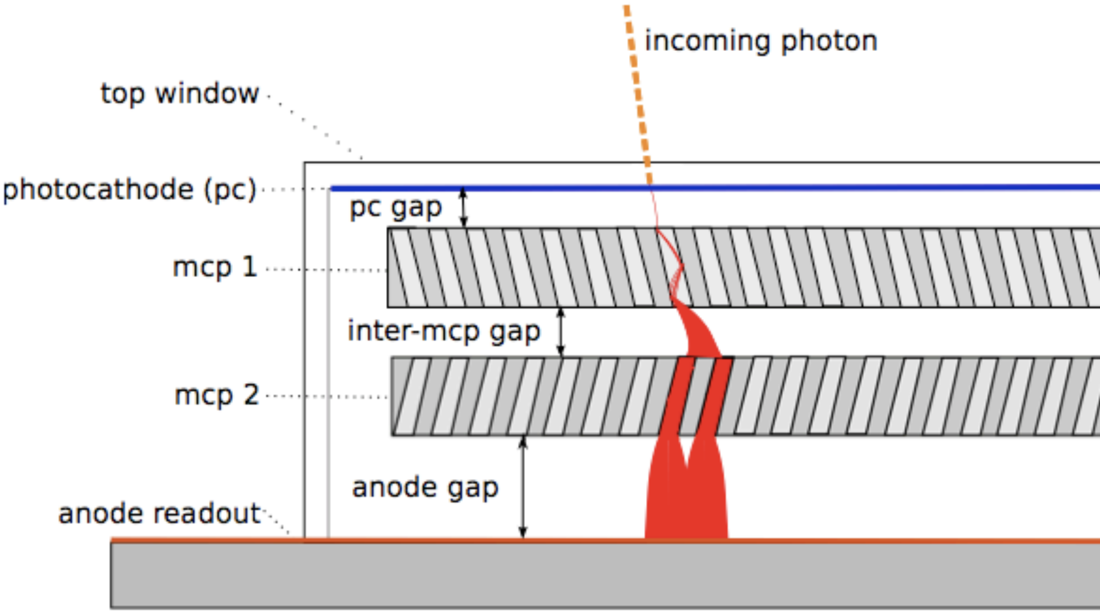
What is an MCP-PMT?



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

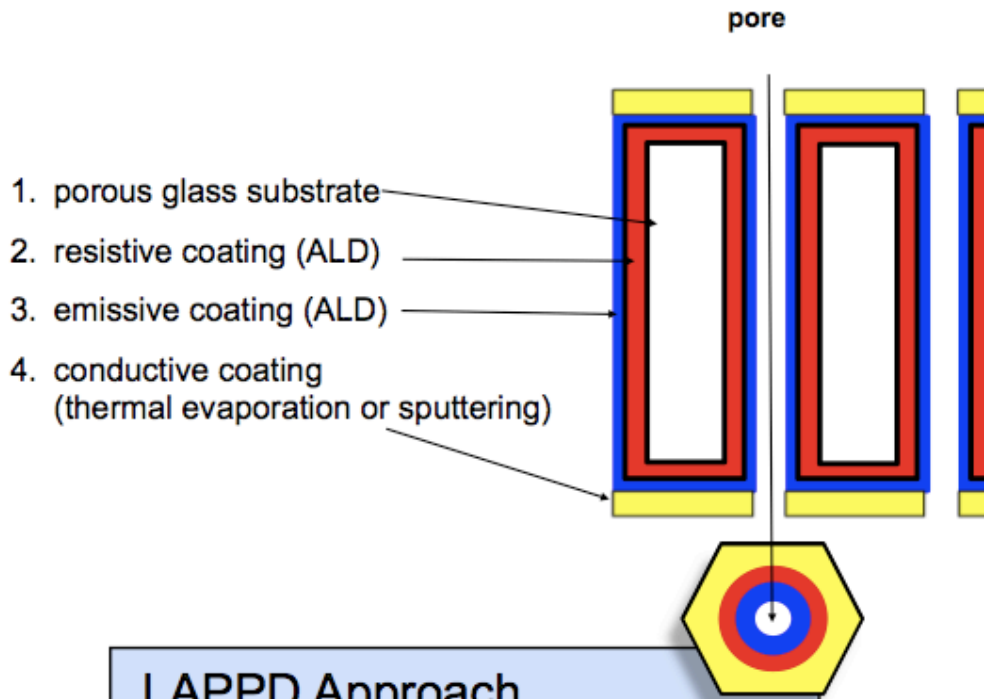


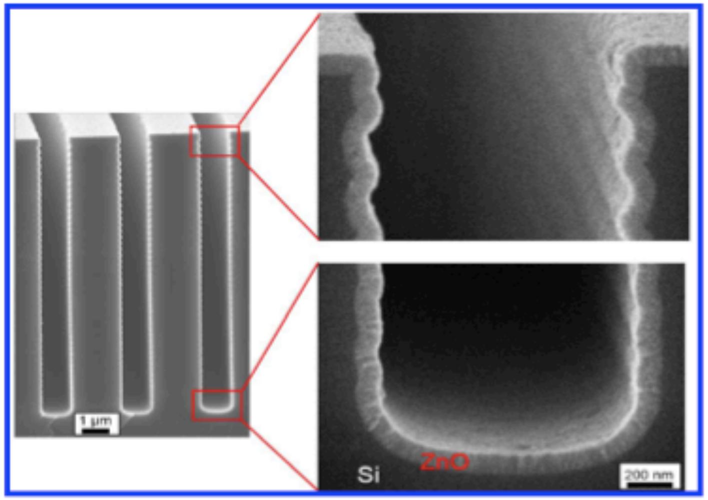
Our Approach

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).





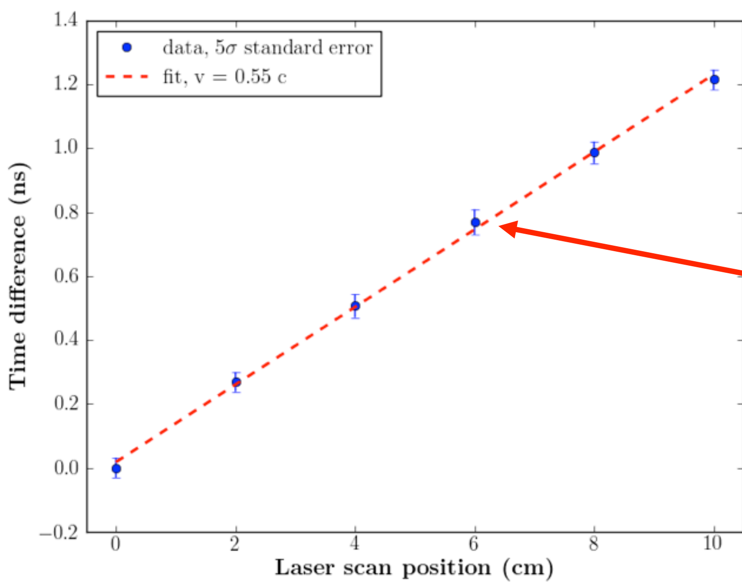
LAPPD Approach

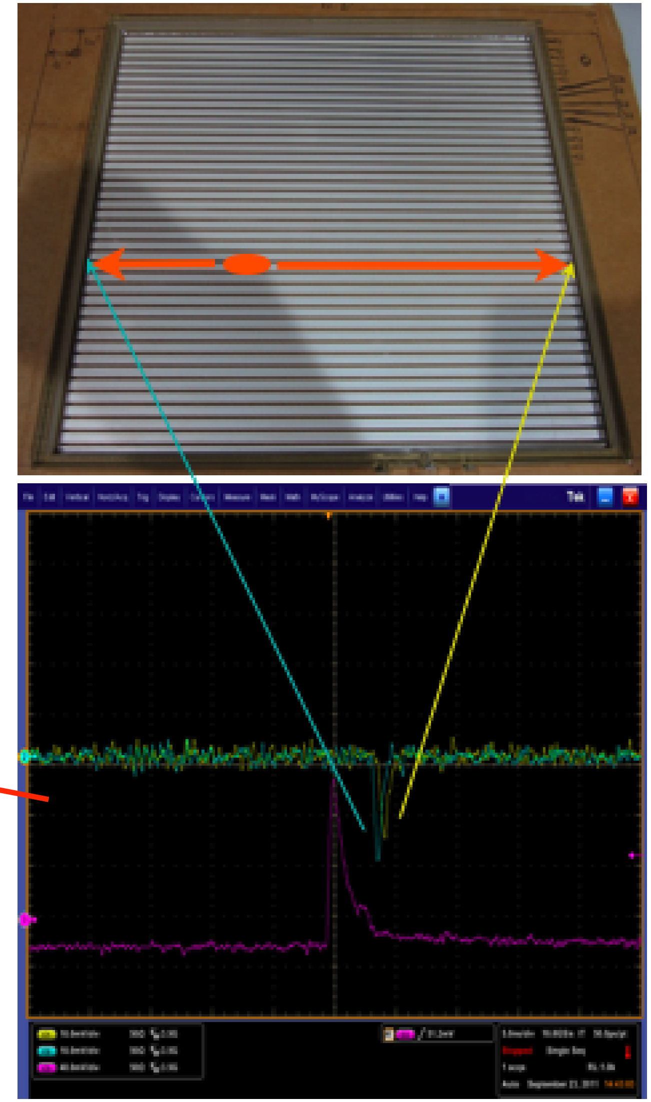
- Separate out the three functions
- Hand-pick materials to optimize performance.
- Use Atomic Layer Deposition (ALD): a cheap industrial batch method.
  - ALD is diffusive, conformal and allows application of material in single atomic monolayers

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



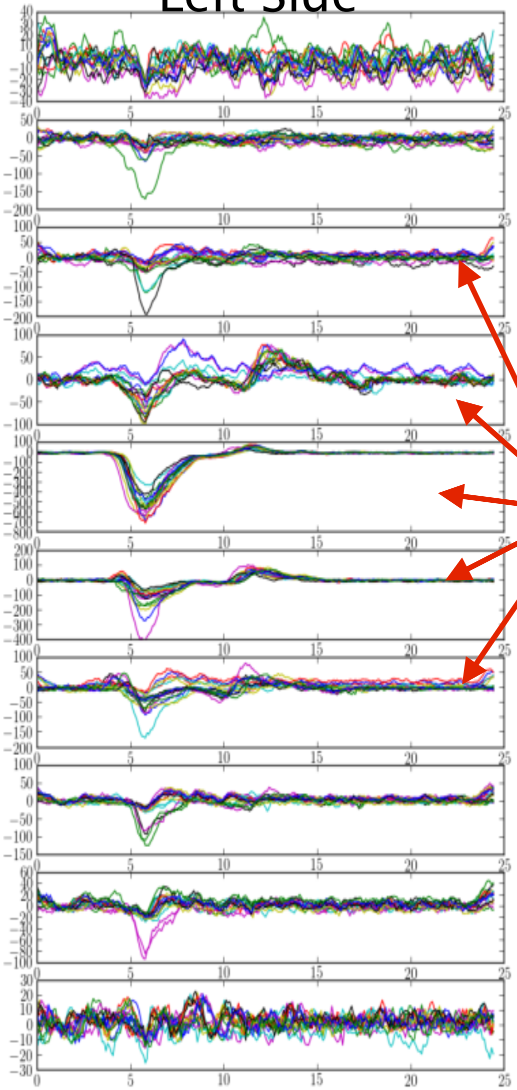


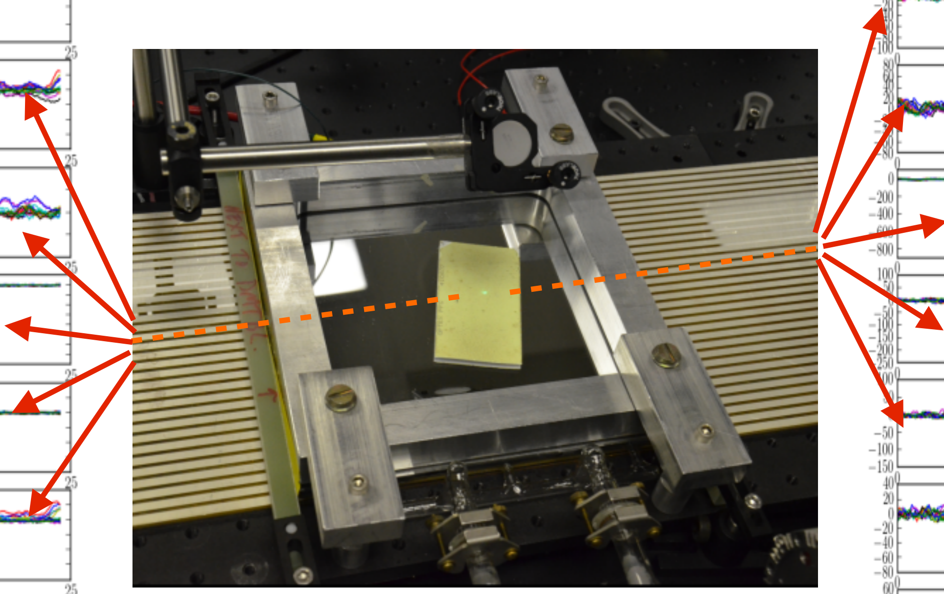
Slope corresponds to ~2/3 c propagations speed on the microstrip lines. RMS of 18 psec on the differential resolution between the two ends: equivalent to roughly 3 mm

Anode design

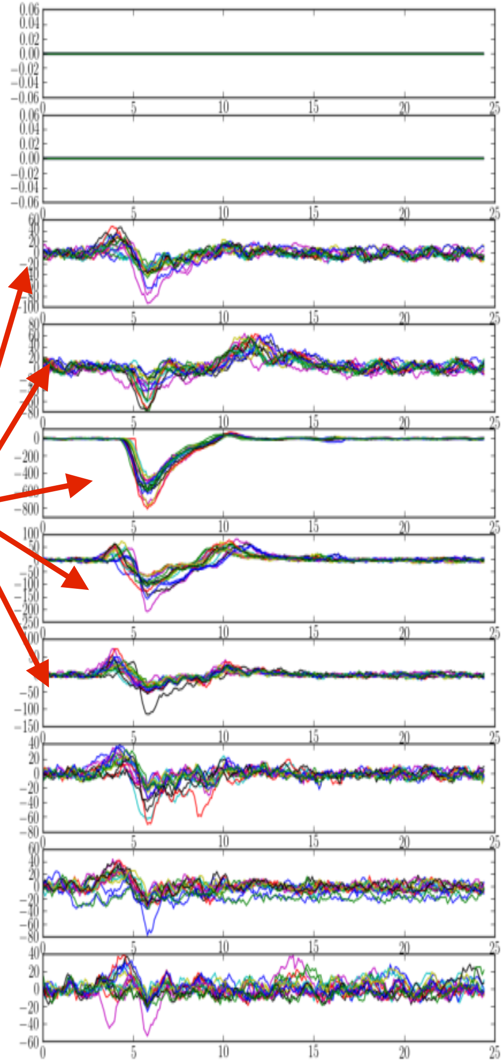
Transverse position is determined by centroid of integrated signal on a cluster of striplines.

Pulses on 10 striplines
Left Side





Credit: Eric Oberla

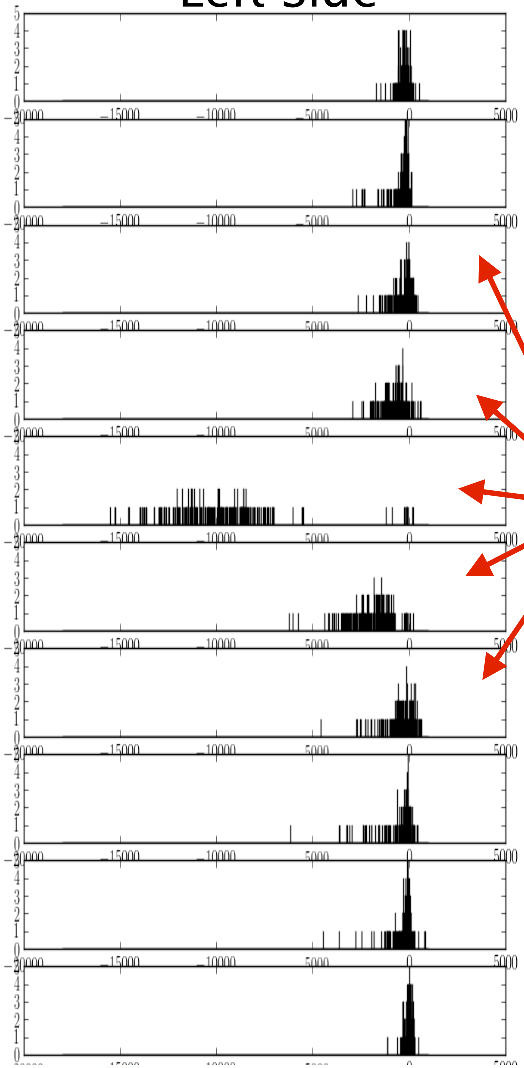


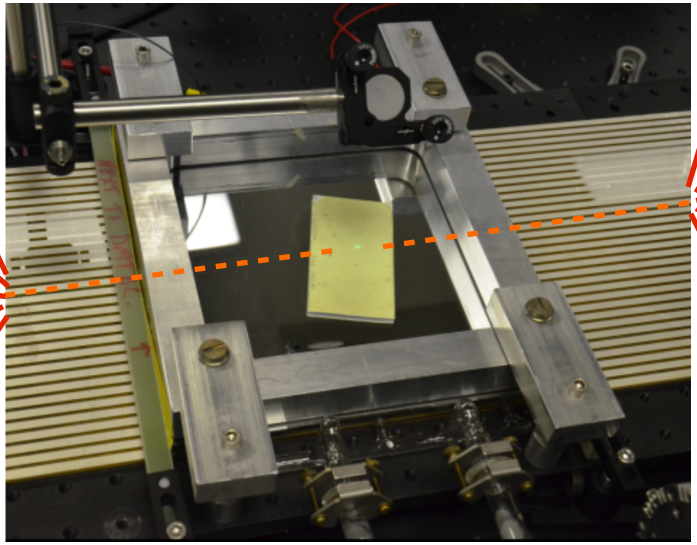
Right Side
Pulses on 10 striplines

Anode design

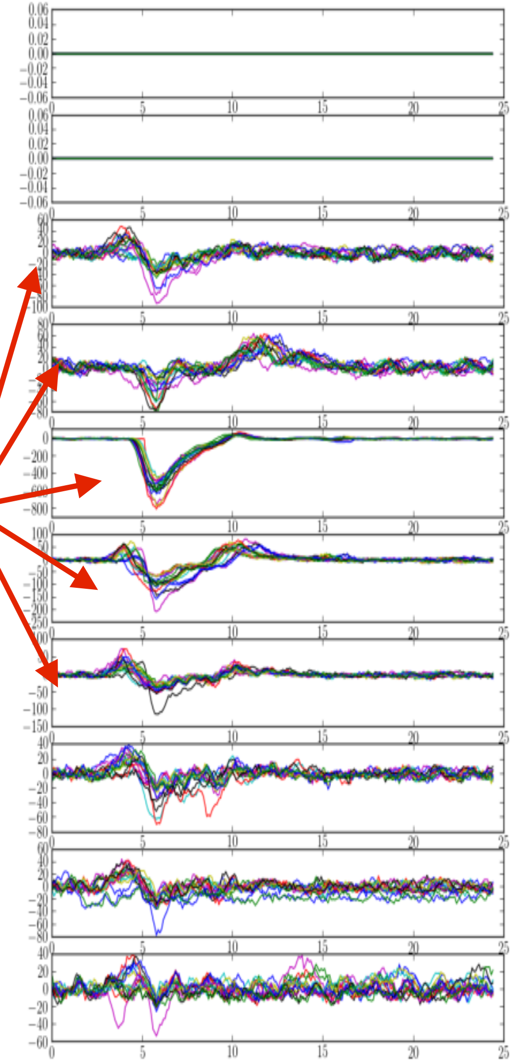
Transverse position is determined by centroid of integrated signal on a cluster of striplines.

Pulse Heights (ADC counts)
Left Side



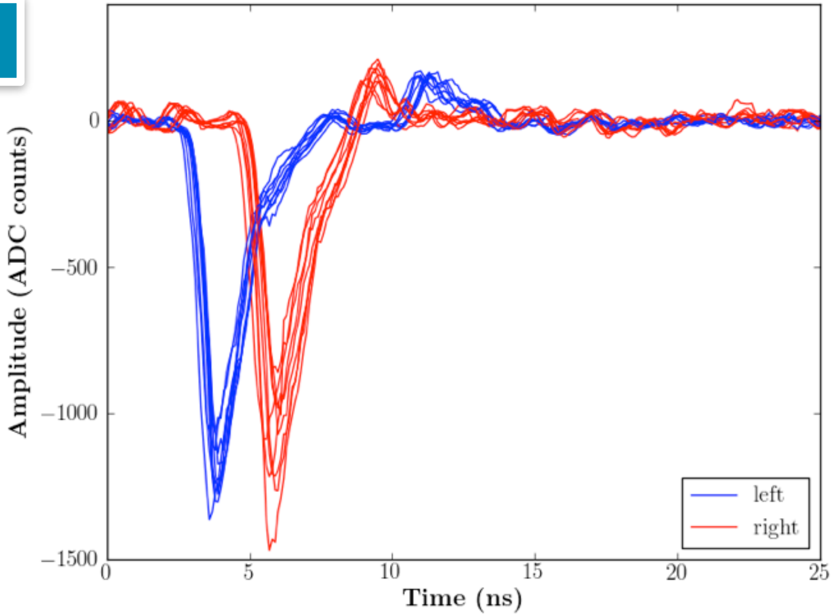


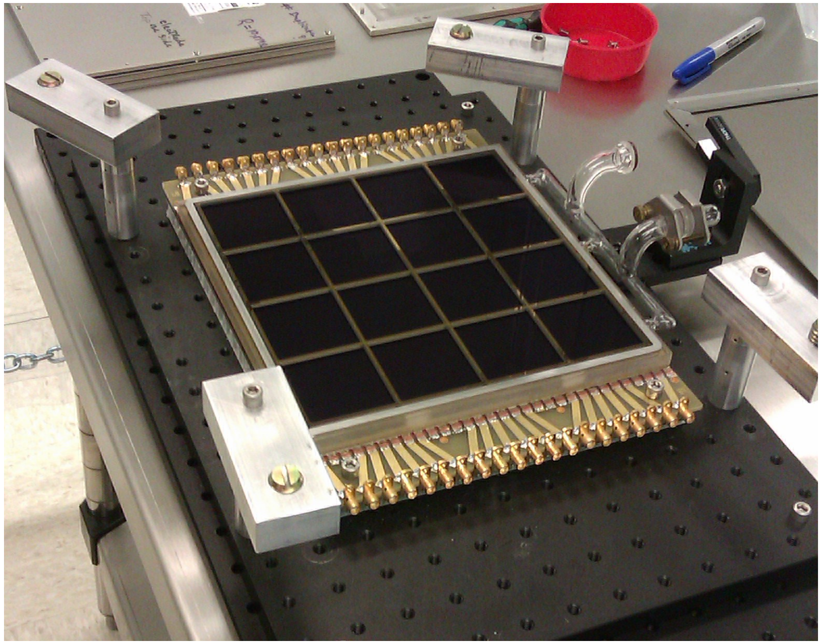
Credit: Eric Oberla



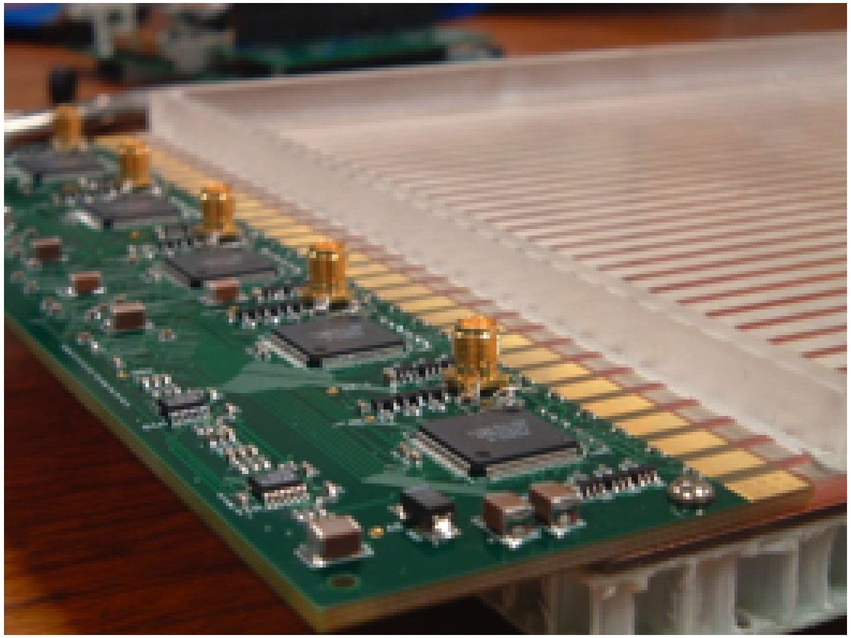
Right Side
Pulses on 10 striplines

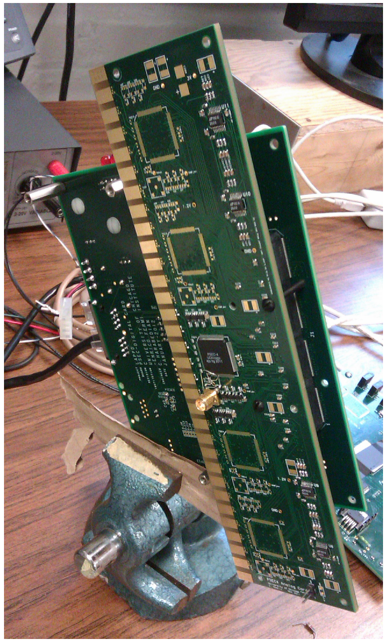
LAPPD





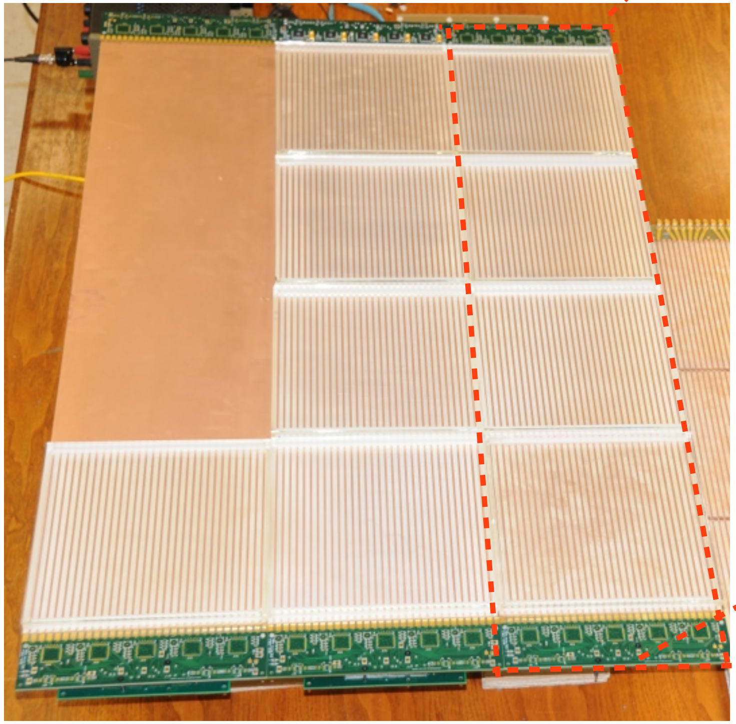
- LAPPD Goal of building a **complete detector system**, including even waveform sampling front-end electronics
- Now testing near-complete glass vacuum tubes ("demountable detectors") with resealable top window, robust aluminum photocathode

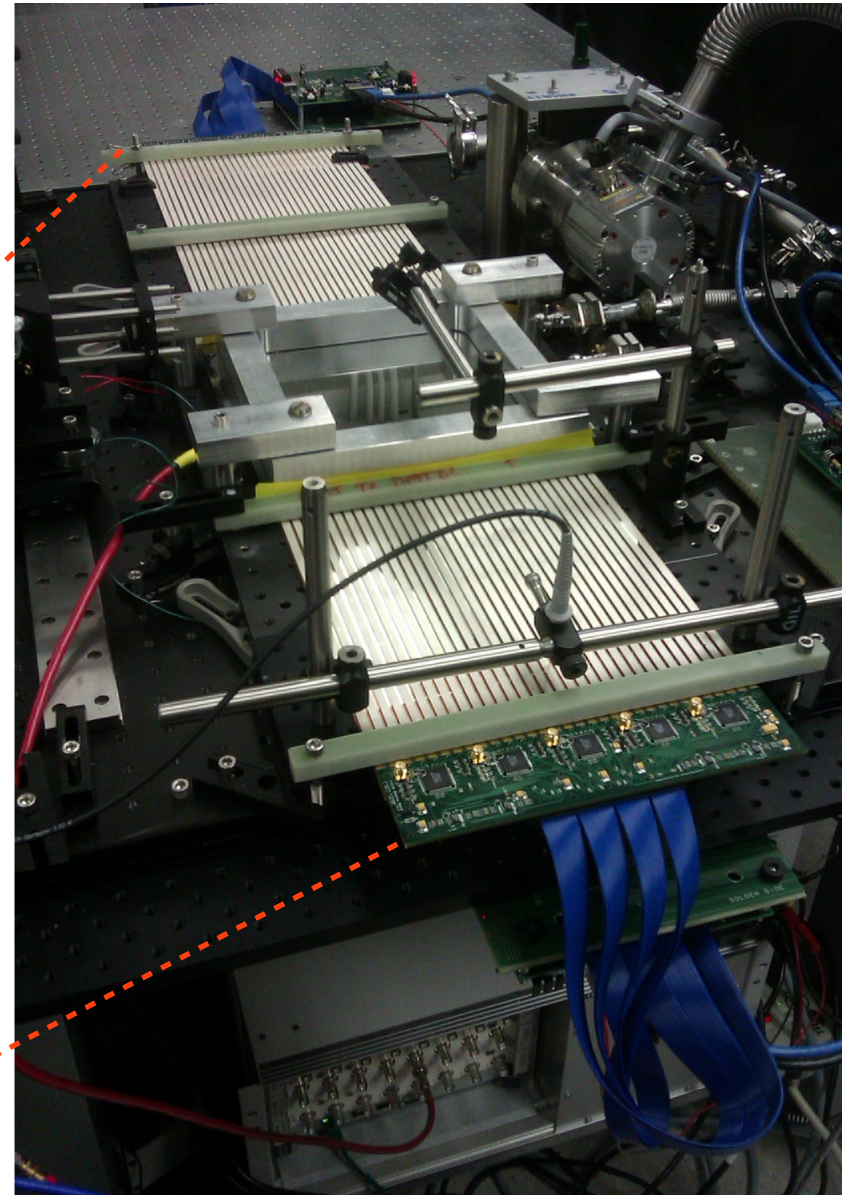




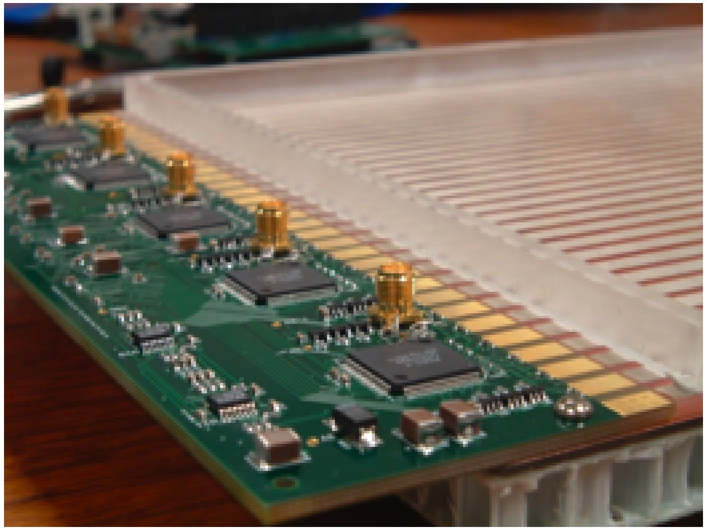
"SuMo Slice"

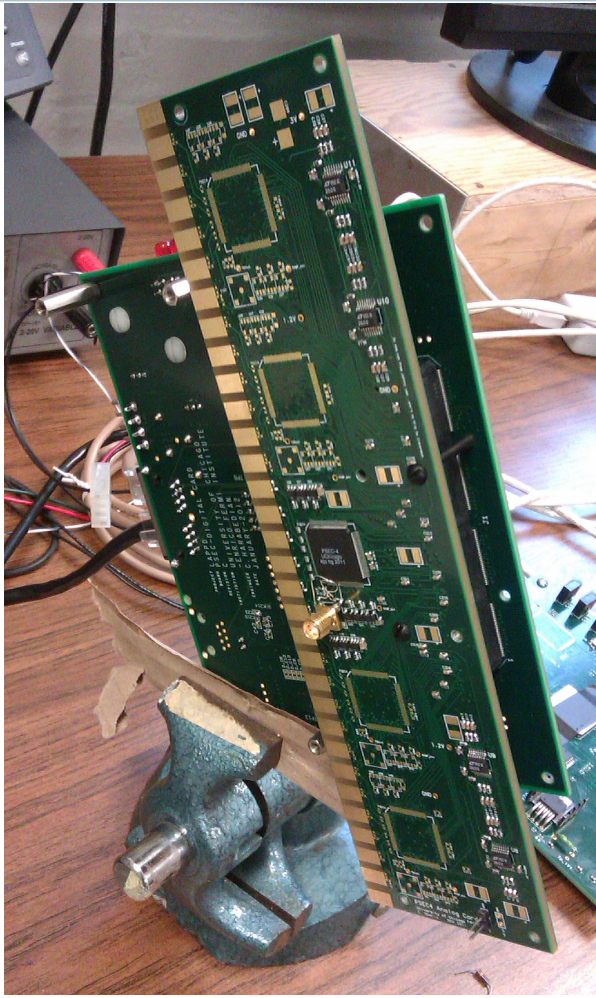
We are now testing a functional demountable detector with a complete 80 cm anode chain and full readout system ("SuMo slice").





Front-end Electronics





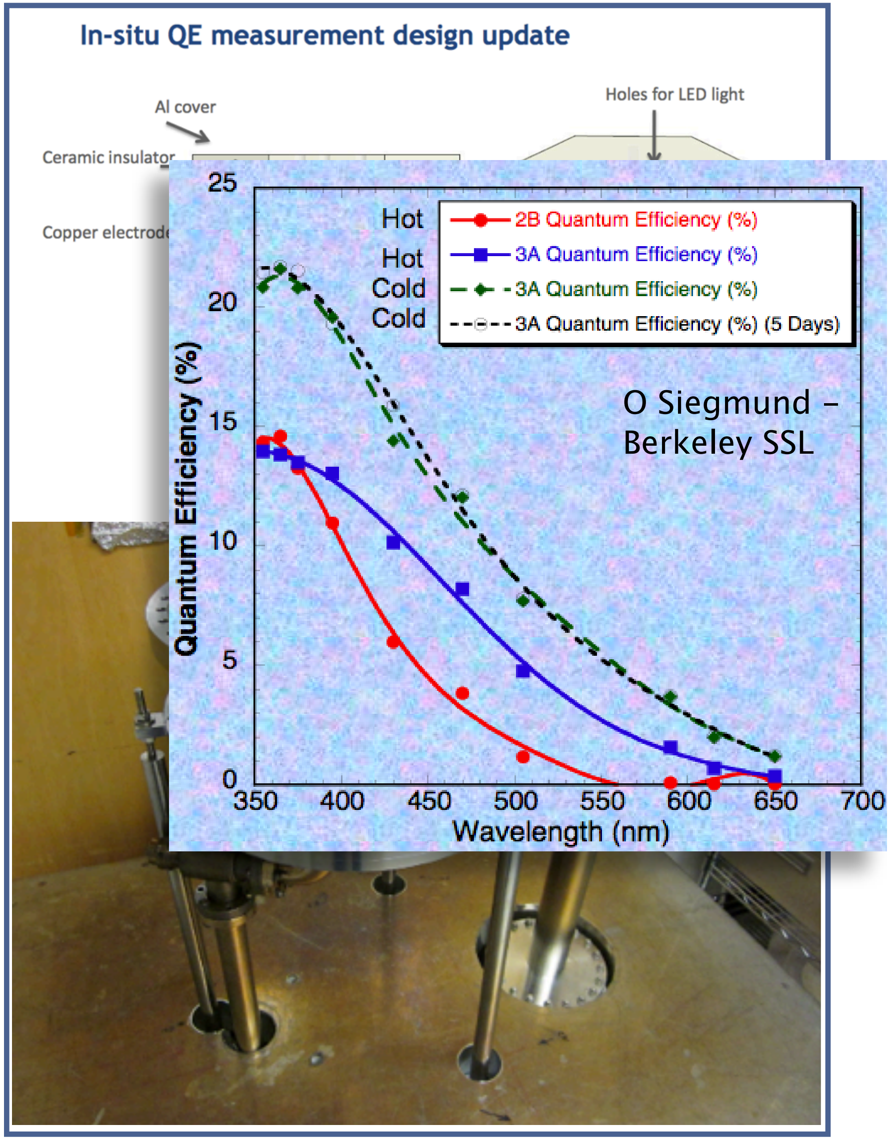
Psec4 chip:
- CMOS-based, waveform sampling chip
- 17 Gsamples/sec
- ~1 mV noise
- 6 channels/chip

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

Large Area Photocathodes



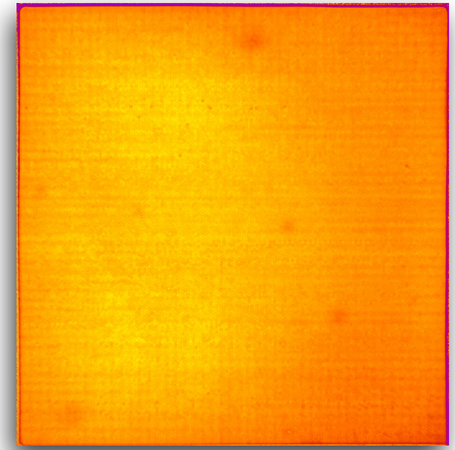
- Two main parallel paths:
  - scale traditional bi-alkali photocathodes to large area detectors. Decades of expertise at Berkeley SSL. Significant work at ANL to study new methods for mass production lines.
  - Also pursuing a deeper microscopic understanding of various conventional photocathode chemistries 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)

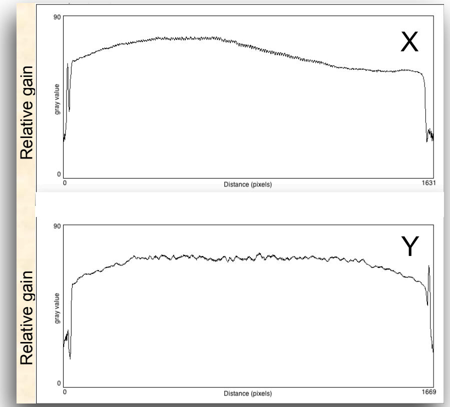
LAPPD

We observe:

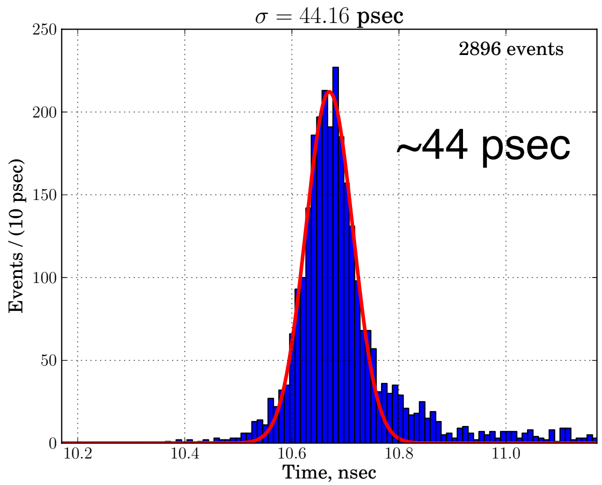
- Typical gains of $O(10^7)$
- Single photoelectron time resolutions of ~40 picoseconds.
- Timing in the many-photoelectron limit approaching single picoseconds

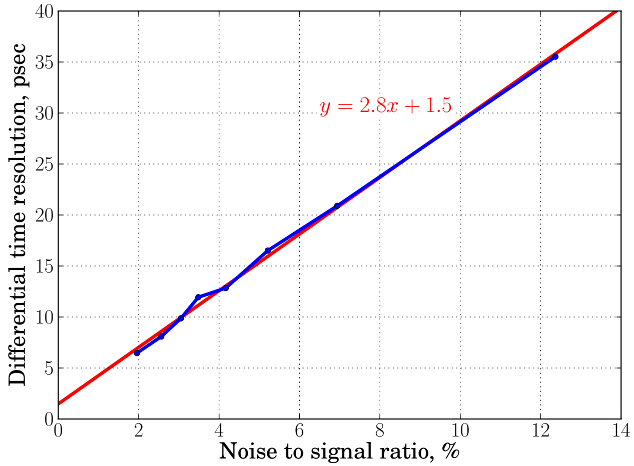


Berkeley SSL



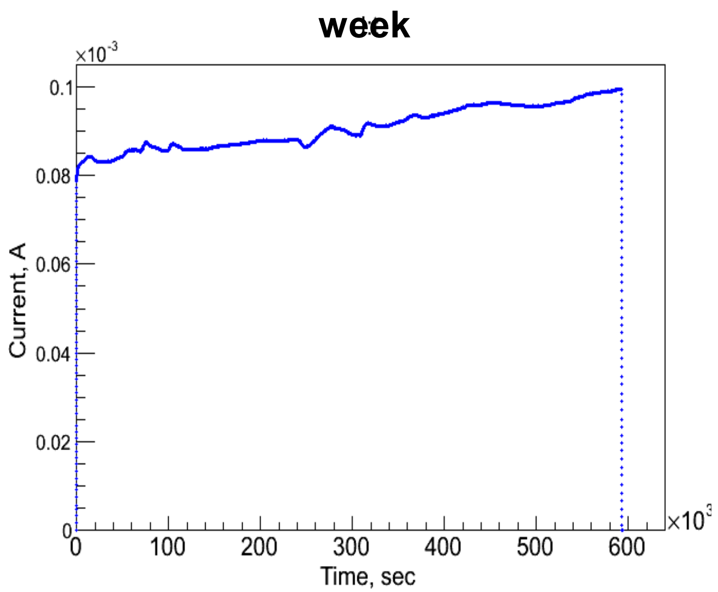
ANL – MCP timing lab

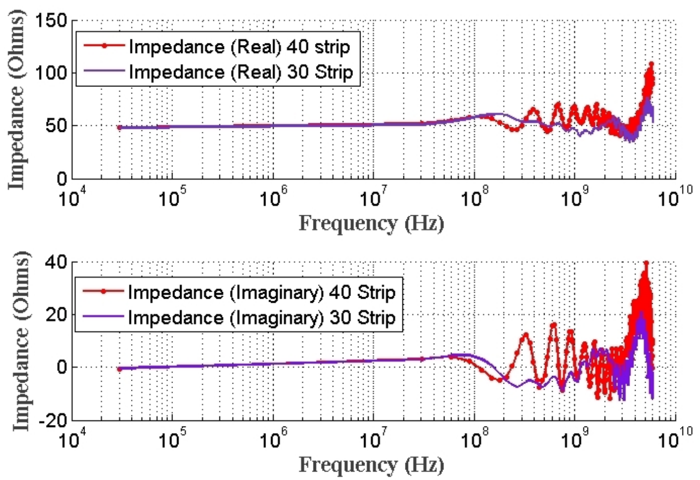


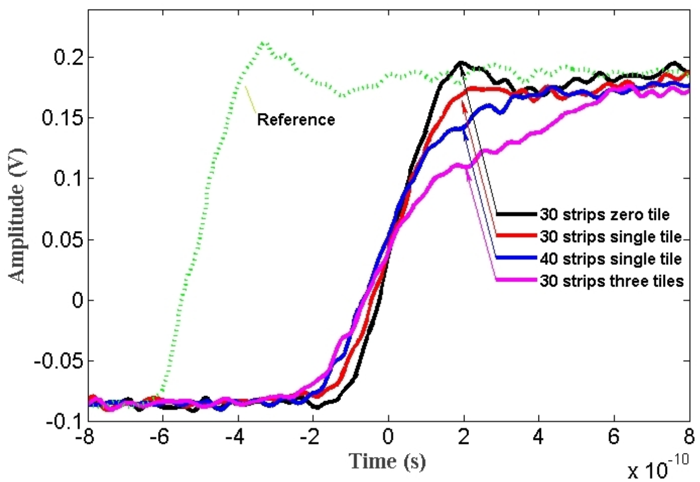


What we measure...Also:

- RF properties
- Losses in anode
- Lifetime and stability issues
- Dark current

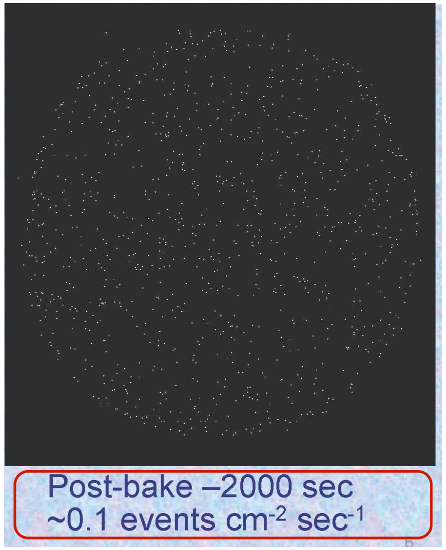






MCP Quality

Low noise



Measurements by

O.H.W. Siegmund, J. McPhate, A.S. Tremsin, S.R. Jelinsky, R. Hemphill

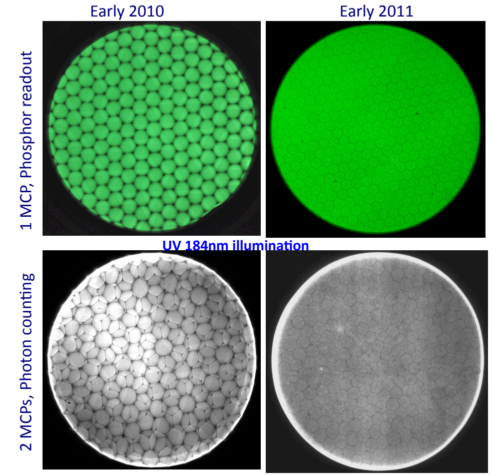
Berekeley SSL

Samples by

J. Elam, A. Mane, Q. Peng

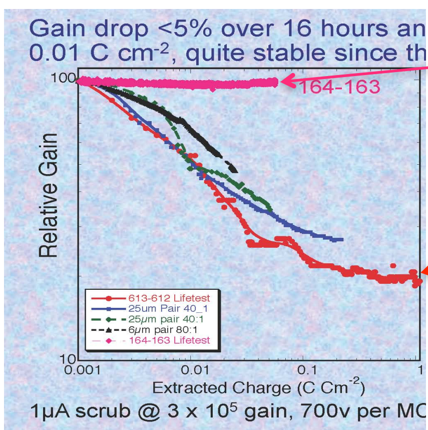
ANL

Rapidly improving substrates (Arradiance)



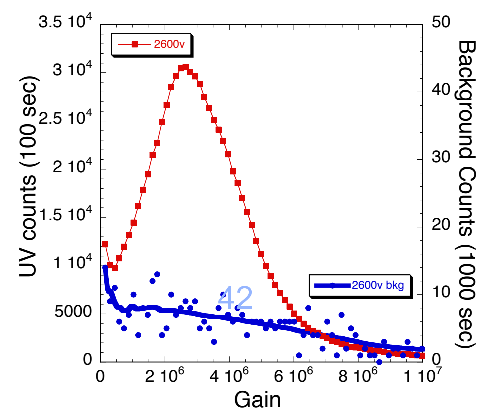
bkgd rate of 0.099 evts cm^{-2} sec^{-1} at 1.3 kV per plate

Short break-in



Measured ANL ALD-MCP behavior

Typical MCP behavior- long scrub-times



Factors That Determine Time Resolution

credit: Stafan Ritt (Paul Scherrer Institute)

$$\Delta t = \frac{\Delta u}{U} \cdot \frac{1}{\sqrt{3 f_s \cdot f_{3dB}}}$$

Assumes zero aperture jitter ↓

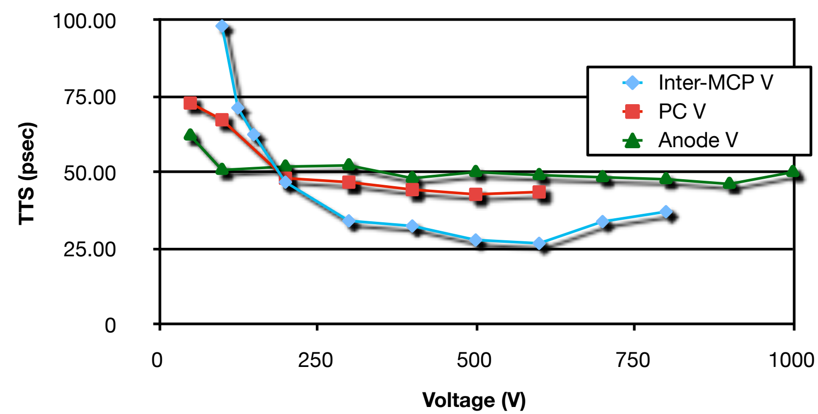
	U	Δu	f_s	f_{3db}	Δt
today:	100 mV	1 mV	2 GSPS	300 MHz	~10 ps
optimized SNR:	1 V	1 mV	2 GSPS	300 MHz	1 ps
next generation:	100 mV	1 mV	20 GSPS	3 GHz	0.7 ps
next generation optimized SNR:	1V	1 mV	10 GSPS	3 GHz	0.1 ps

At the Front End:

- Sampling rate (f_s)
  Nyquist-Shannon Condition
- Analog bandwidth (f_{3DB})
- Noise-to-signal ($\Delta u/U$)

B Adams (APS-ANL), M Chollet (APS-ANL), A Elagin (UoffC/ANL), R Obaid (UofC), A Vostrikov (UofC), M Wetstein (UofC/ANL)

TTS Vs Various Operational Voltage



Intrinsic to the MCP:

- Operational voltages
- Gain
- Geometry
  - Pore size
  - Continuous vs discrete dynode

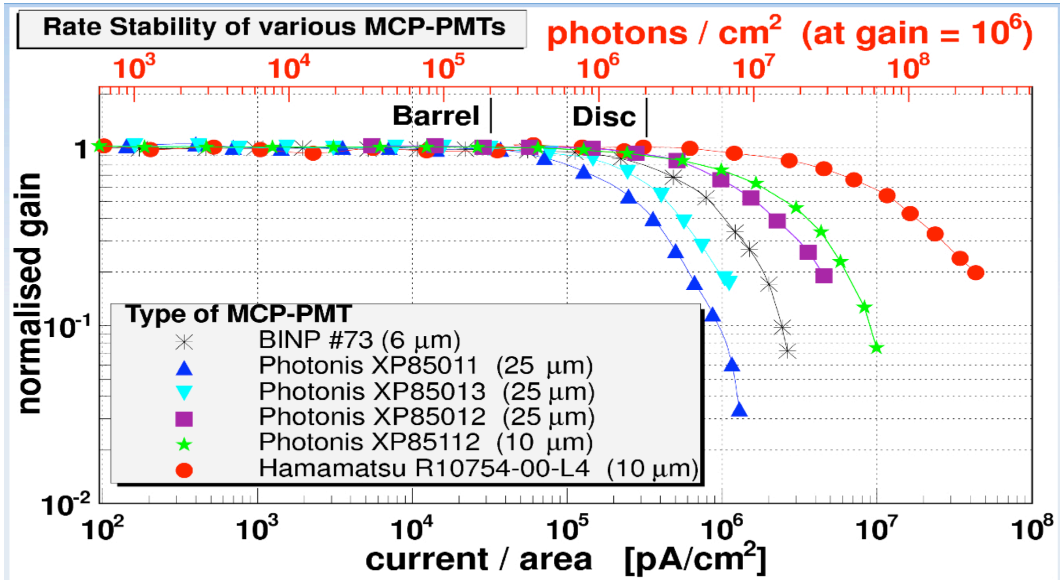
see: workshop on factors that limit time resolution in photodetectors: http://psec.uchicago.edu/workshops/fast_timing_conf_2011/

Factors That Determine Rate Limitations

- The rate capacity of MCPs is primarily driven by pore capacitance and resistance (RC circuit)
- Sctive pores will deplete some charge from their neighbors, decreasing the overall relaxation time
- Rate capacity depends not only on the event frequency, but the spatial distribution

- Rate capacity can be improved
  - by reducing MCP resistance
  - reducing pore size
  - operating at lower gain
- Some commercial plates are already capable of stable operation at MHz rates and are being tested for use in accelerator applications.
- See work by
  - J Va'vra, Anton Tremsin, Ossy Siegmund
  - PANDA Collaboration
  - (among others…)

From Fred Uhlig's talk at NDIP Lyon 2011



- XP85112 (10μm) and XP85012 (25μm) stable up to ~ 2 MHz/cm² s.ph.
- Hamamatsu R10754 stable up to ~ 7 MHz/cm² s.ph.

Rate Limitations of ALD-MCPs

- ALD-based MCPs are expected to perform similarly to commercial plates with comparable parameters.
- Several properties of ALD-MCPs may even be advantageous in high rate contexts
  - Resistance is in the surface not bulk (potentially faster relaxation time):
  - MCPs are made of pure materials (potentially less ion feedback, longer photocathode lifetimes)
  - MCP gain behavior seems more stable with time (so far)
  - **This needs to be tested**

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:
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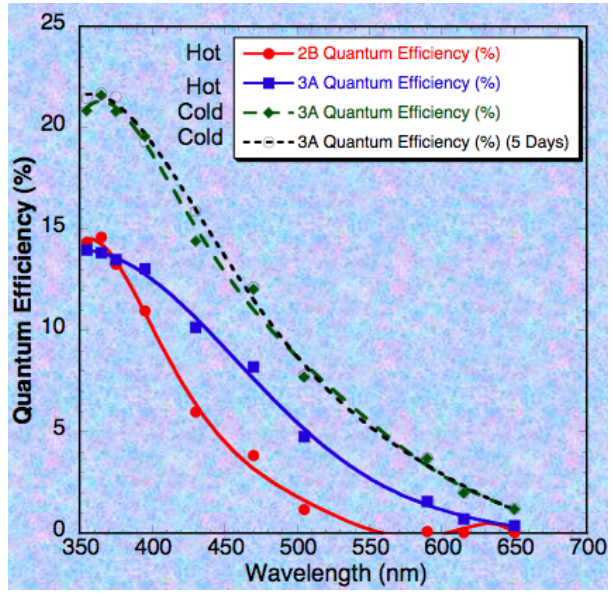
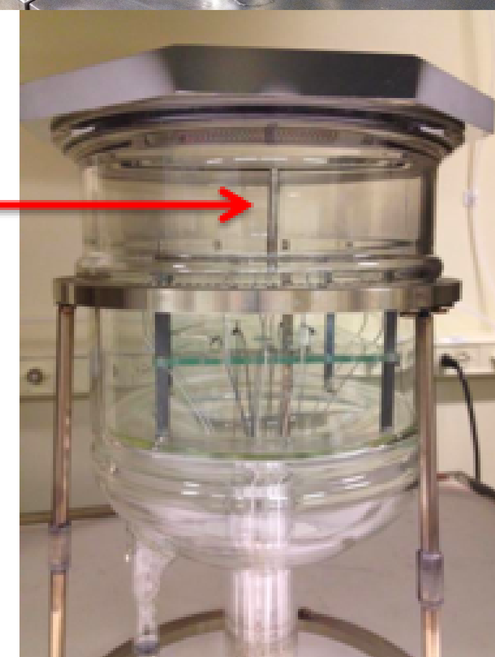


8" Tile-Assembly Chamber (UCB)



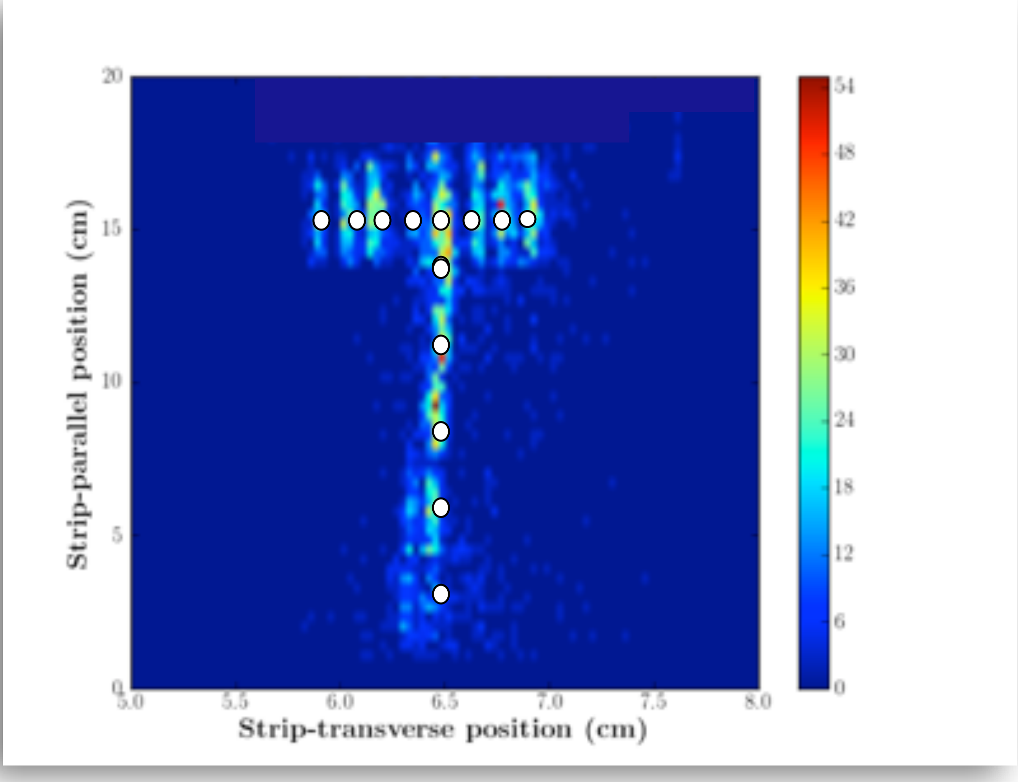
The "Chalice" (ANL)

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

DIGITAL Photon Counting

LAPPDs are essentially digital photon counters

- One can separate between photons based on spatial and time separation in a single photosensor (charge not even very necessary)



LAPPDs are essentially digital photon counters

- One can separate between photons based on spatial and time separation in a single photosensor (charge not even very necessary)

with conventional PMTs

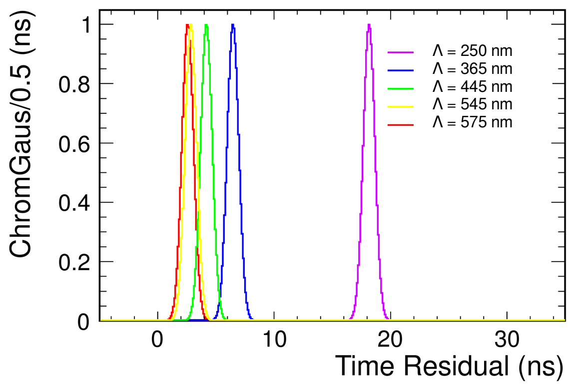
- Measure a single time-of-first-light and a multi-PE blob of charge
- Likelihood is factorized into separate time and charge fits
- History of the individual photons is washed out

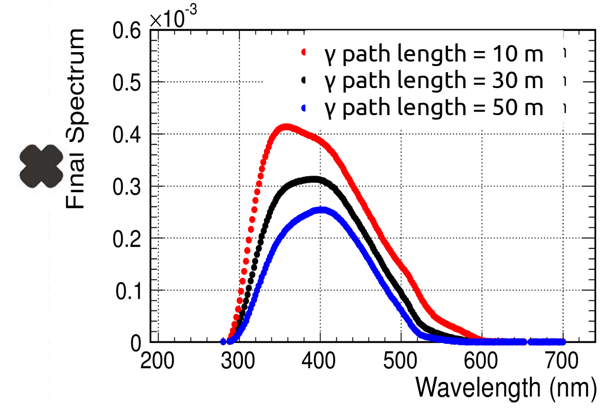
with hires imaging tubes

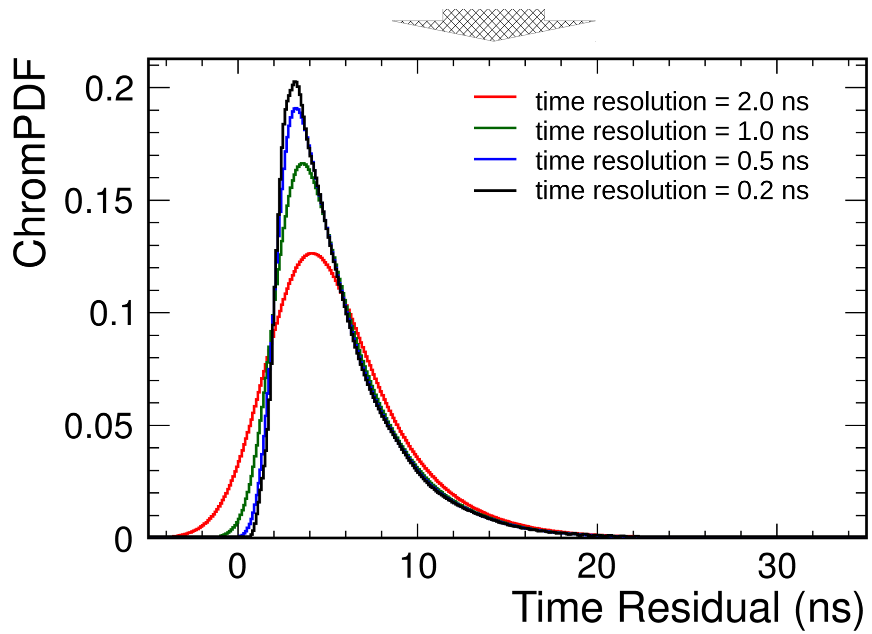
- Measure a 4-vector for each individual photon
- Likelihood based on simultaneous fit of space and time light
- one can separately test each photon for it's track of origin, color, production mechanism (Cherenkov vs scintillation) and propagation history (scattered vs direct)

"Simple Vertex" Reconstruction

- 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 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.



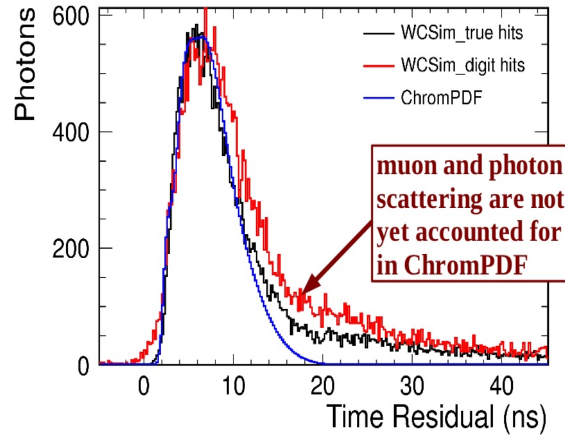


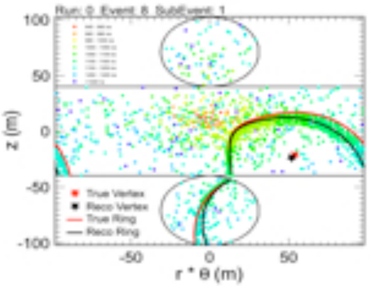


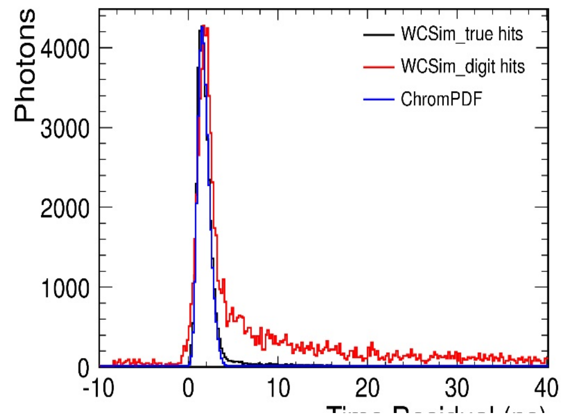
Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

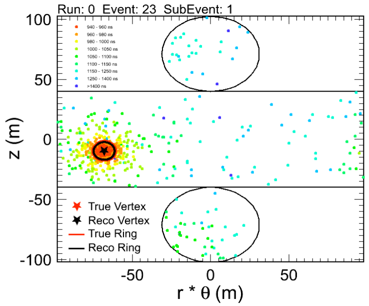
“Simple Vertex” Reconstruction

- 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 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.









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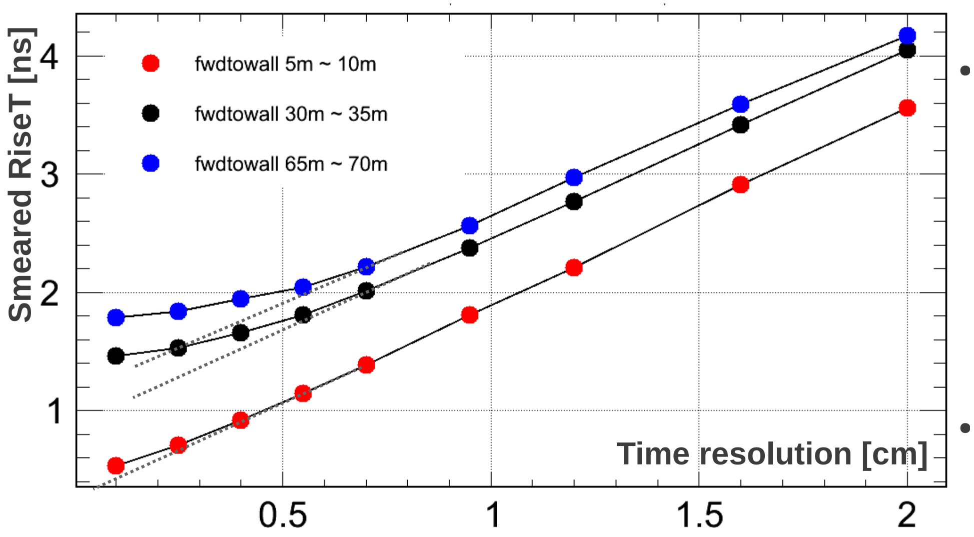
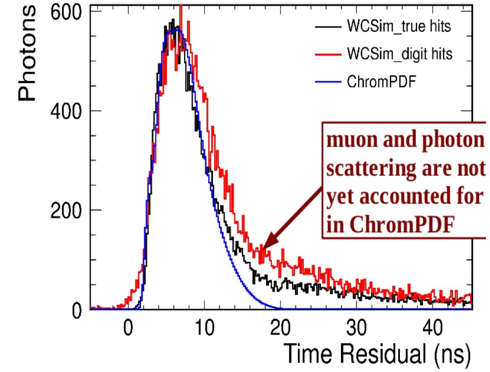
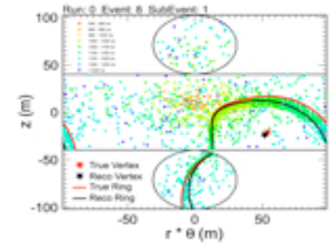
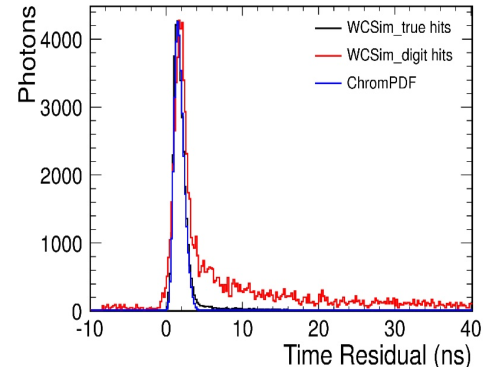
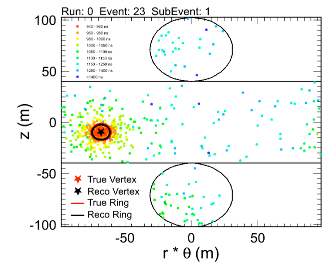
Do These Approaches Scale Up?





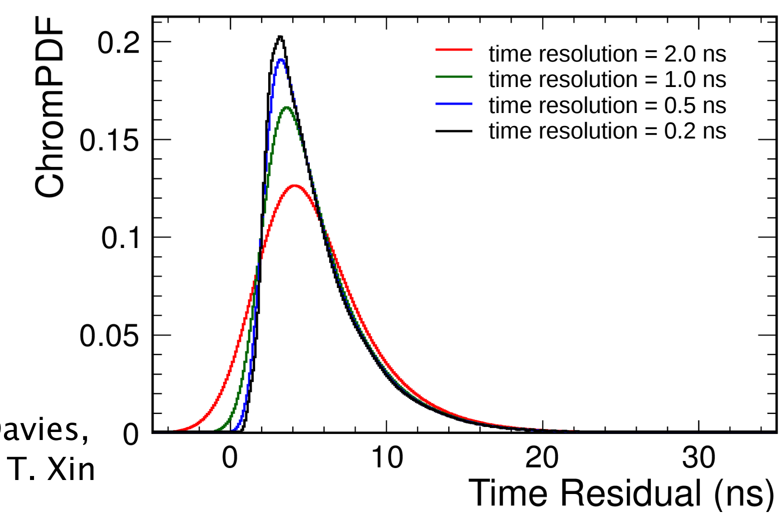






Over large length scales, optical transport of light in water becomes a problem. So does the cost of instrumenting large volumes with photosensors.

How well can the concept of detailed track reconstruction scale to detectors with many 100s of kilotons of water (and low coverage)?



I. Anghel, E. Cantos, G. Davies, M. Sanchez, M. Wetstein, T. Xin

Simple Vertex Reconstruction

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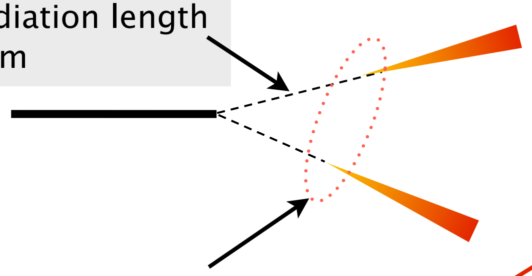
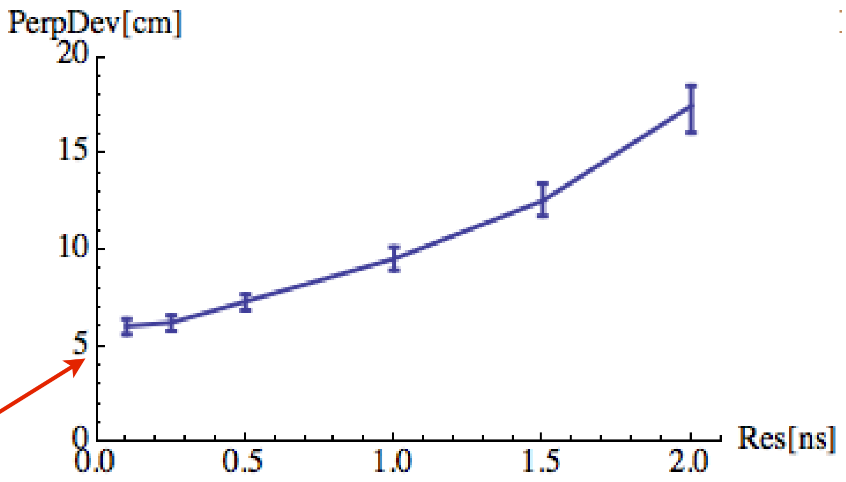
- Separating between multiple vertices depends on differential timing (T0 is irrelevant)
- We study the relationship between vertex sensitivity and time resolution using GeV muons in water. This study is performed using the former LBNE WC design, with 13% coverage and varying time resolution.
- Transverse vertex reconstruction is better than 5 cm for photosensor time resolutions below 500 picoseconds.

~1 radiation length
~37 cm



vertices are separated:
at 7 degrees: ~4.5 cm
at 15 degrees: ~9.7 cm

Optical TPCs are scalable to 100s of kilotons



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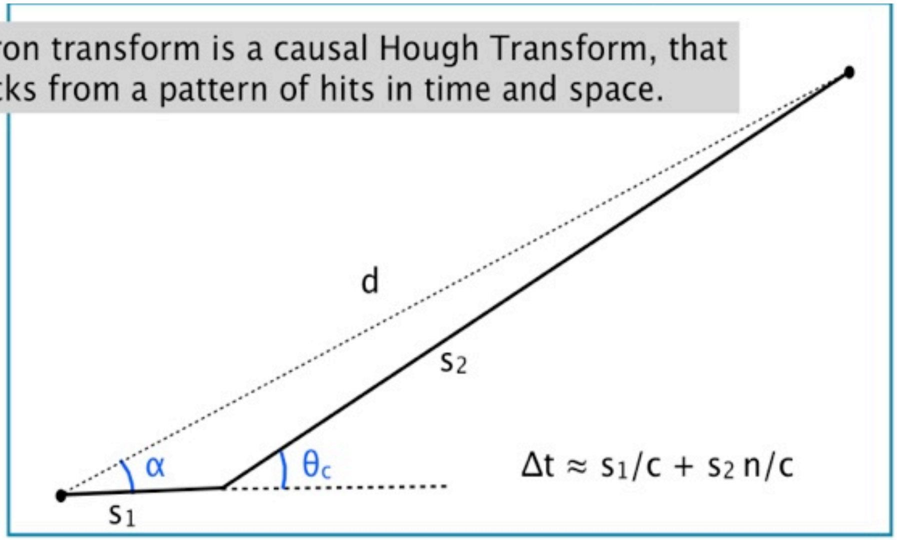
Isochron

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



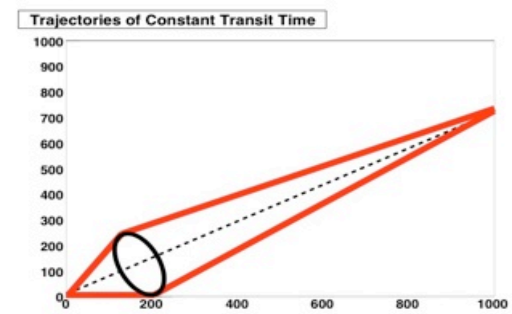
Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns:

s_1 and α

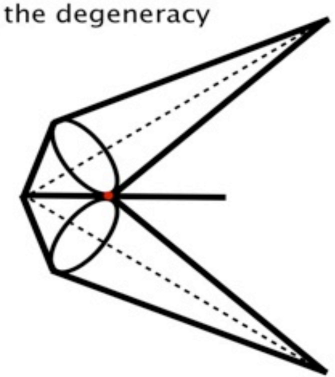
but there are two constraints:

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

For a single PMT, there is a rotational degeneracy (many solutions).



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



M. Wetstein

Isochron

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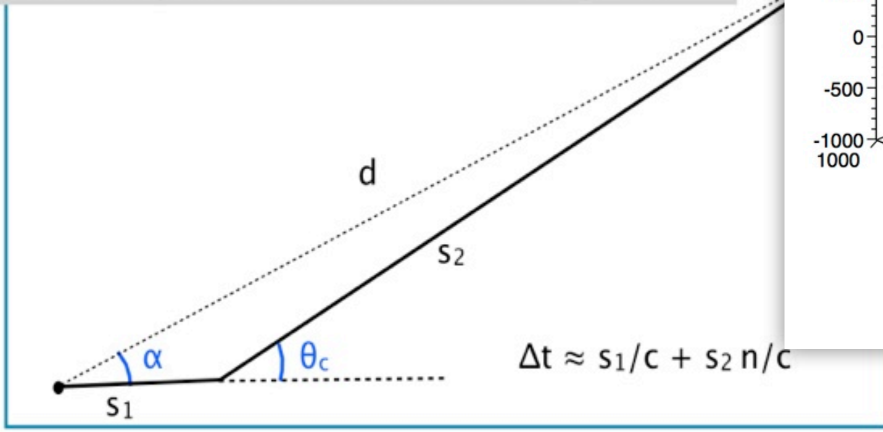

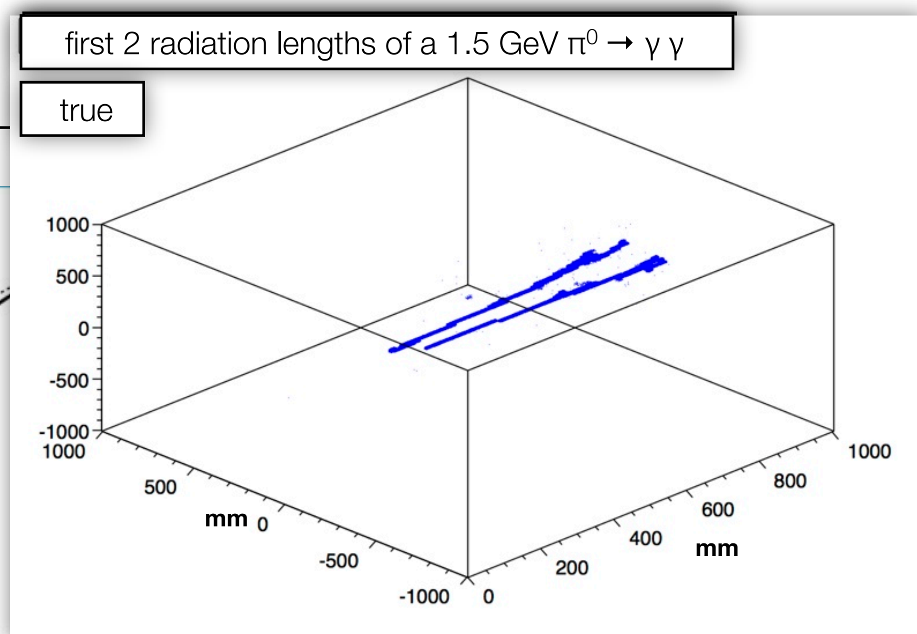

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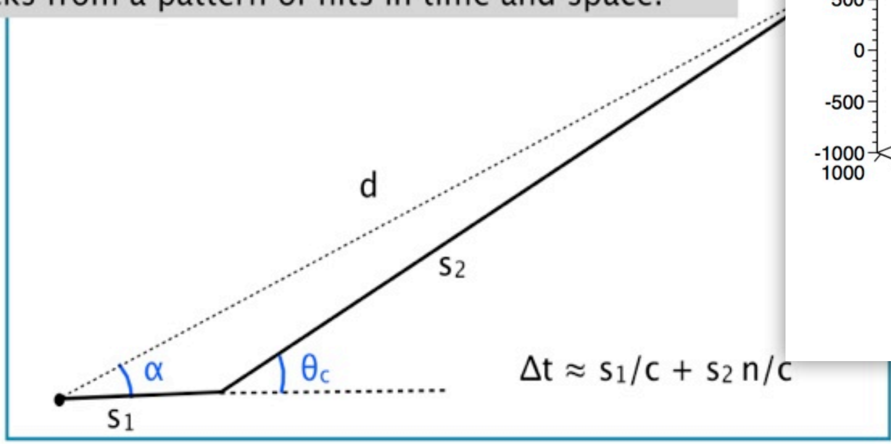

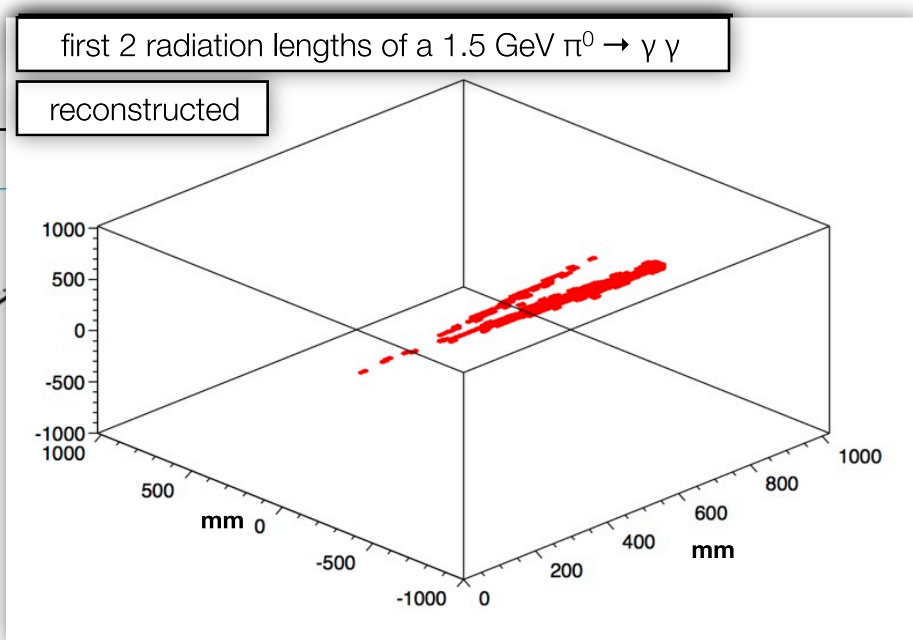

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s_1 and α

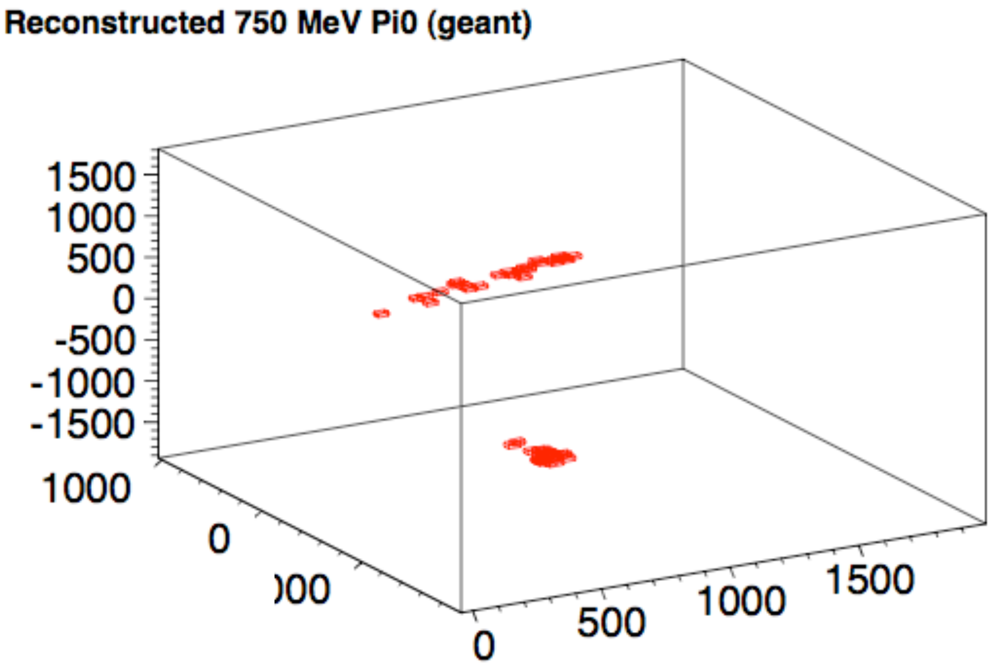
but there are two constraints:

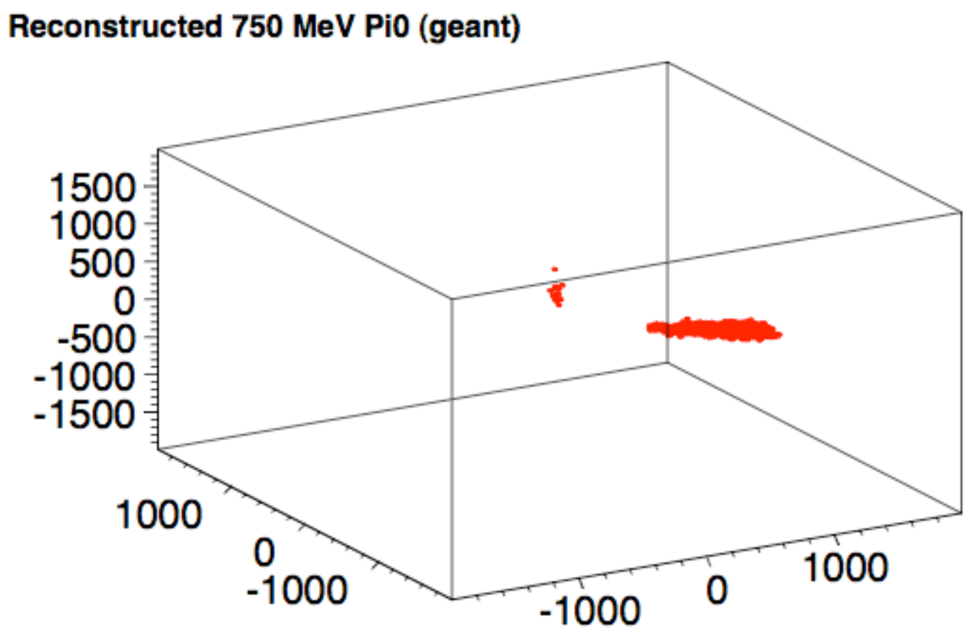
$s_1 + s_1 = d$ and $\Delta t_{measured} = s_1/c + s_2\, n/c$

Could be useful for full pattern-fitting approached by providing a seed topology and restricting the phase space of the fit.

M. Wetstein

Comparing Isochron Reconstruction with Truth





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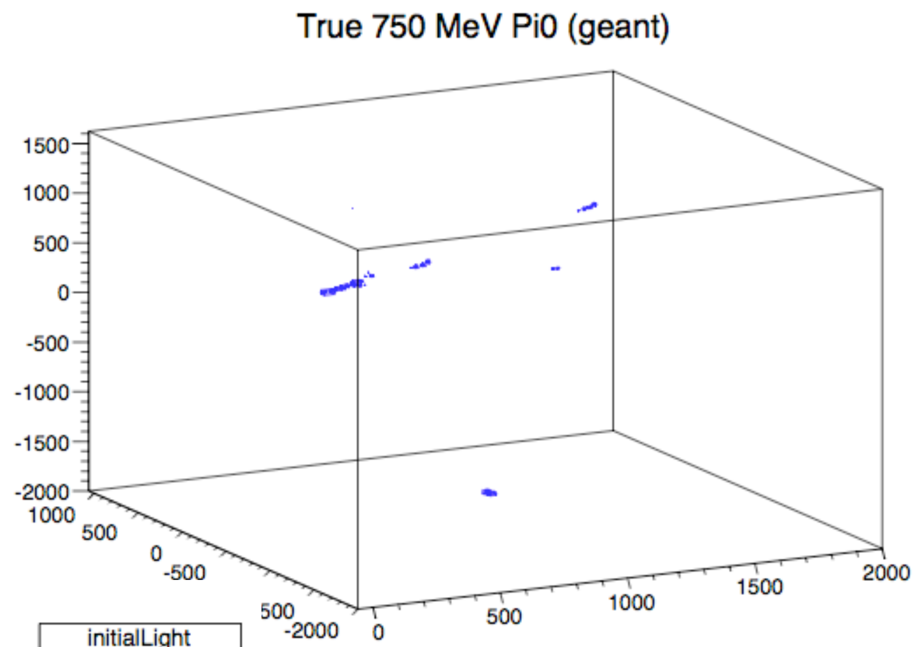
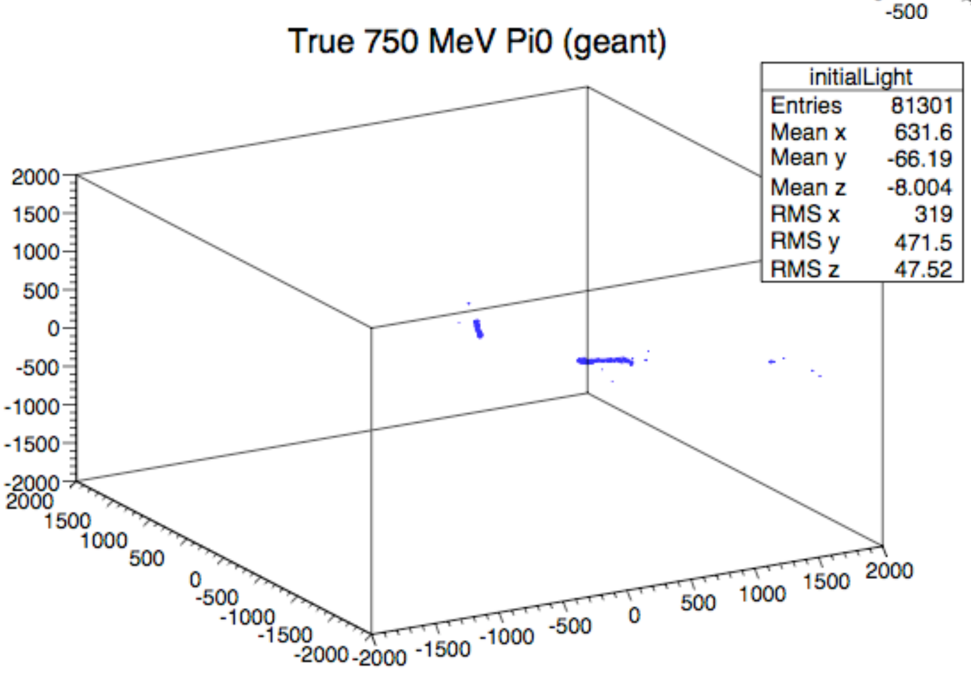
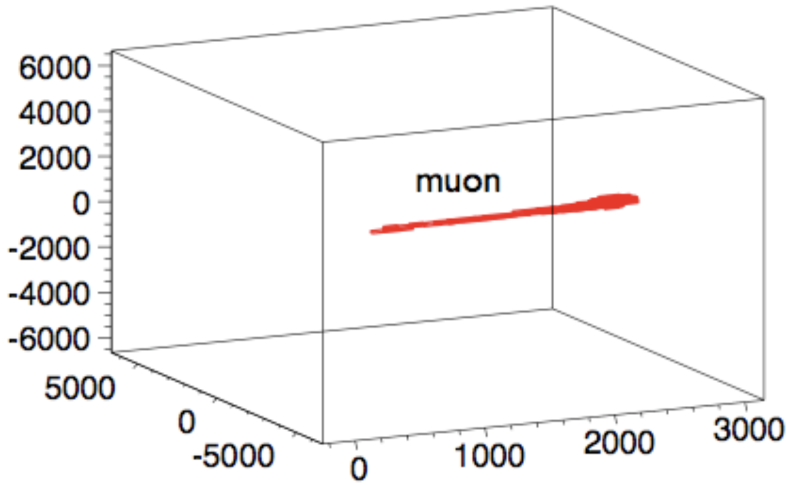
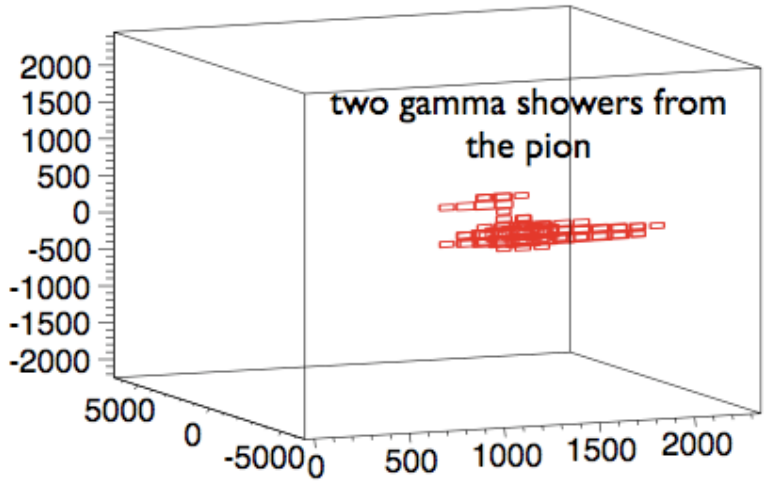
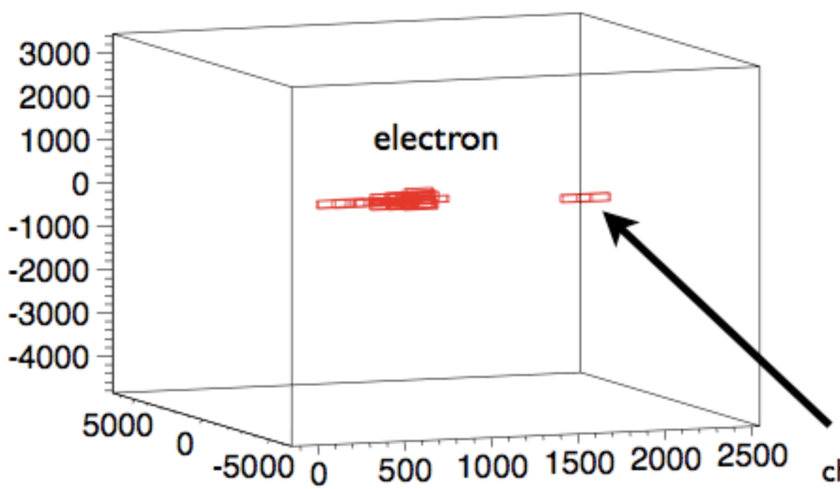




Reconstructing Geant Events

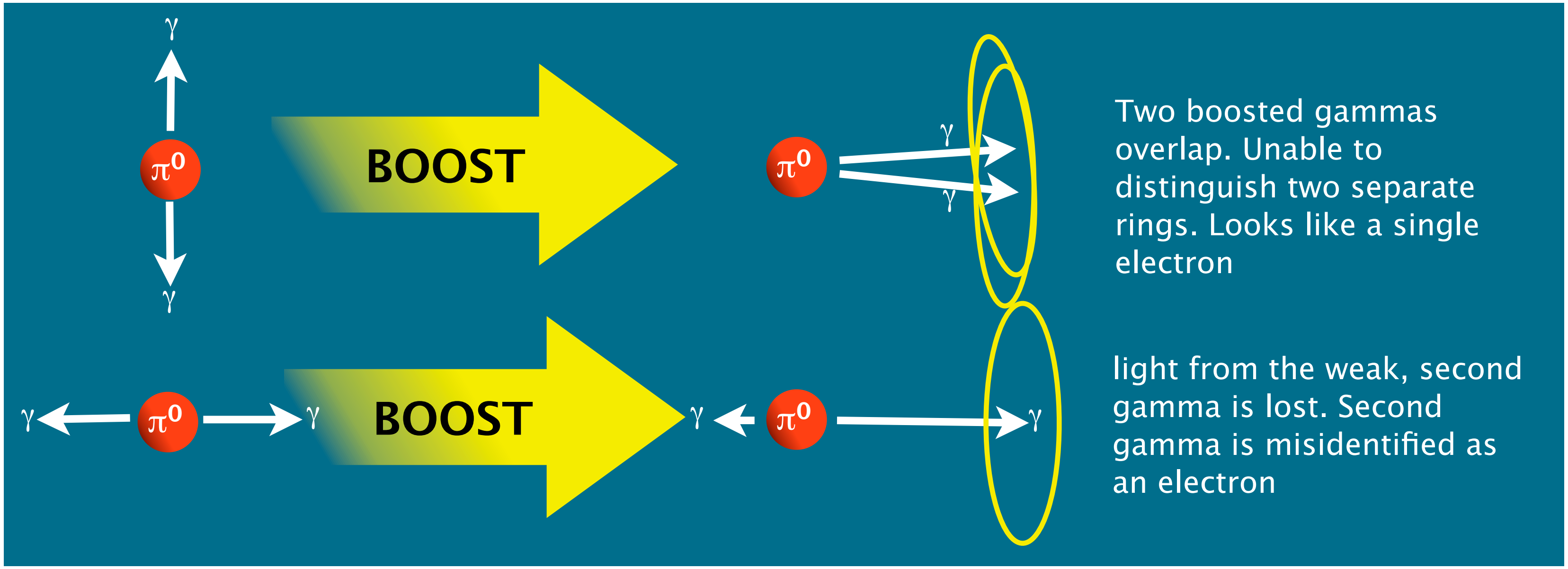






check out the detached shower from the bremstrahlung!!

Granularity



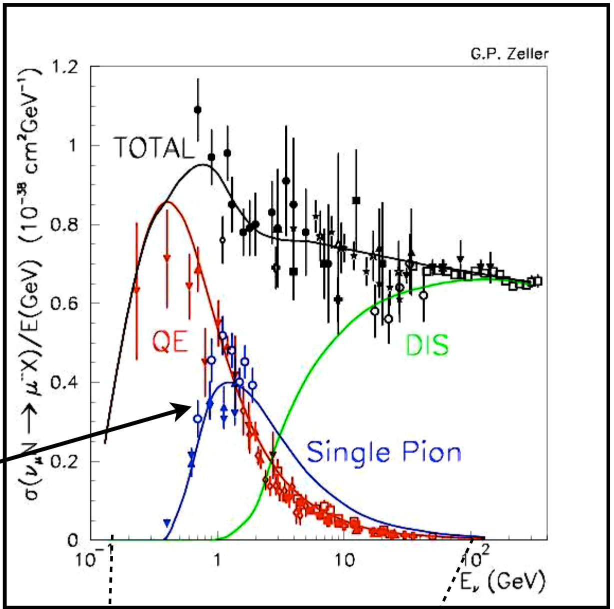
Largest reducible background at ~GeV energies. In WC, in order to achieve a pure electron sample (~1% π^0), one needs harsh quality cuts at the cost of signal efficiency.

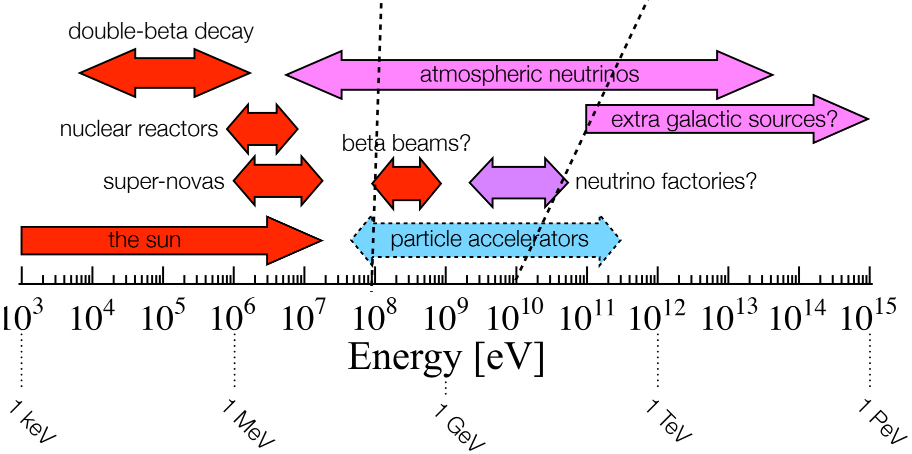
There is still a room for significant improvement in the physics capabilities for a given mass of water.

Granularity

Medium energy ranges typical of accelerator and atmospheric neutrino physics fall into the "transition region" between Quasi-elastic scattering and deep inelastic scattering.

Pion production (from excited nuclear states) peaks at these energies.





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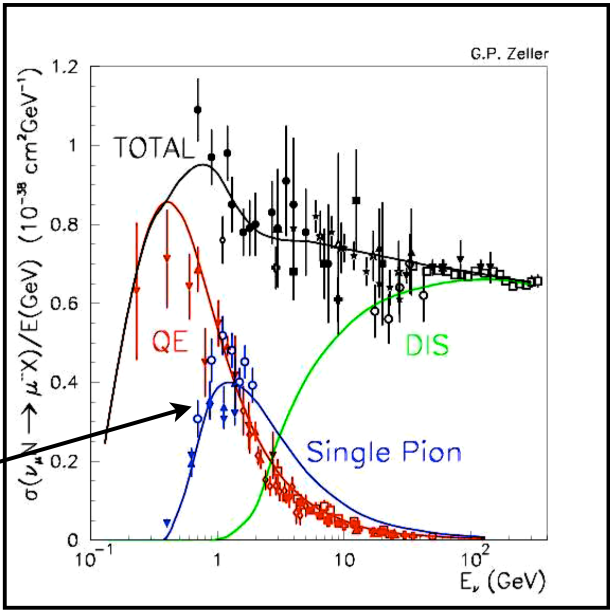

Pion production (from excited nuclear states) peaks at these energies.

CC

$$\nu_\mu p \to \mu^- p \pi^+, \qquad \bar{\nu}_\mu p \to \mu^+ p \pi^-,$$
$$\nu_\mu n \to \mu^- p \pi^0, \qquad \bar{\nu}_\mu p \to \mu^+ n \pi^0,$$
$$\nu_\mu n \to \mu^- n \pi^+, \qquad \bar{\nu}_\mu n \to \mu^+ n \pi^-$$

NC

$$\nu_\mu p \to \nu_\mu p \pi^0, \qquad \bar{\nu}_\mu p \to \bar{\nu}_\mu p \pi^0,$$
$$\nu_\mu p \to \nu_\mu n \pi^+, \qquad \bar{\nu}_\mu p \to \bar{\nu}_\mu p \pi^+$$
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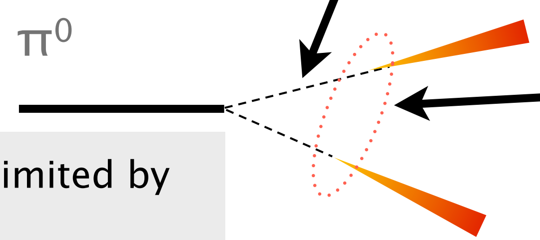
Granularity

On average, this amounts to separating the two vertices from which the Cherenkov cones radiate...

~1 radiation length
~37 cm

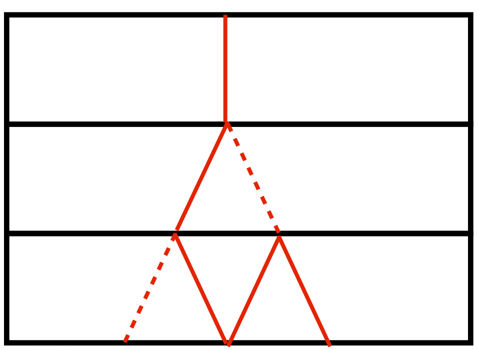


vertices are separated:
at 7 degrees: ~4.5 cm
at 15 degrees: ~9.7 cm

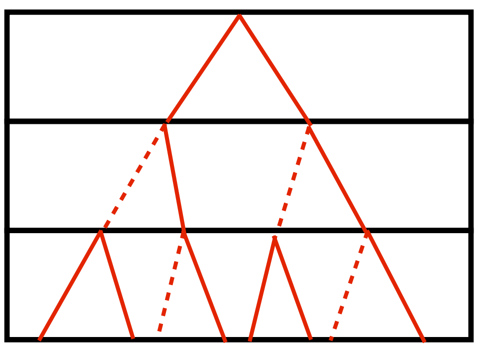
- Finding a single event vertex is limited by our ignorance of T_0.
- Vertex separation is not...

Can we reconstruct the first several stages of an EM shower?

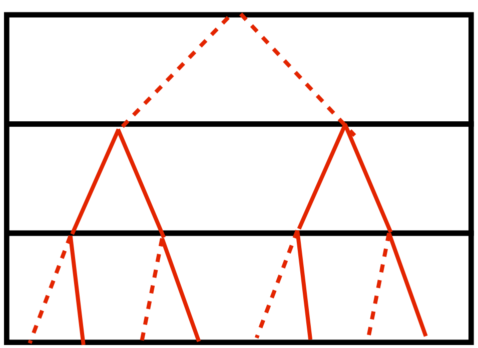
electron shower



single gamma



pi0



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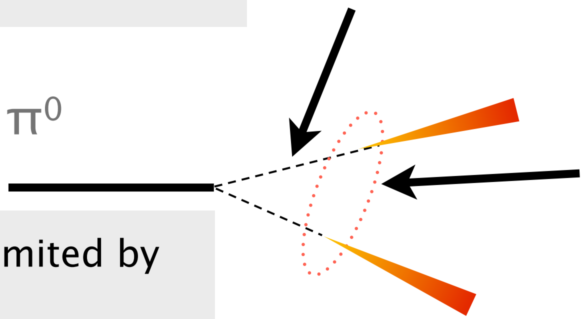

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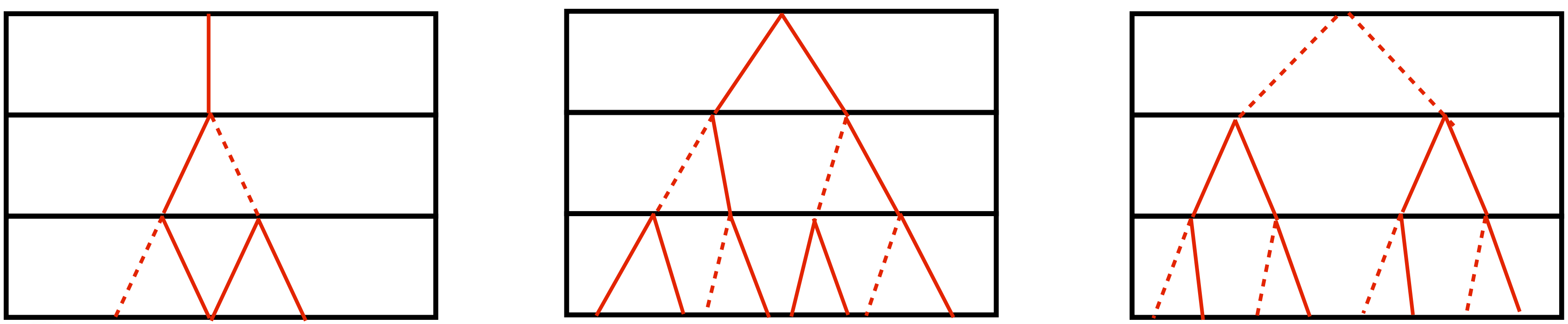


Low Energy/Heavy Particle Sensitivity

More light/light below Cherenkov threshold

Charged particles only produce Cherenkov light when $v > c/n$

For massive particles, the threshold for Cherenkov production is >100 MeV

Particle	Threshold
electron	> 0.6 MeV
muon	> 120 MeV
pion	> 160 MeV
kaon	> 563 MeV
proton	> 1070 MeV

	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \to e^+\pi^0$	45%	0.2	45% ?	0.1
$p \to \nu K^+$	14%	0.6	97%	0.1
$p \to \mu^+ K^0$	8%	0.8	47%	0.2
n-nbar	10%	21	?	?

SUSY favored proton decay mode:

$$p \to K^+ \bar{\nu}$$

63.5 % $\to \mu^+ \nu$ (152 MeV)

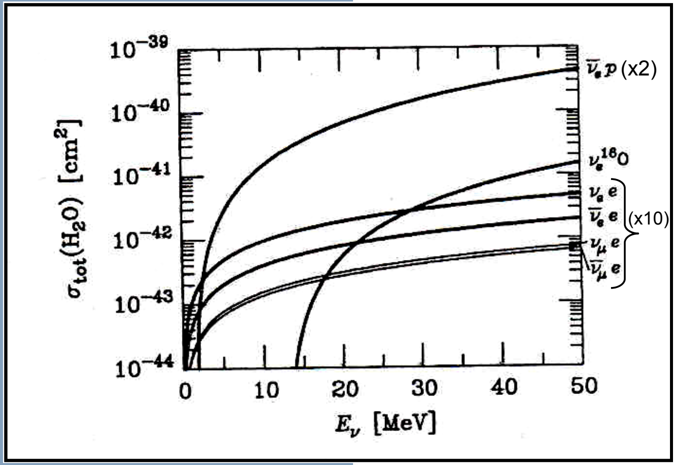
20.7 % $\to \pi^0 \pi^+ \to 2\gamma\ \mu^+ \nu$ (135 MeV, 4 MeV)

Inefficient channel in water. Cannot see the Kaon

Low Energy/Heavy Particle Sensitivity

Seeing neutrons

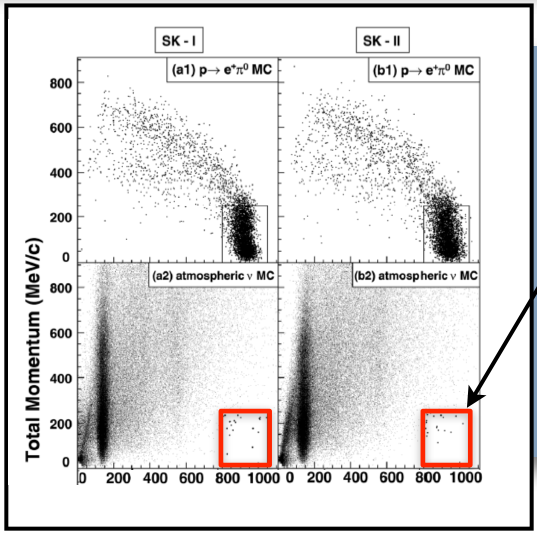
K. Zuber, Neutrino Physics, IOP, 2004



At O(10) MeV energies, inverse beta decay (IBD) has the largest cross-section in water. Neutrons are important for tagging IBD signal events.

Important for:

- Supernova neutrinos
- Solar neutrinos
- Geo neutrinos
- Reactor neutrinos



Atmospheric neutrino interactions can fall in the signal region for proton decay in the p→eπ^0 channel.

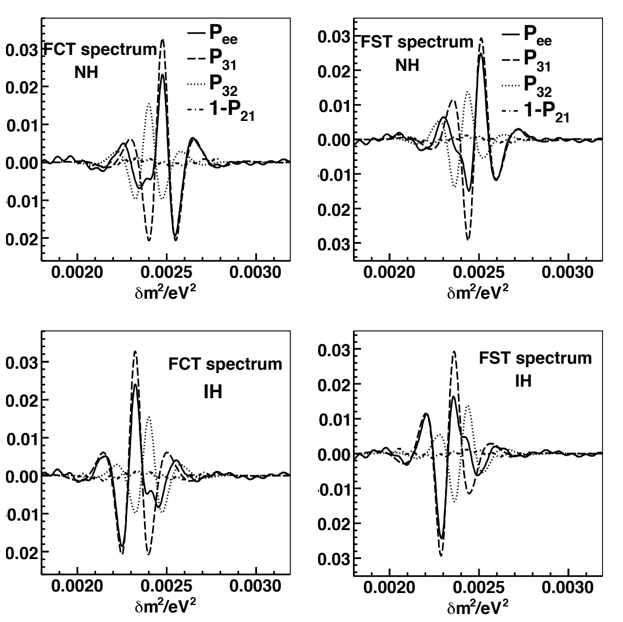
Identifying neutrons is important in tagging this, the largest reducible background.

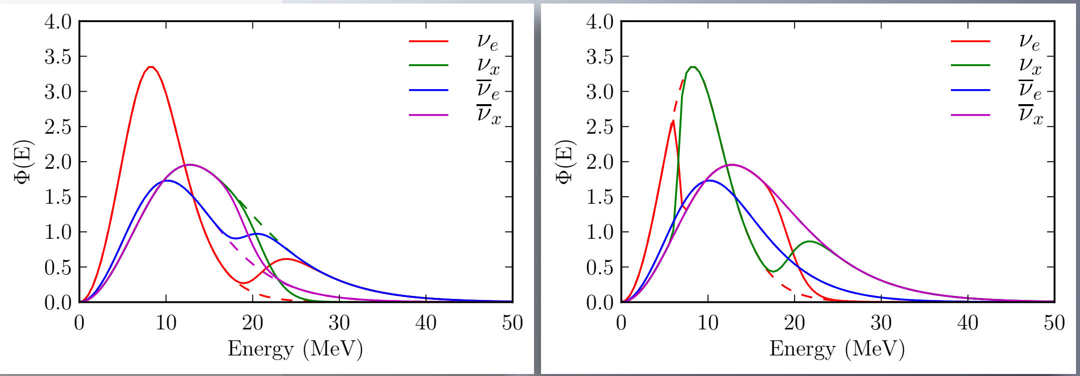
Energy Resolution

Daya Bay II

- Proposed reactor neutrino experiment to determine the neutrino mass hierarchy based on a novel approach.
- 10 kton liquid scintillator detector on a 60 km baseline

Need excellent energy resolutions: 3%/sqrt(E)!





- Core Collapse Supernova
  - the ultimate intensity frontier
    - ~99% of energy is carried away by neutrinos
    - neutrino densities are so high that neutrino–neutrino interactions dominate
  - an experiment we could never afford to build
  - predicted to occur a few times a century in our galaxy

More on Supernova Physics

source:
The 2010 Interim Report of the LBNE Collaboration Physics Working Groups

events w/ neutron tag   events w/ NO neutron tag

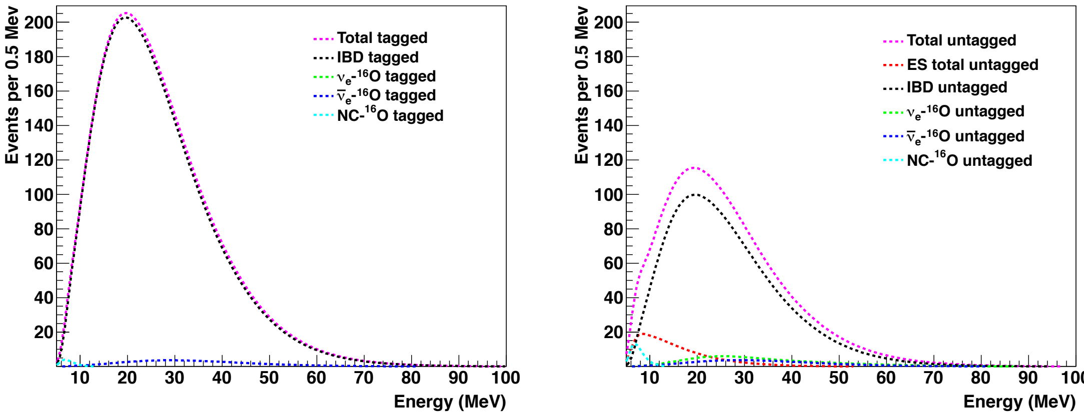


FIG. 46. Total events in WC showing contribution from the different interaction channels, for neutron-tagged (left) and untagged (right) events.

- SN burst interactions with a neutron provide a very pure IBD sample
- Interactions without an FS neutron provide a more pure sample of non-IBD interactions.

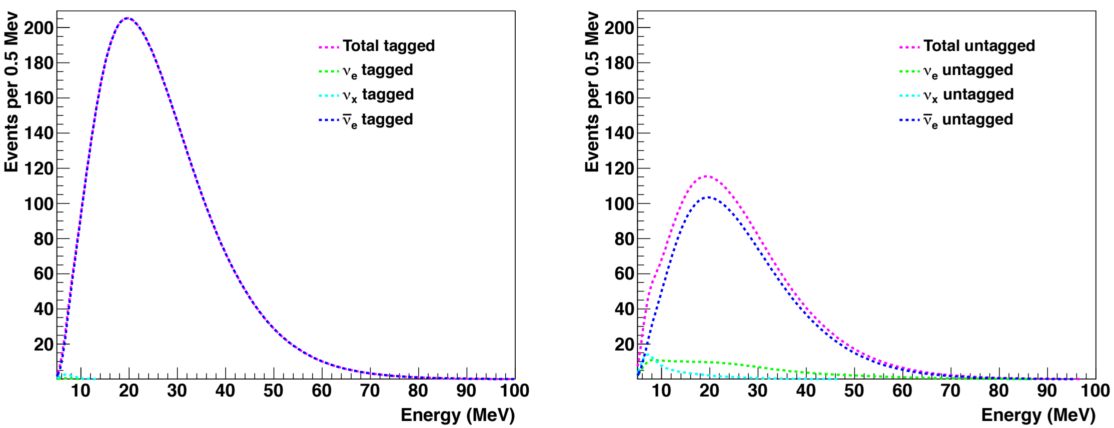


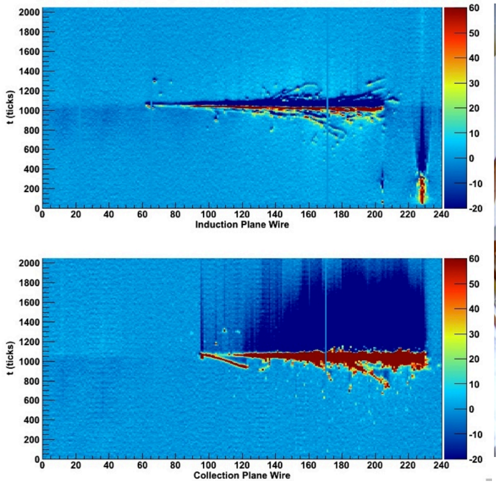
FIG. 47. Total events in WC showing contribution from the different flavors, for neutron-tagged (left) and untagged (right).

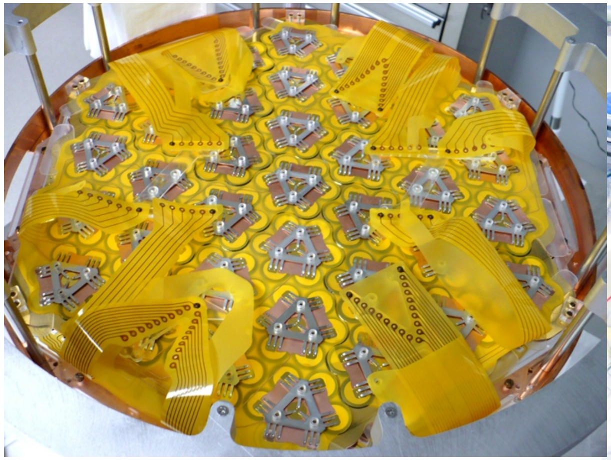
- Interactions with neutrons provide a very pure sample of $\bar{\nu}_e$
- Interactions without an FS neutron provide a more pure sample of ν_e, ν_x, $\bar{\nu}_x$

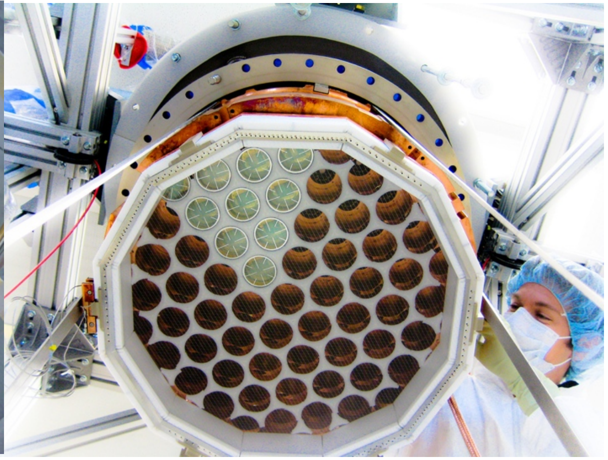
Other Possible Opportunities

LAPPD-based detectors can be non-cryogenic, but they don't have to be. This technology Could be useful for photodetection in cryogenic experiments:

- LBNE near and far detectors (LAr)
- double beta decay (dark matter) experiments?

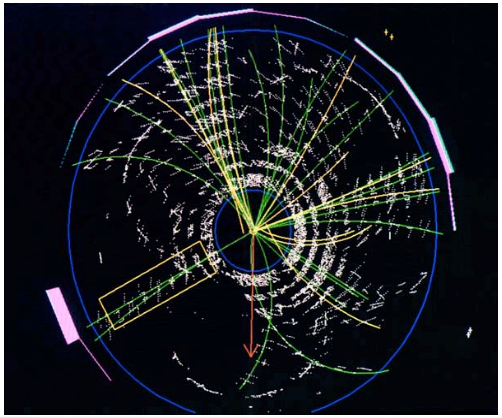


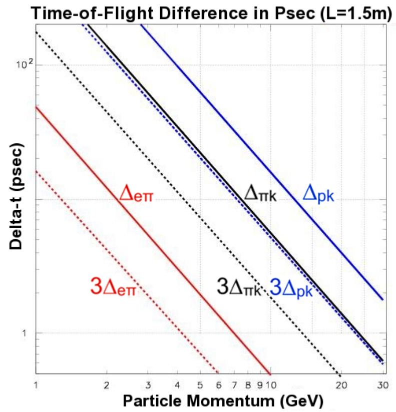




LAPPD was inspired by collider applications: time-of-flight based particle ID.

Also many potential practical applications: PET, security...





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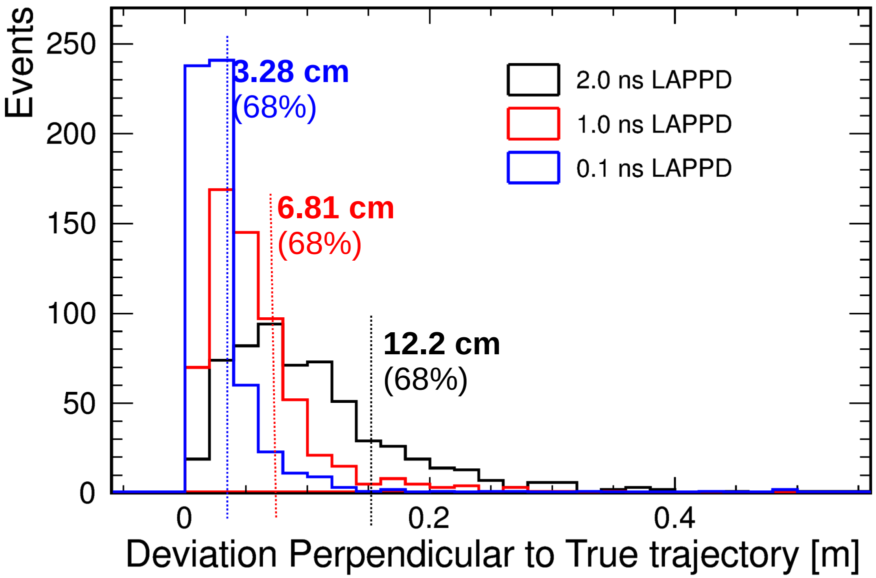
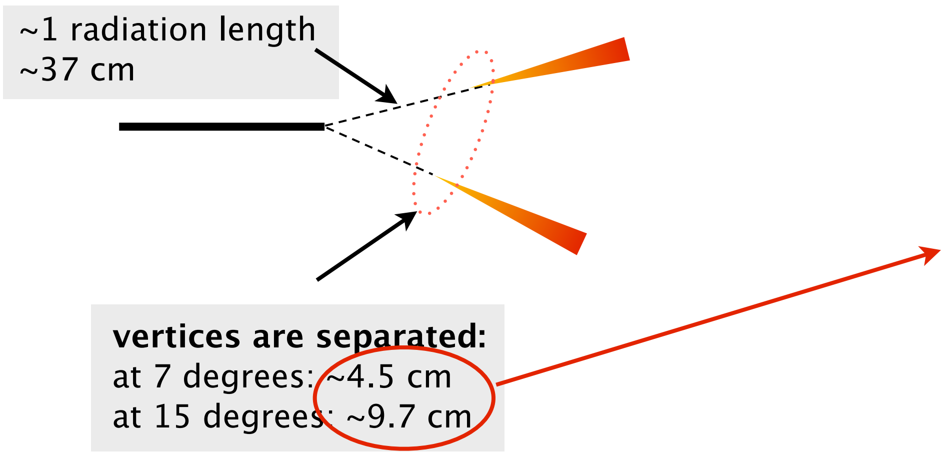
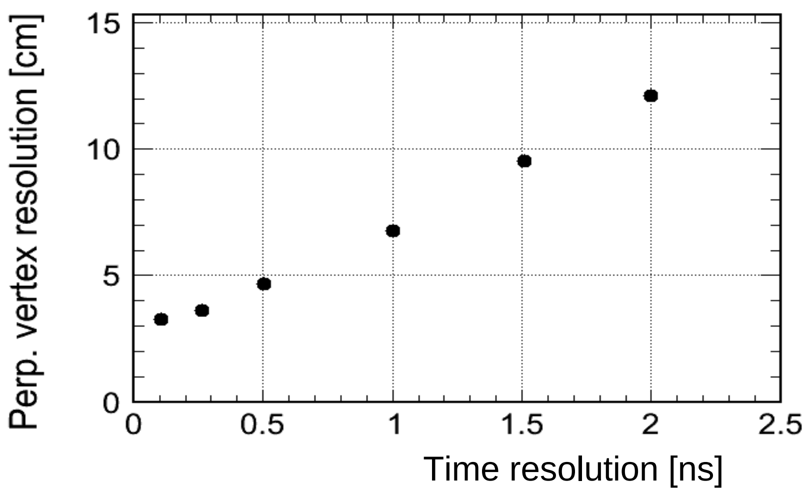






Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

Chemical Enhancements to the Target Volume

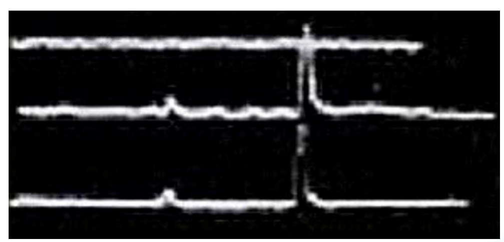
- high energy neutrino events are accompanied by n
- assume proton decay is not accompanied by n
  - * surely not for free proton
  - * also not for γ-tag states
- consider Gd addition to WC to increase n-capture tag efficiency
- Gadolinium R&D underway at SK

Inverse Beta Decay Detection with Gd

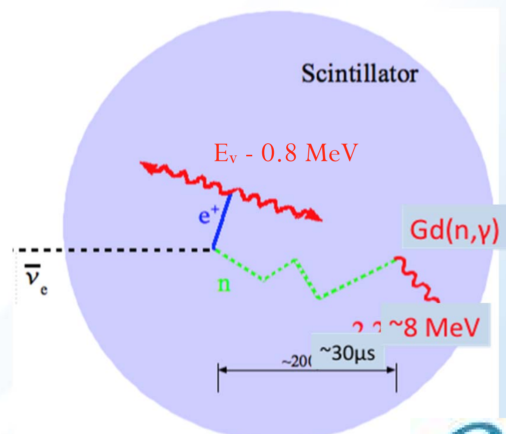
- $E_{threshold} = 1.8\ MeV$
- *'Large' cross section* $\sigma \sim 10^{-42}\ cm^2$
- *Distinctive coincidence signature in a large liquid scintillator detector*

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + {}^{A}Gd \rightarrow {}^{A+1}Gd + \gamma' s$$



Cowan & Reines, Savannah River 1956



This slide is courtesy of M. Yeh.

Low Energy/Heavy Particle Sensitivity

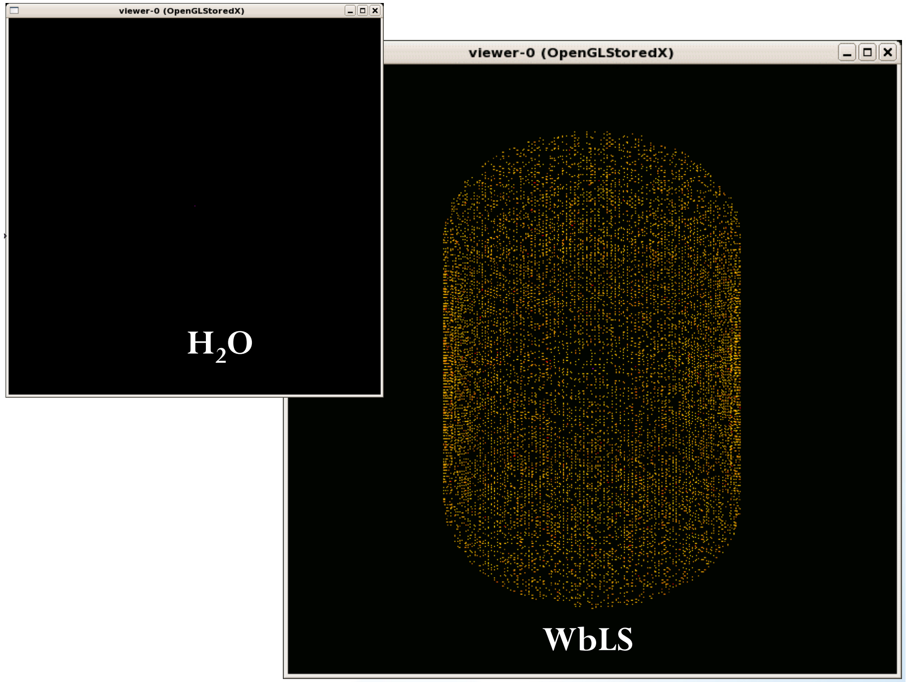
More light/light below Cherenkov threshold

Charged particles only produce Cherenkov light when v > c/n

For massive particles, the threshold for Cherenkov production is >100 MeV

Particle	Threshold
electron	> 0.6 MeV
muon	> 120 MeV
pion	> 160 MeV
kaon	> 563 MeV
proton	> 1070 MeV

K+ in water and liquid scintillator

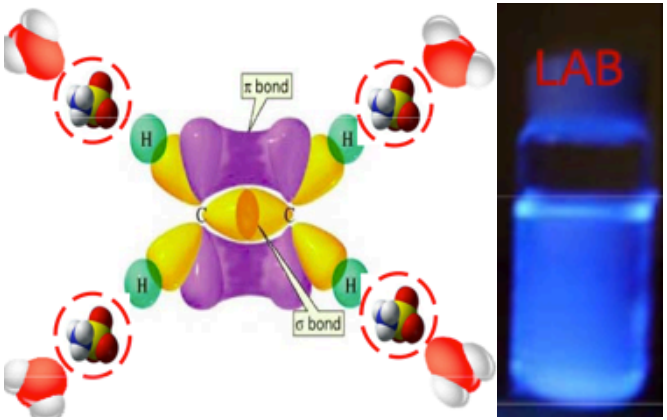


New Developments in Water-Based Detectors: Possibility of Water-Based Scintillator

Linear Alkylbenzene (LAB) – Industrial detergent
Key innovations:

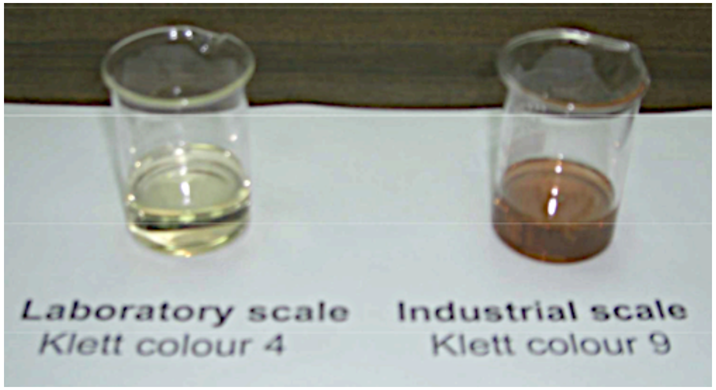
- ability to create stable solutions
- purification to achieve longer attenuation lengths

Minfang Yeh et al, Brookhaven National Lab



Ideal for large scale experiments

- Non-toxic
- Non-flammable
- Stable
- Cheap



The scintillation light might be difficult to resolve with timing, but...

- It may be possible to have both Cherenkov and scintillation light, separated in time
- The spatial/statistical gains would be considerable.

This slide is courtesy of M. Yeh.

New Developments in Water-Based Detectors: Possibility of Water-Based Scintillator

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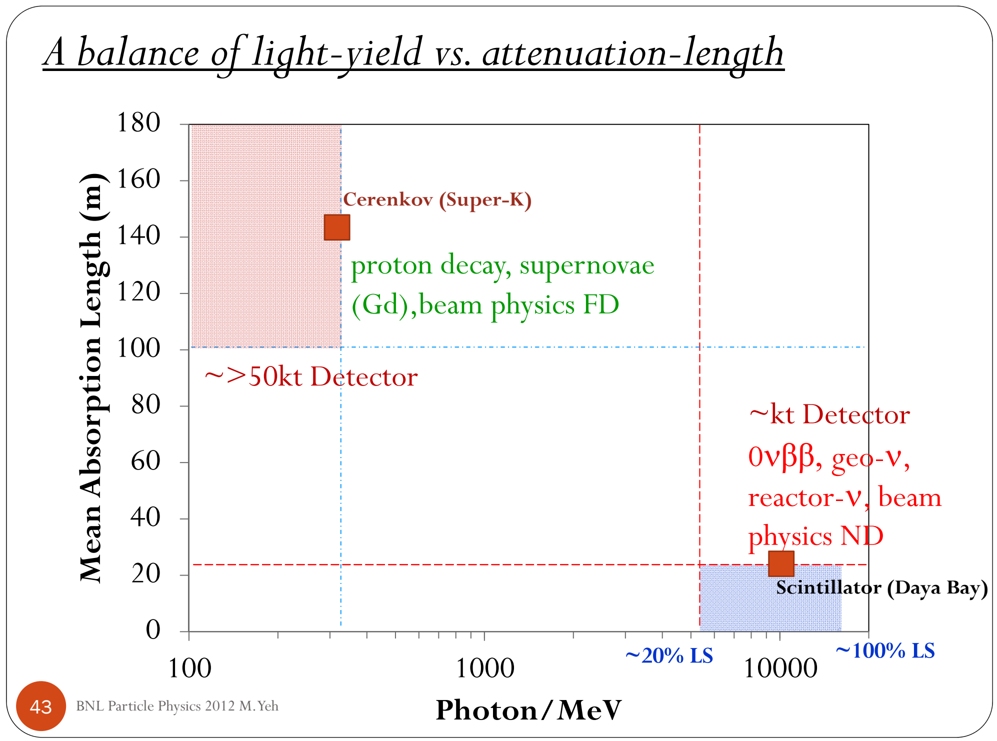

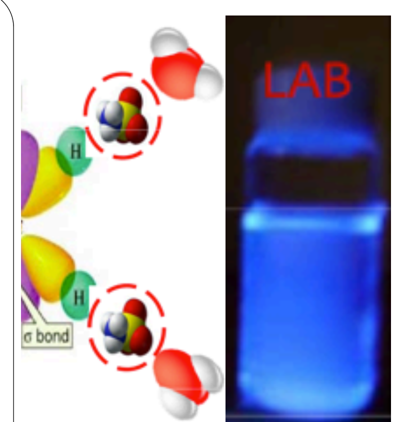

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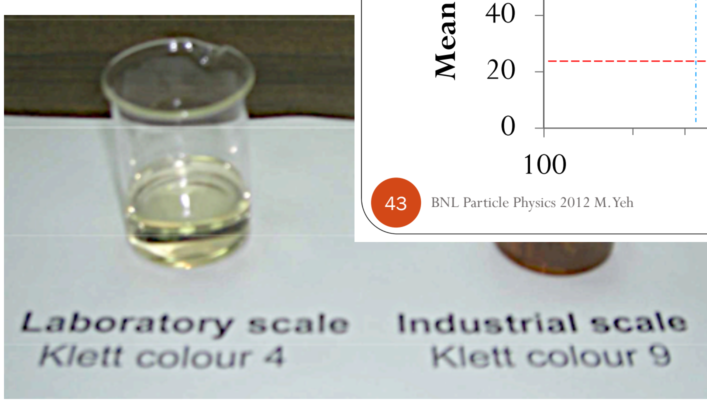


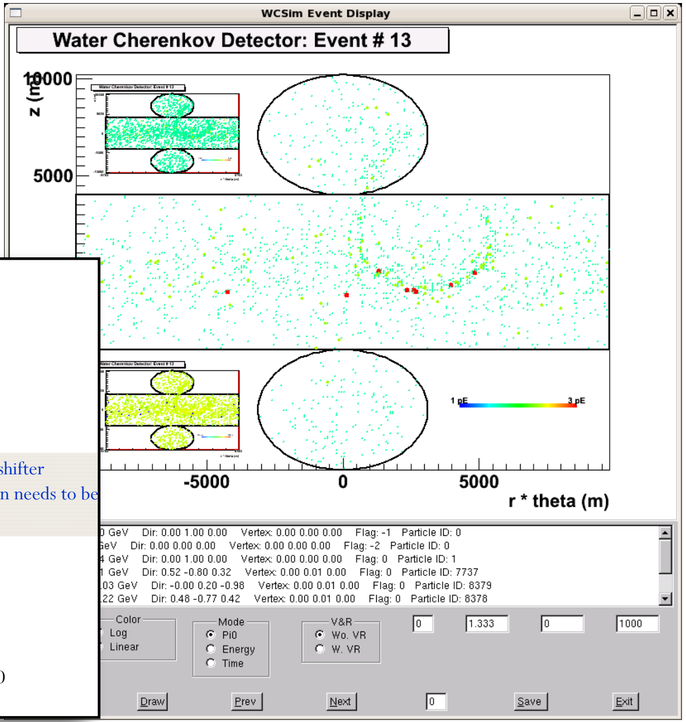
This slide is courtesy of M. Yeh.

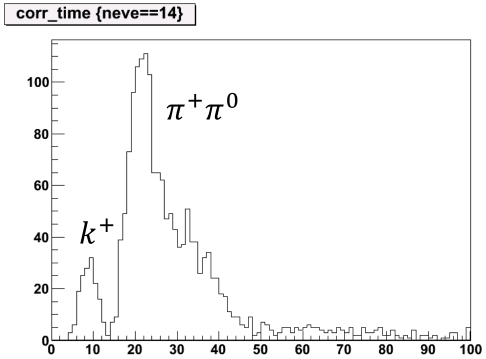
Discriminating Between Scintillation and Cherenkov Light

Can potentially tune:

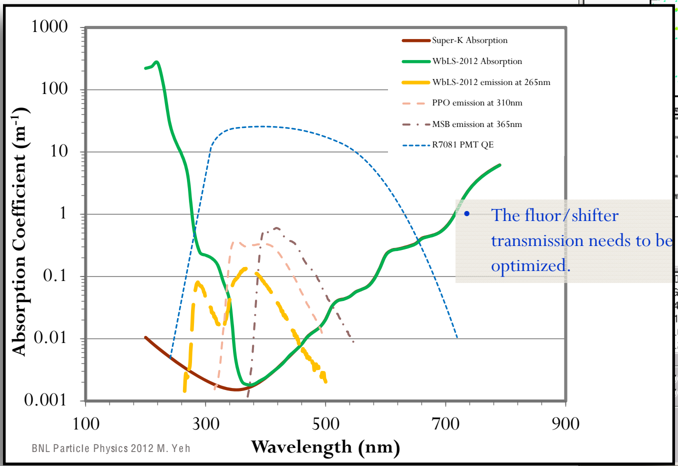
- relative light yield
- wavelength
- timing

A quick look of $k^+ \rightarrow \pi^+\pi^0$





- Very clear Cerenkov ring even without cut



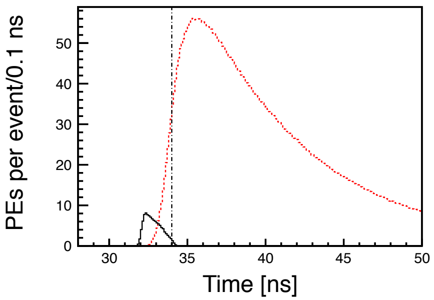
This slide is courtesy of M. Yeh.

Optical TPC with scintillator

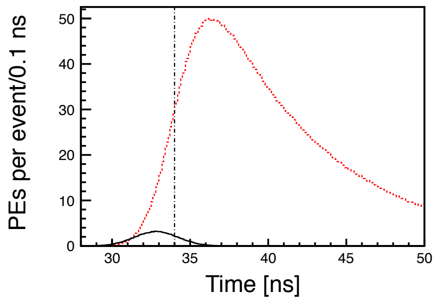
Optical TPC concept is more general than pure Cherenkov.

It may be possible to use timing to separate between Cherenkov and scintillation light in liquid scintillator volumes, capitalizing of the advantages of each separately.

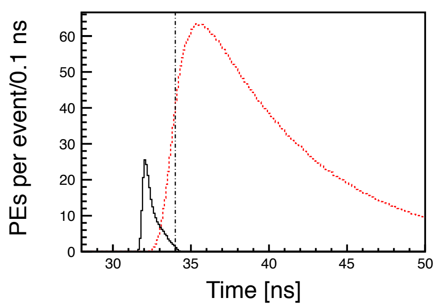
One can use the scintillation light for low E sensitivity. <u>And the Cherenkov light for directionality</u>.



(a) Default simulation.



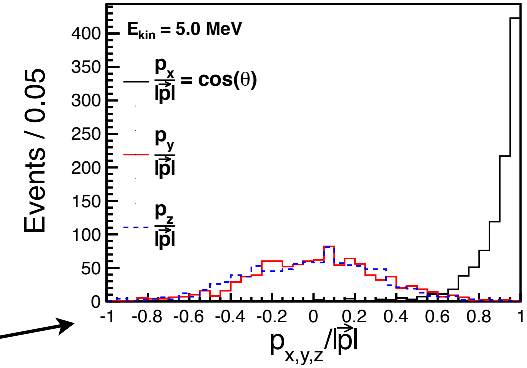
(b) Increased TTS (1.28 ns).

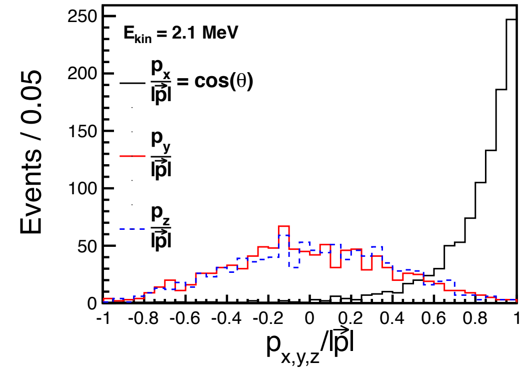


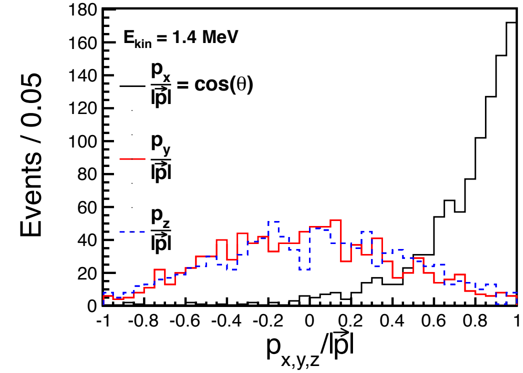
(c) Red-sensitive photocathode.

C. Aberle, A. Elagin, H.J. Frisch, M. Wetstein, L. Winslow. Measuring *Directionality in Double-Beta Decay and Neutrino Interactions with Kiloton-Scale Scintillation Detectors;*

Submitted to JINST, Nov. 2013. e-Print: arXiv:1307.5813







Energy Resolution

Sen Qian

	KamLAND	Daya Bay II
Detector	~1 kt Liquid Scintillator	➢10 kt Liquid Scintillator
Energy Resolution	6%/√E	3%/√E
Light yield	250 p.e./MeV	1200 p.e./MeV

More photons, how and how many ?

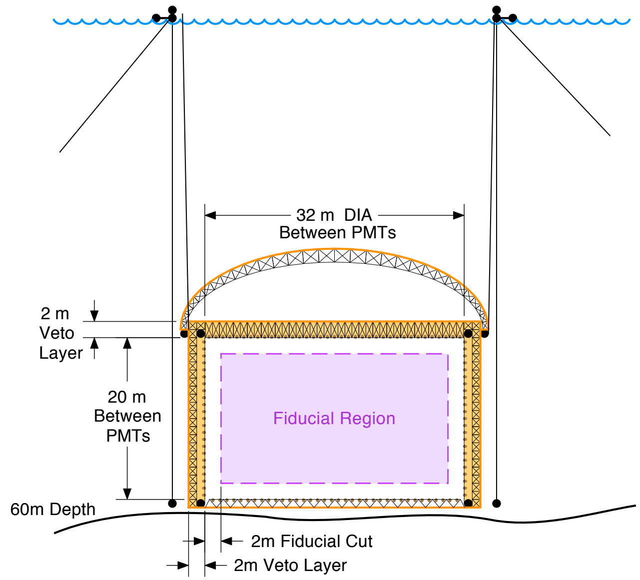
How?

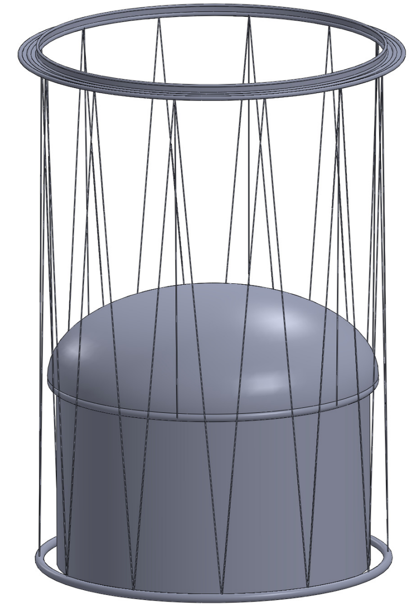
***4.3 –* 5.0 ➔ (3.0 – 2.5)% /√E**

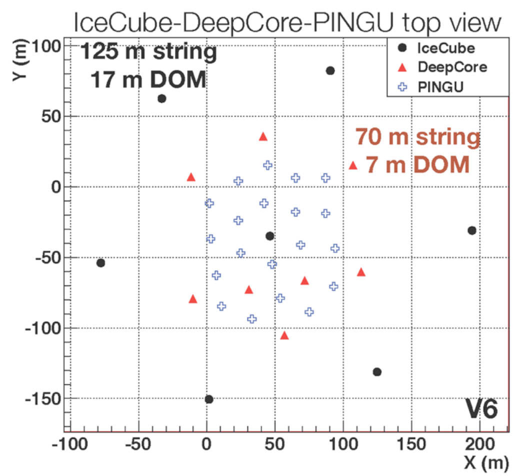
- Increased QE
- Light collection
- Higher Light yield
- Digital photon counting?

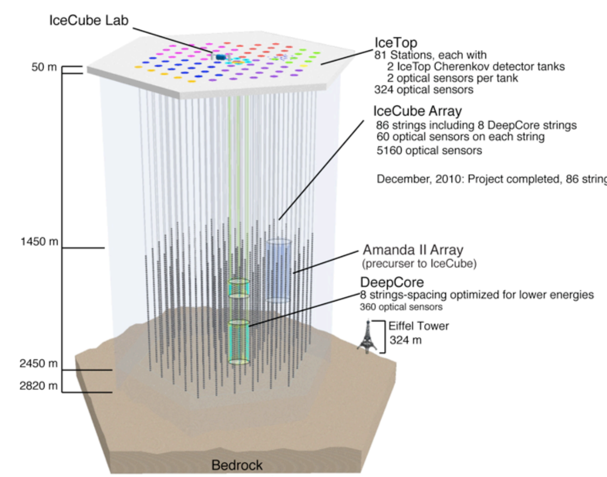
One last strategy – gradualism

- Programs like CHIPS (Cherenkov detectors In mine PitS) explicitly focused on developing modular, economic systems.
- Are there ways to avoid excavation costs?
- A lot of large neutrino experiments suffer from high, front-loaded budgets
- Are there ways to spread the cost, to install fiducial mass gradually over time?
- IceCube is similar in that one can keep adding new strings over time.









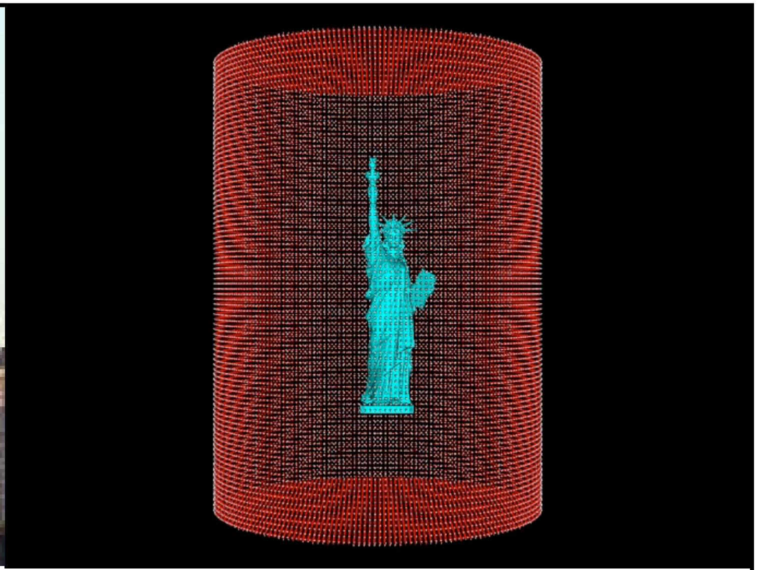
Detecting Neutrinos – a numbers game

Incredibly small cross sections demand:
- high intensity beams
- **large fiducial mass**
- time
- low noise

LENA, the proposed European liquid scintillator detector: A nice addition to the Philly skyline?

credit Jürgen Winter

Proposed LBNE Water Cherenkov detector would have comfortably contained the Statue of Liberty



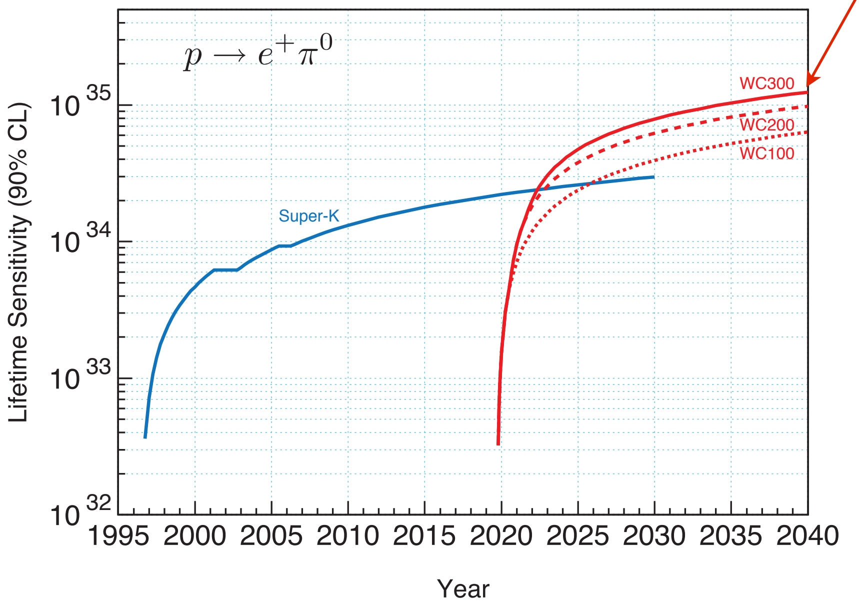
credit Anthony La Torre

Detecting Neutrinos (proton decay) – a numbers game

Incredibly small cross sections demand:

- high intensity beams
- large fiducial mass
- **time**
- low noise

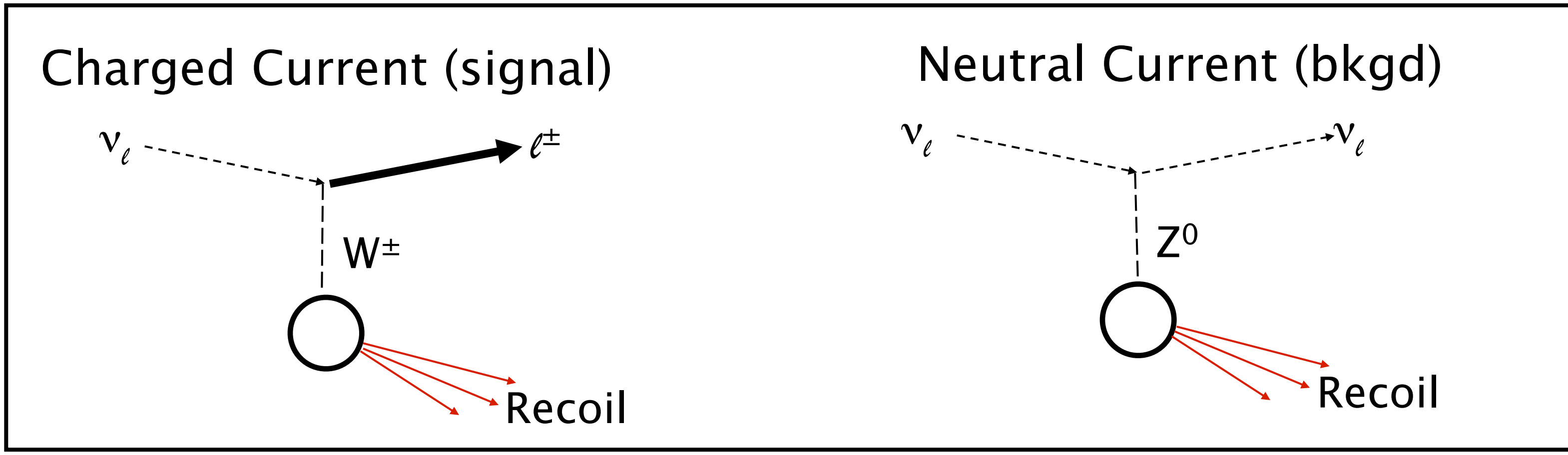
I turn 61 here.

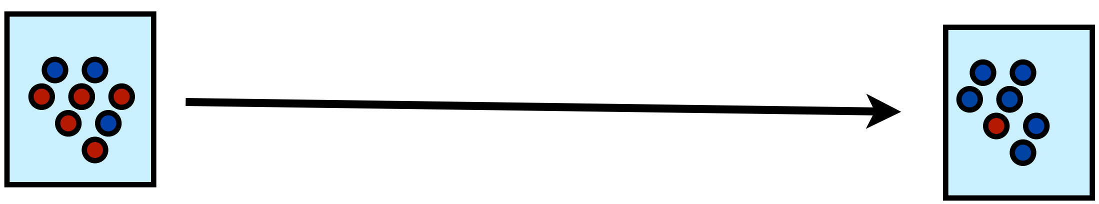


plot by Ed Kearns, BU

Neutrino Detection Basics

- We detect neutrinos through the products of their interactions with matter.
- Neutrino flavor can be determined by charged-current interactions, which produce charged leptons of like flavor.





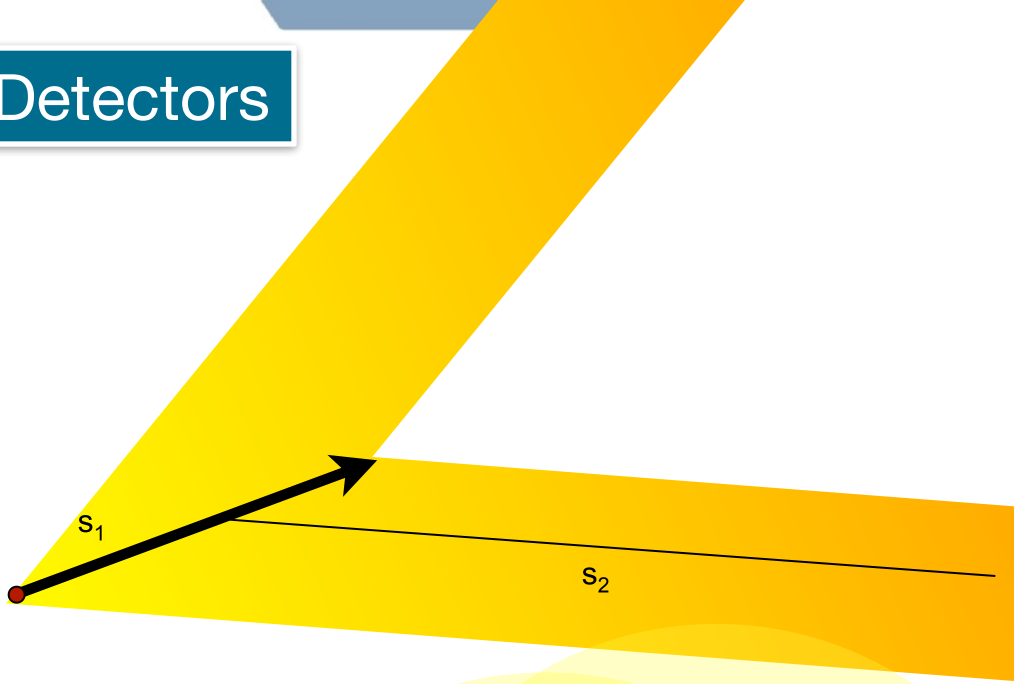
this experiment measures blue appearance and red disappearance.

Typical neutrino oscillation experiments count the relative fractions of leptons of each flavor produced at a near detector, compared with those fractions at a far detector

Light Production In Neutrino Detectors

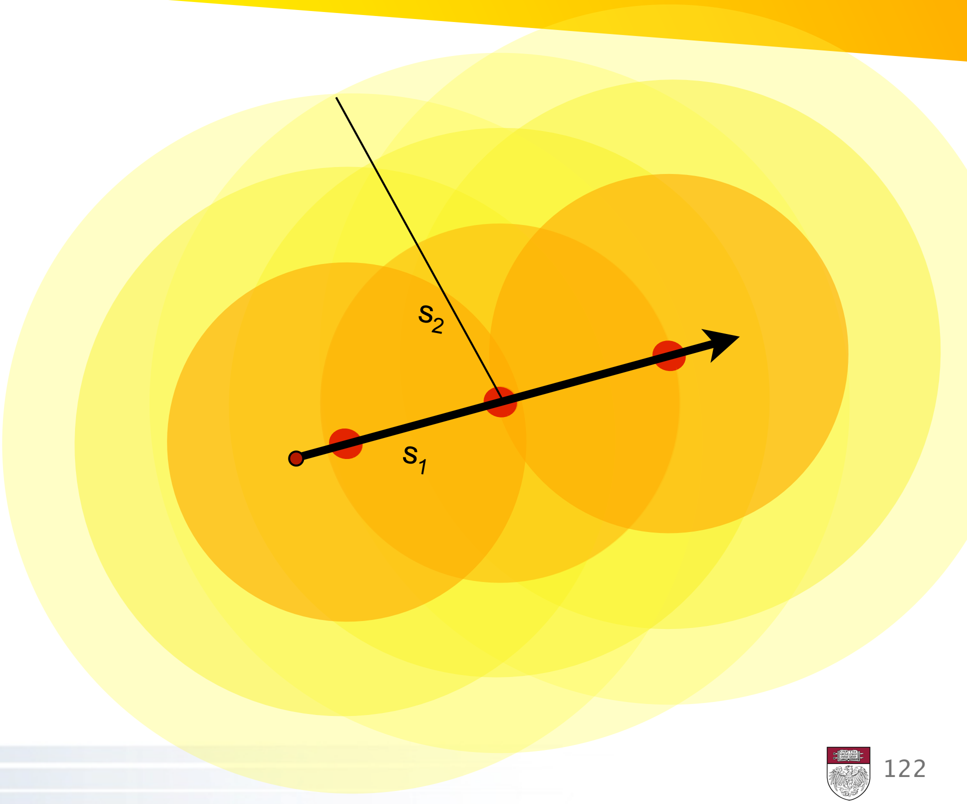
Cherenkov Effect

- An shockwave of optical light is produced when a charged particle travels through a dielectric medium faster than the speed of light in that medium: c/n
- This light propagates at an angle $\theta_C = \text{acos}(1/n\beta)$ w.r.t. the direction of the charged particle…
- Geometry is well-constrained



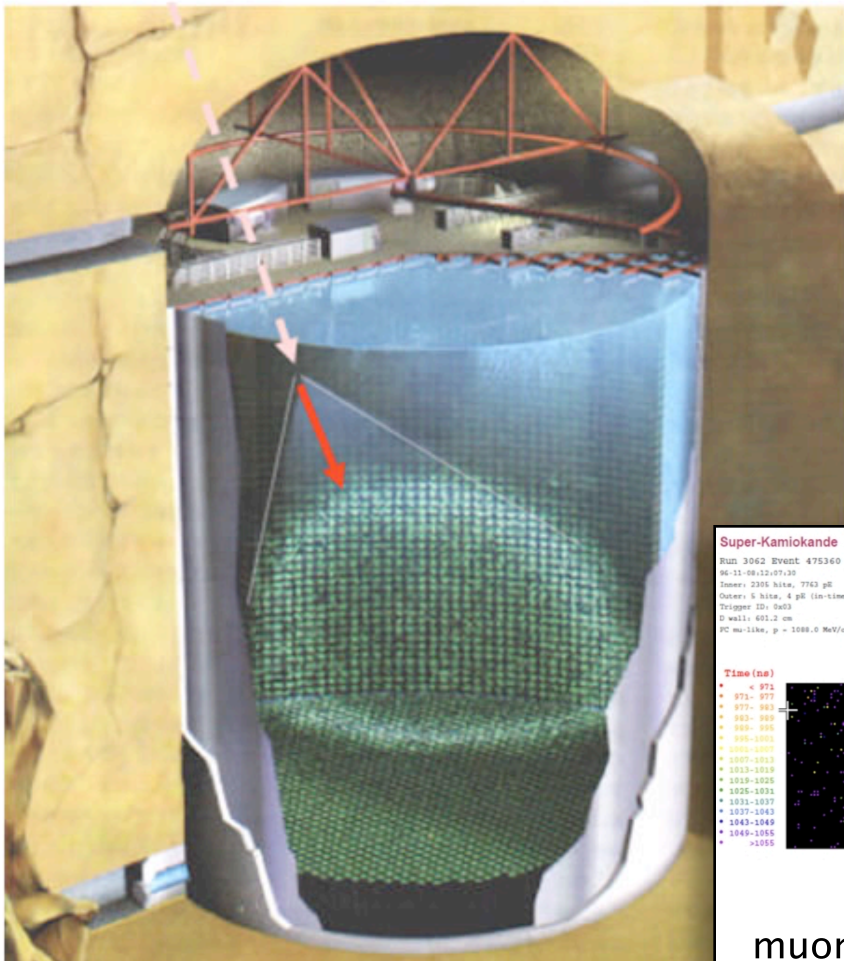
Scintillation

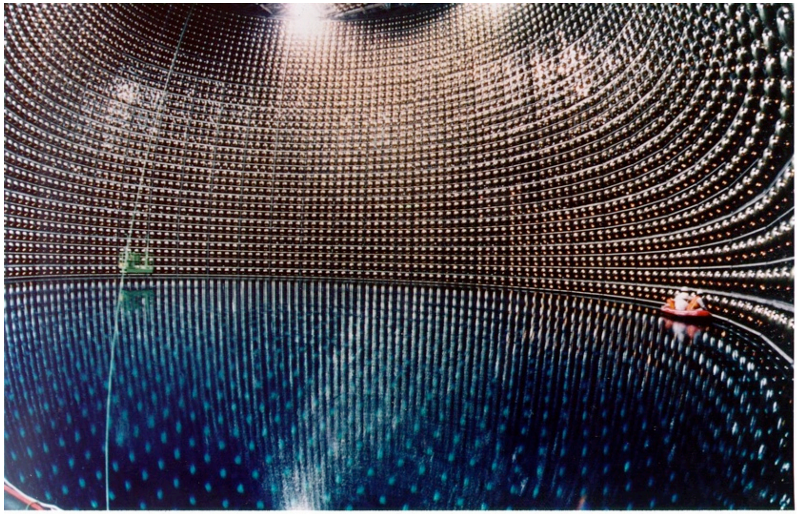
- Light produced by flourescence of ionized atoms
- Narrower spectral range
- Light yield is much higher
- Energy threshold lower
- But, light is emitted isotropically about emission points along the track
- Emission times are delayed and dispersed

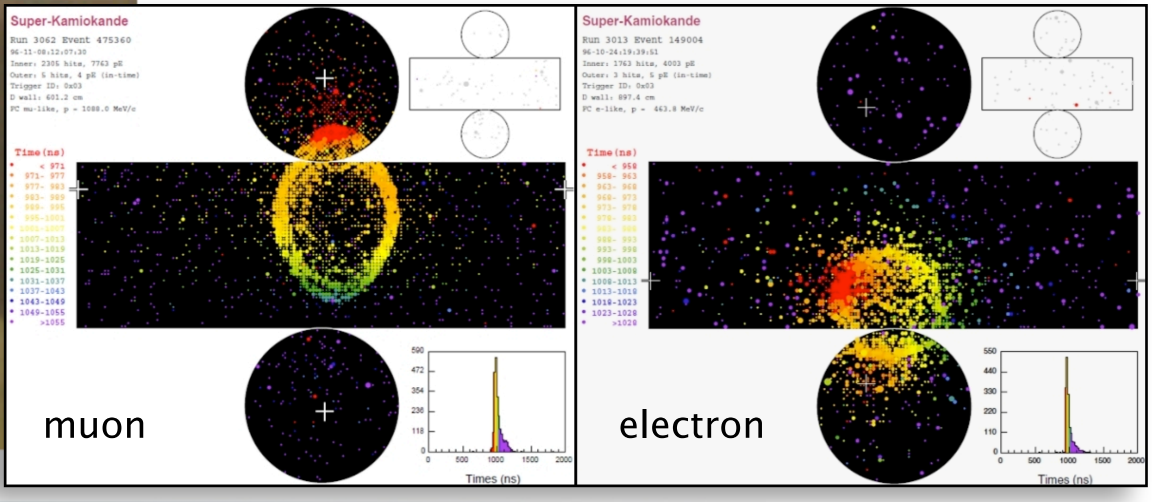


Light Detection In Neutrino Detectors

- Water Cherenkov detector – volume of water instrumented with photosensors on the bounding surface (or in a 3D array)
- Detects ring patterns produced by Cherenkov light from charge particles







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

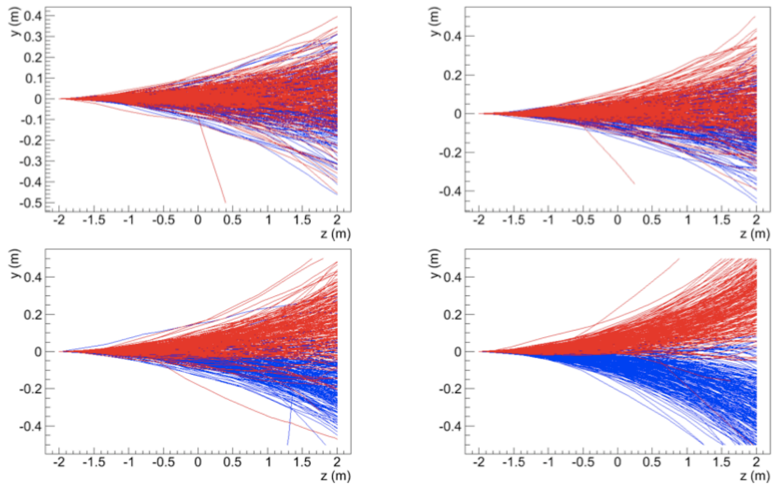


Figure: $B = 100$ gauss (top), $B = 500$ gauss (bottom).

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

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

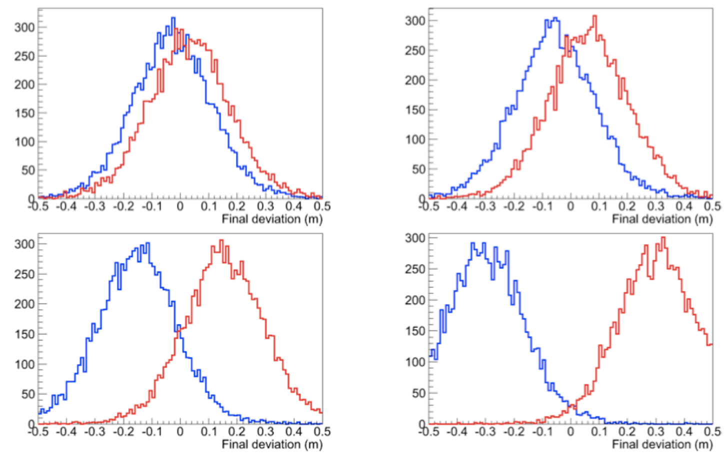


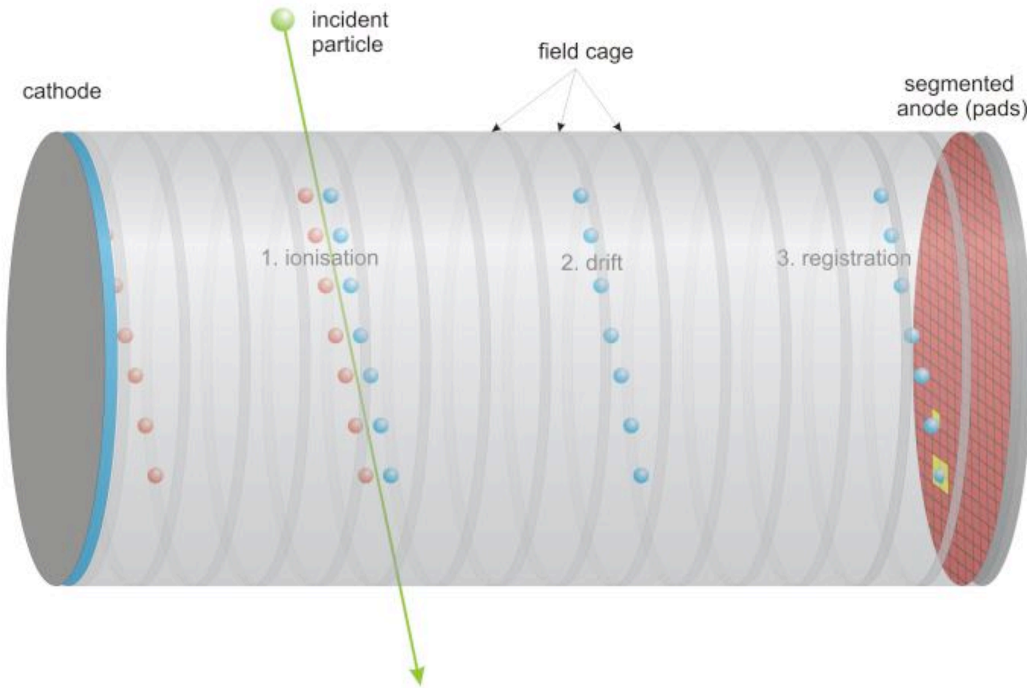
Figure: $B = 100$ gauss (top), $B = 500$ gauss (bottom).

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

Work by Alexander Vostrikov (U. Chicago)

Time Projection Chamber (TPC)

David Nygren

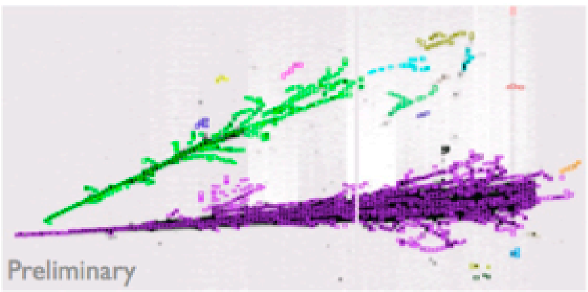


- Incident particles ionize a gas or cryogenic liquid.
- x and y positions of the track are determined by a segmented anode
- z positions are determined by drift time of charges in E-field.

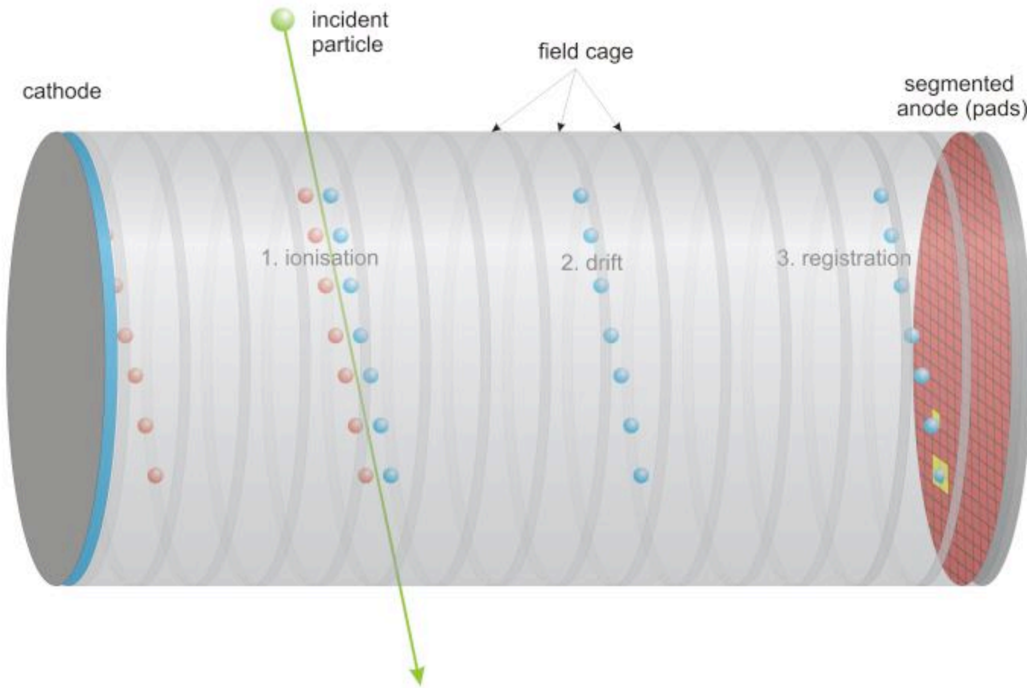
Time Projection Chamber (TPC)

David Nygren

2 reconstructed EM showers in LAr



(M. Soderberg, Yale - talk at Neutrino 2010)



- Incident particles ionize a gas or cryogenic liquid.
- x and y positions of the track are determined by a segmented anode
- z positions are determined by drift time of charges in E-field.

Summary of Tasks/Expertise

- Operation of LAPPDs in a Water Cherenkov detector
  - adapt electronics to the specific needs of ANNIE
  - operational demonstration
  - submersion in water
- Implementation of reconstruction strategy
  - simulations guided design
  - optimization of timing based reconstruction

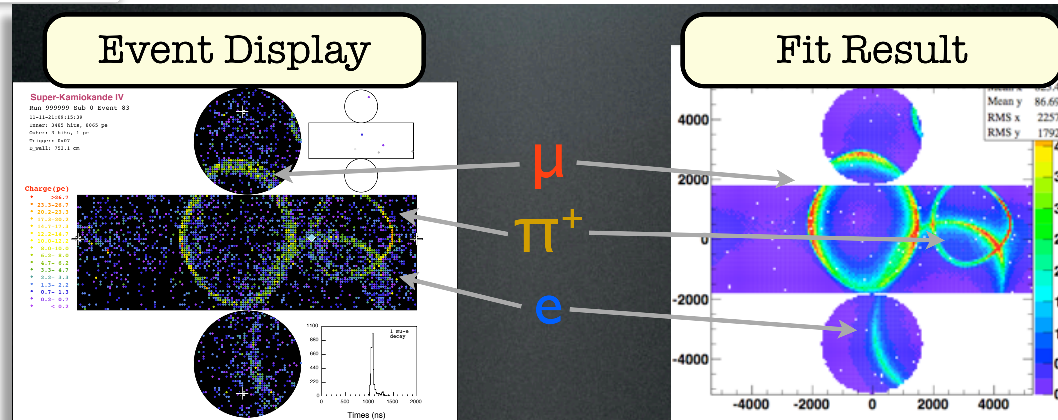
LAPPDs	ANL, U Chicago
Electronics	U Chicago, U Hawaii
Conventional PMTs	UC Davis, UC Irvine
Water System	UC Davis, UC Irvine
Simulations and Reconstruction	Iowa State, U Chicago, Queen Mary, UC Irvine

Pattern of Light Fitting With LAPPDs

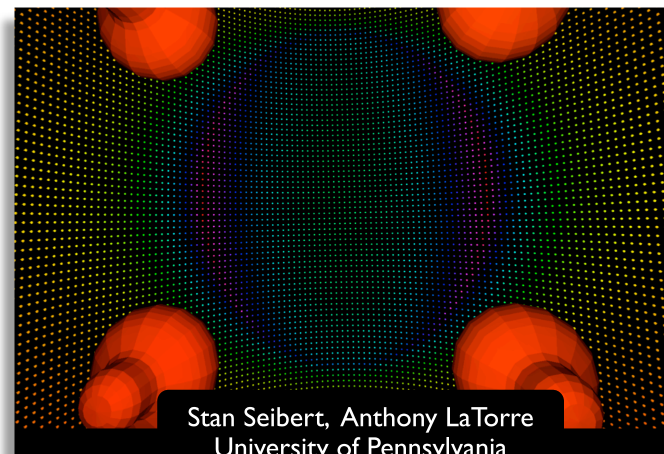
Several things to consider:

LAPPDs are digital photon counters – one can separate photons in space and time (not just estimating based on charge). Likelihood must be viewed in terms of optical photons rather than "charge"

Because we have time and space information on a photon-by-photon basis, correlations between time and space contain good information. One might not want to factorize the time and space likelihoods.



M. Wilking



Key Elements of a vacuum phototube

vacuum envelope:
hermetic seal, evacuated inside

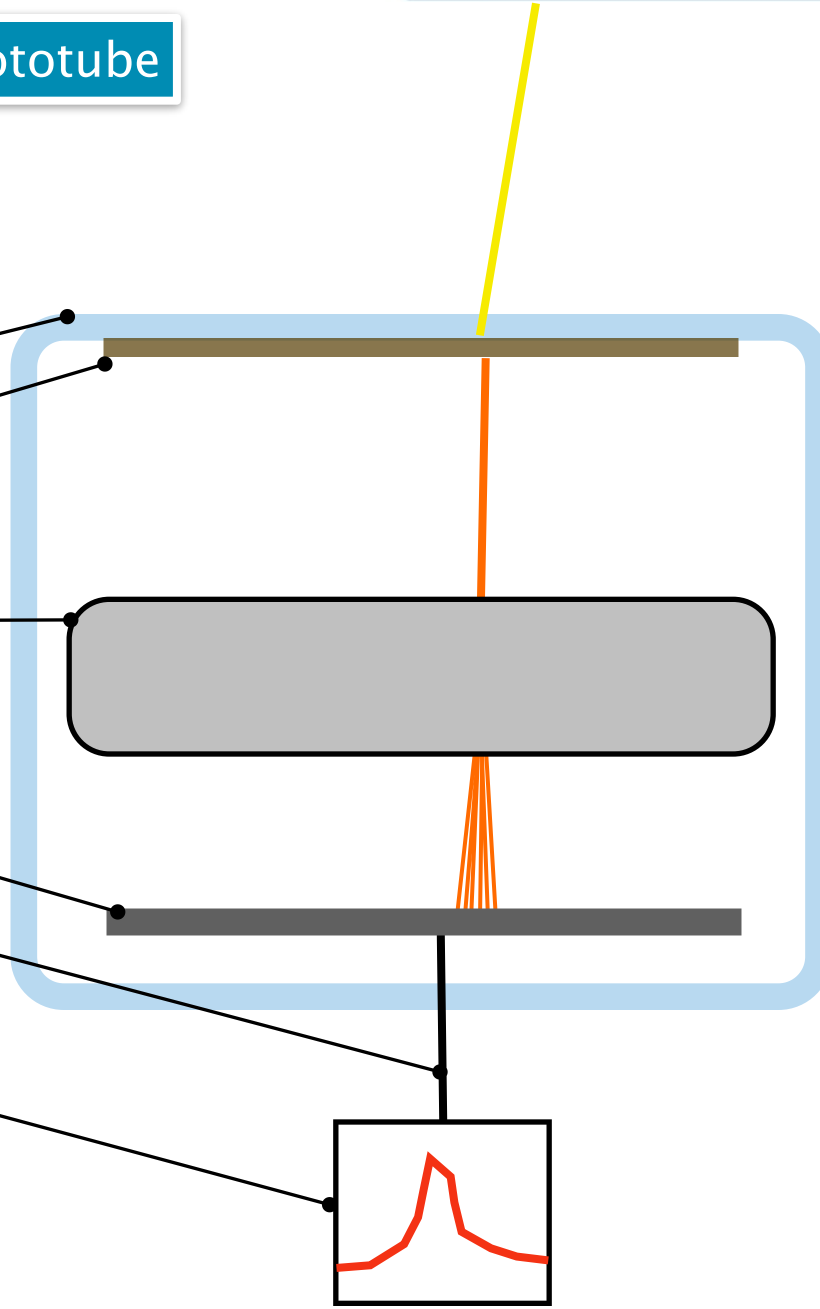
photocathode (PC):
Convert from photons to electrons

gain stage:
amplification of the original electrons

anode:
collects the signal

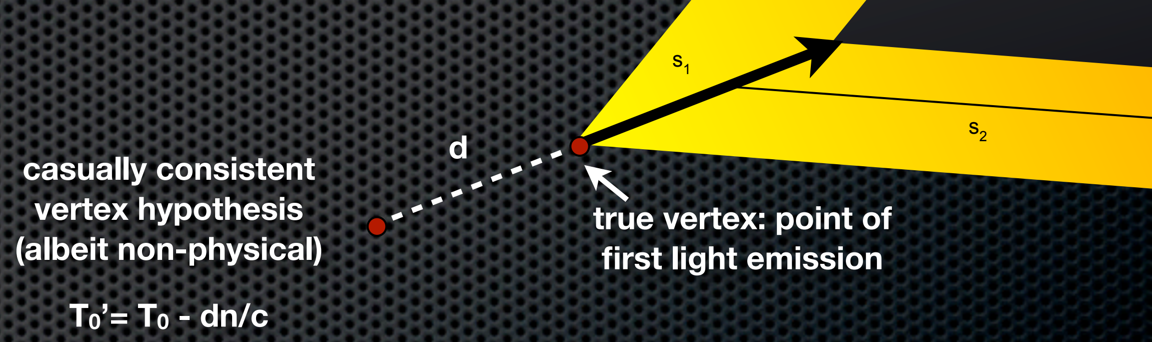
feedthrough:
bring signal out through the vacuum body

readout electronics:
measure and digitize the pulse



Timing-based vertex fitting

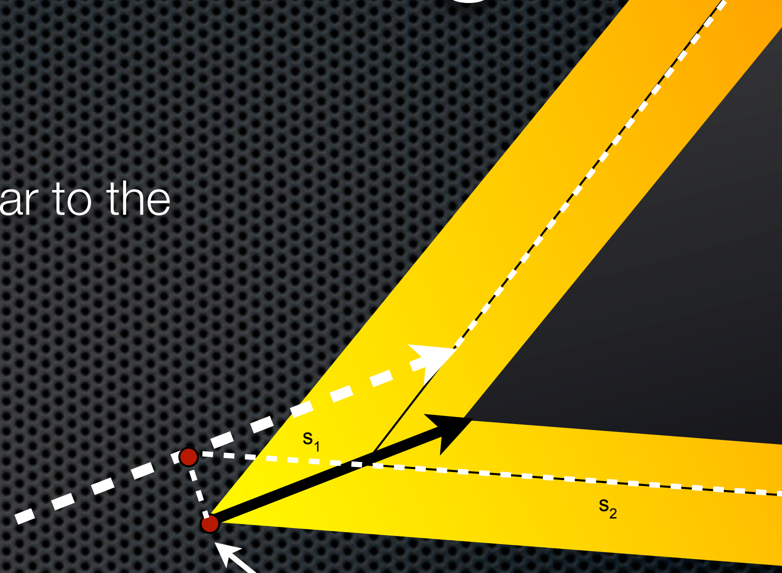
Based on pure timing, vertex position along the direction parallel to the track is unconstrained



Must used additional constraint: fit the "edge of the cone" (first light)

Timing-based vertex fitting

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

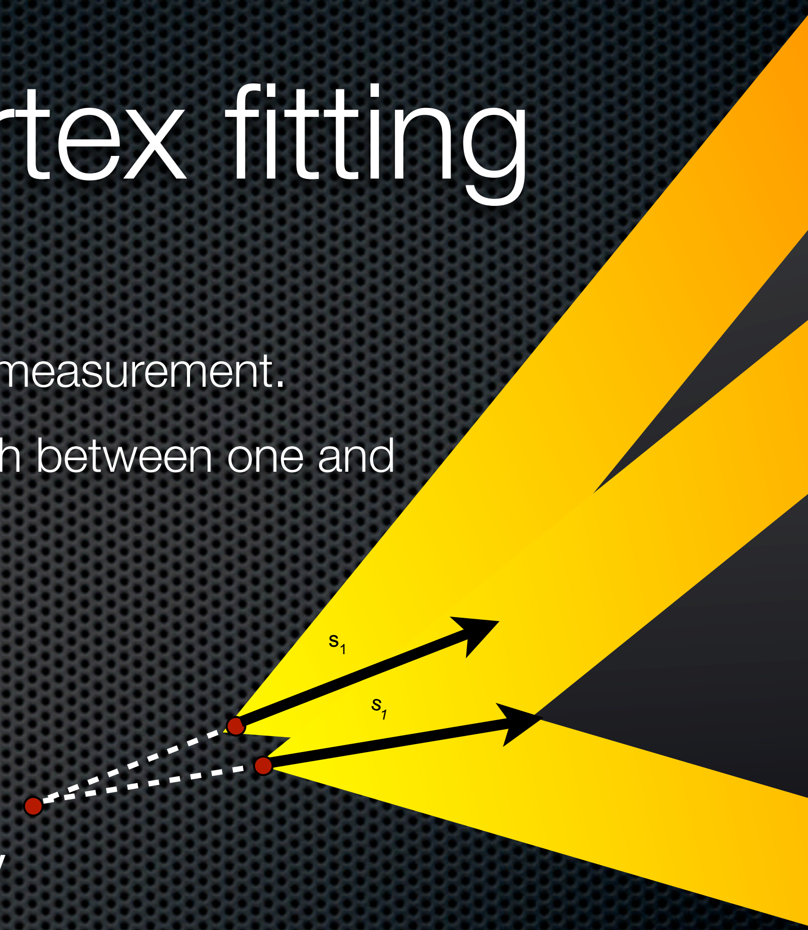


For single vertex fitting, we expect the transverse resolution to improve significantly with photosensor time-resolution!

Timing-based vertex fitting

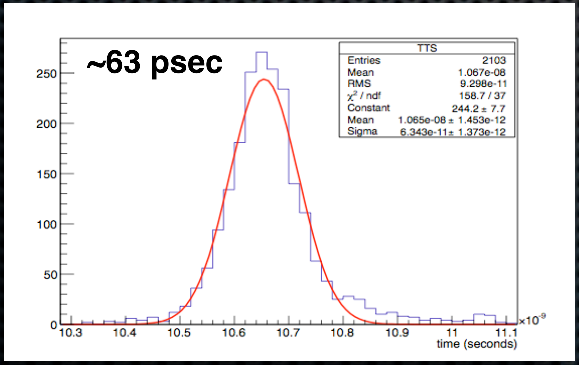
Fortunately, multi-vertex separation is a differential measurement.

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)

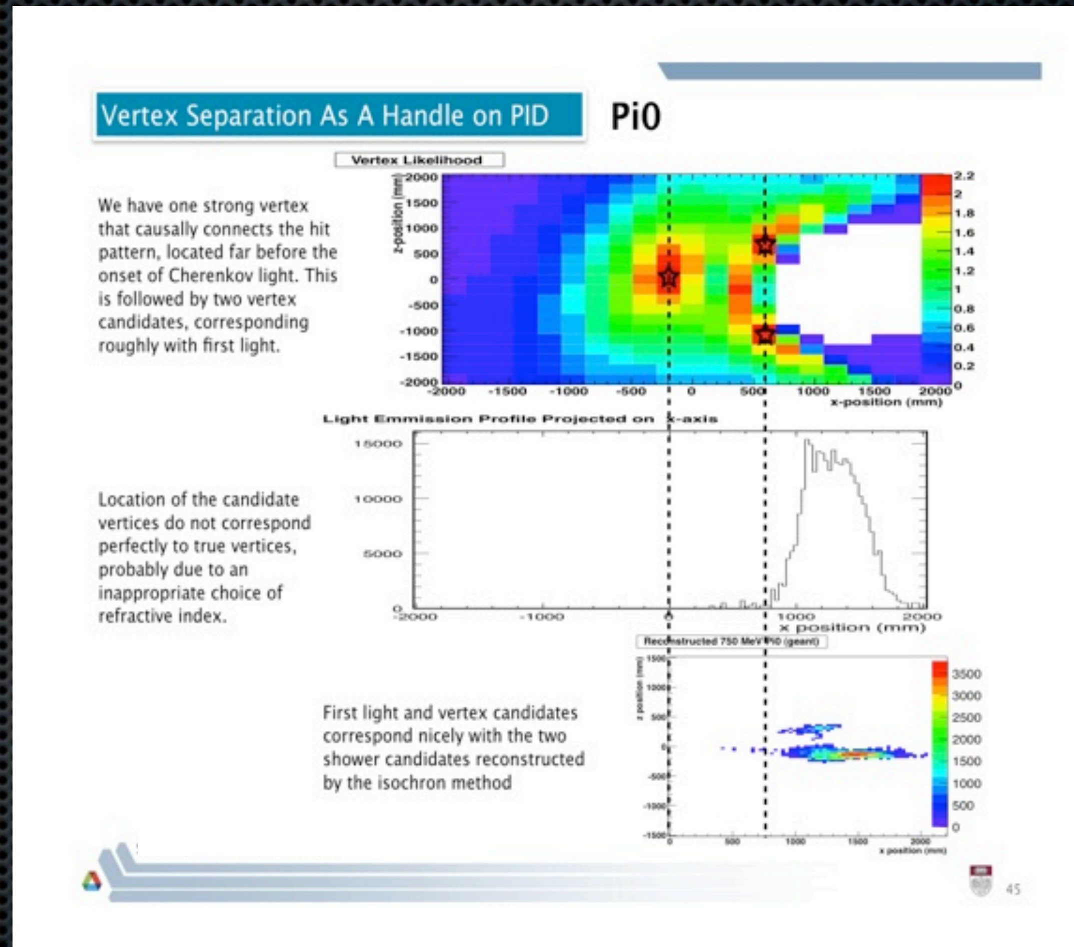


100 picoseconds ~ 2.25 centimeters

Isochron method

M. Wetstein

- 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



Isochron method

M. Wetstein

- 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.