University of Chicago

Argonne NATIONAL LABORATORY

ANNIE:

The Atmospheric Neutrino Neutron Interaction Experiment

Matt Wetstein

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on behalf of the ANNIE Collaboration:

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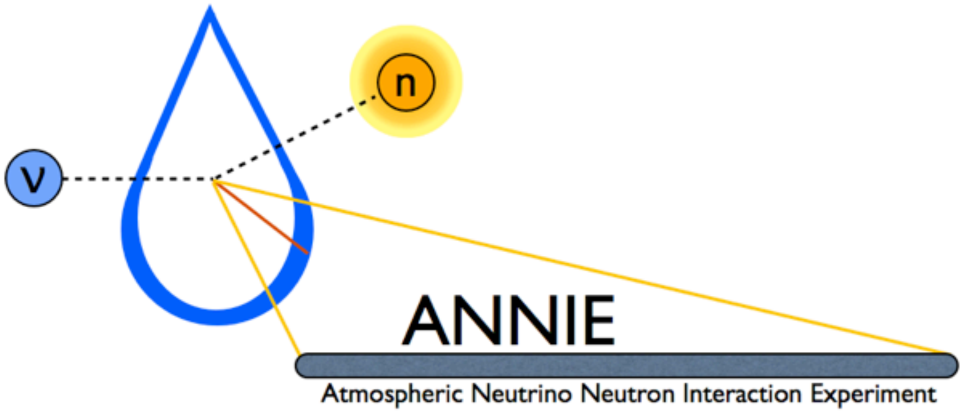
ANT2014

September, 2014

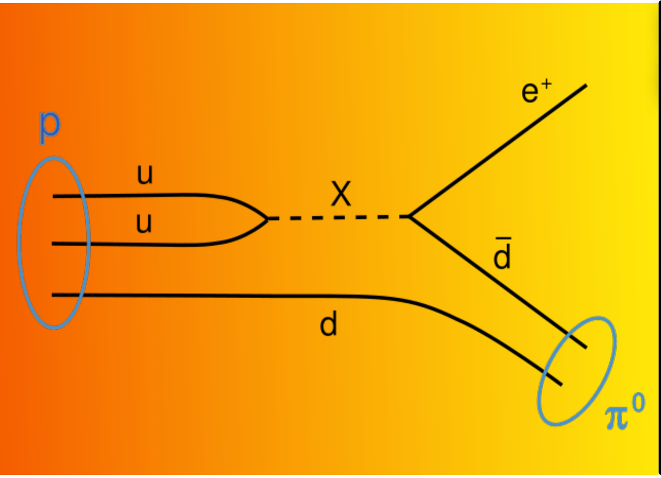
U.S. DEPARTMENT OF ENERGY

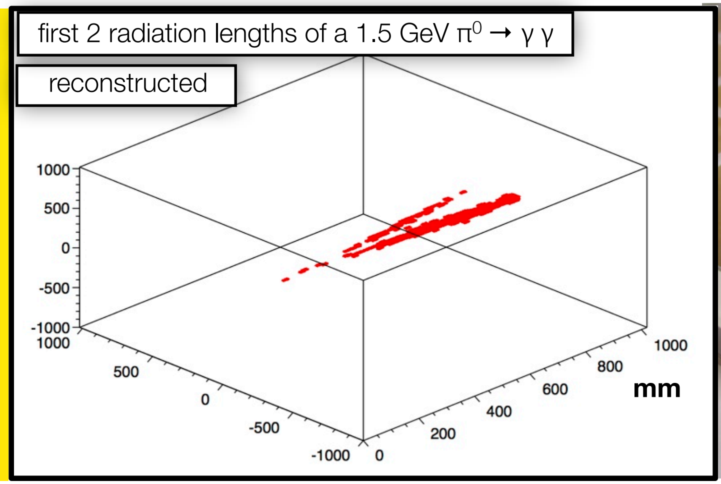
What is ANNIE?

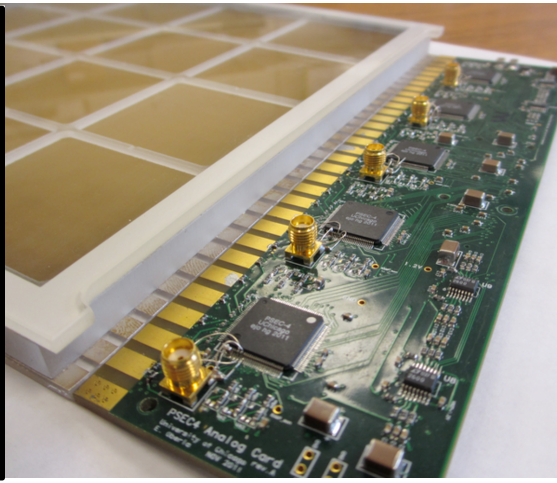
- A measurement of the abundance of final state neutrons from neutrino interactions in water, as a function of energy.



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

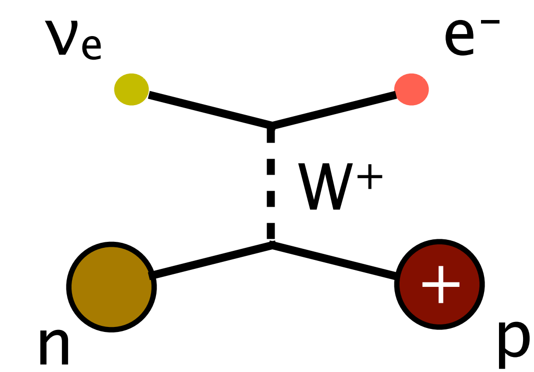




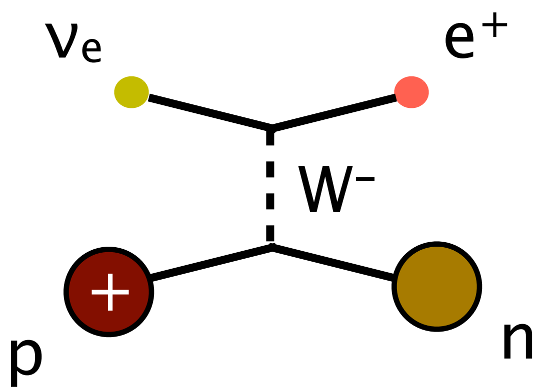


- Demonstration of a new approach to neutrino detection: *Optical Time Projection Chamber* using new photosensor technology.

Additional physics impact



Charged current neutrino interactions always reduce the the number of neutrons by 1.



Charged current anti-neutrino interactions always increase the total number of neutrons by 1

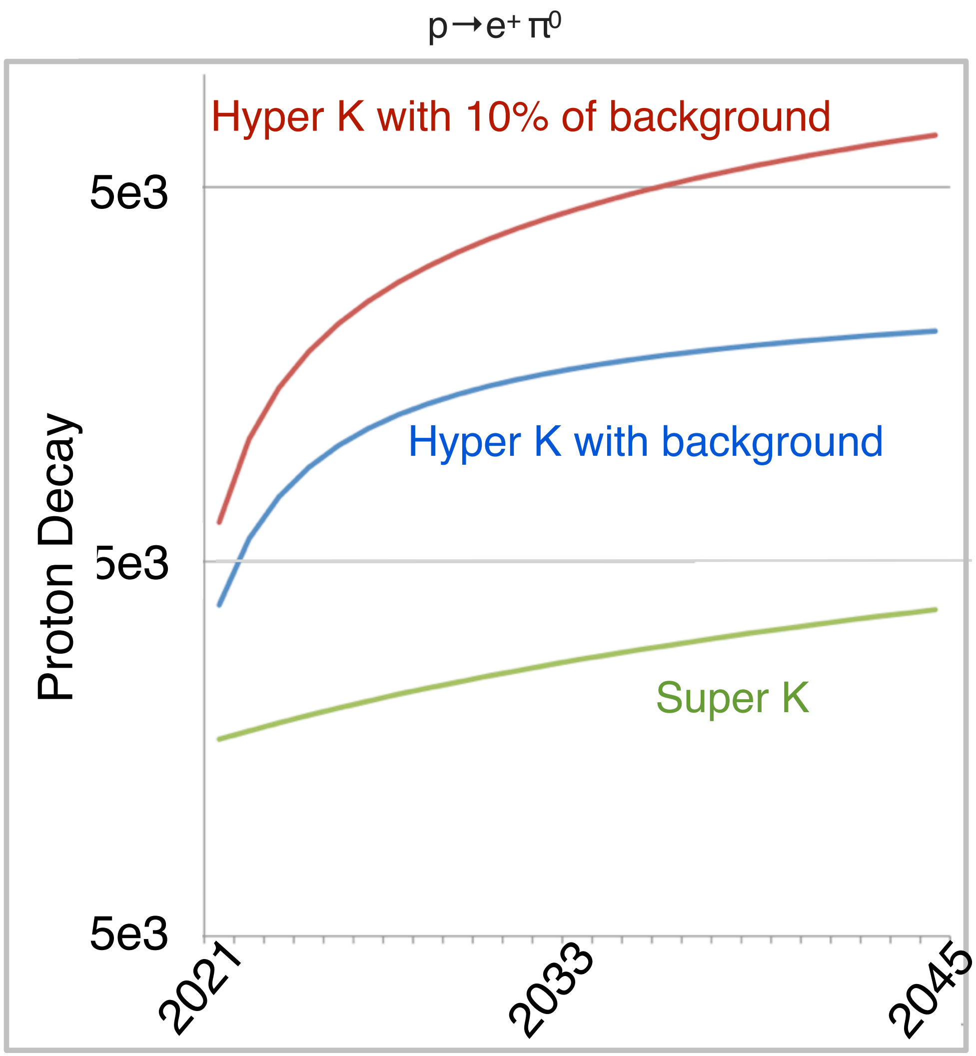
Higher order and larger scale nuclear effects can increase the number of final state neutrons. Both neutral current and charged current interactions can produce neutrons this way.

Motivation

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

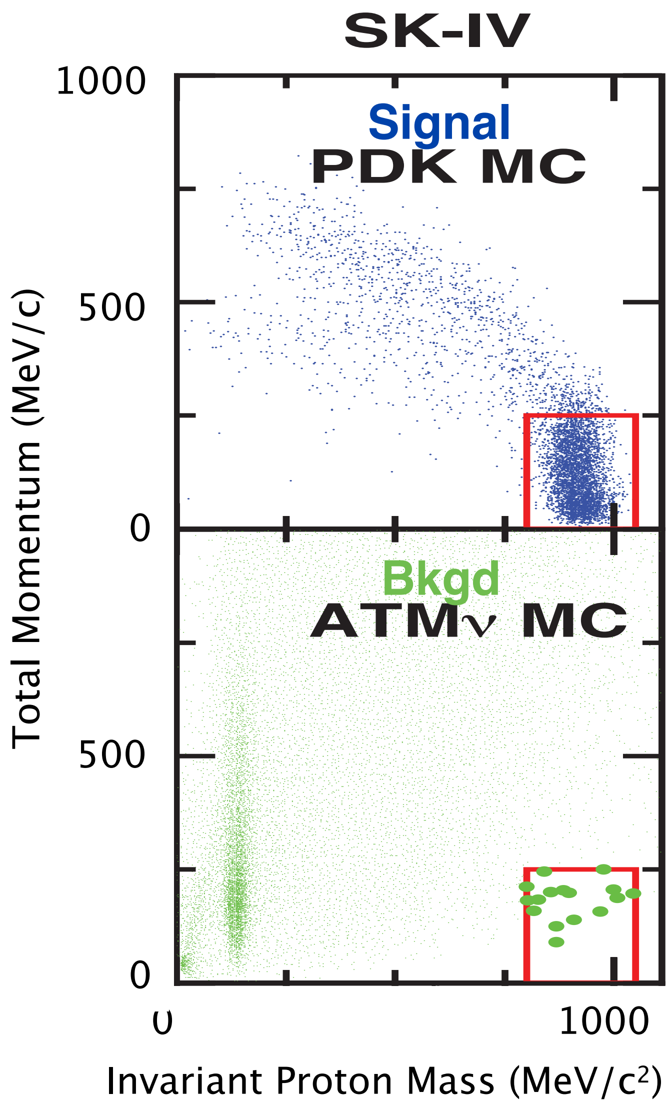
However, at such scales, previously negligible backgrounds from atmospheric neutrinos start to limit this sensitivity.

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



Motivation

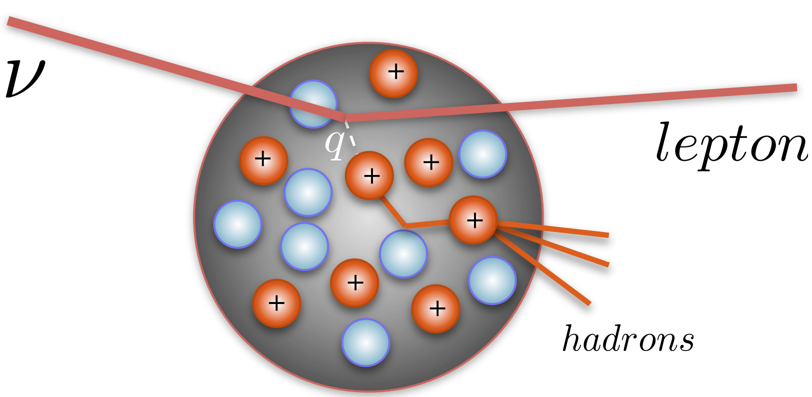
Backgrounds come almost exclusively from atmospheric neutrino interactions.

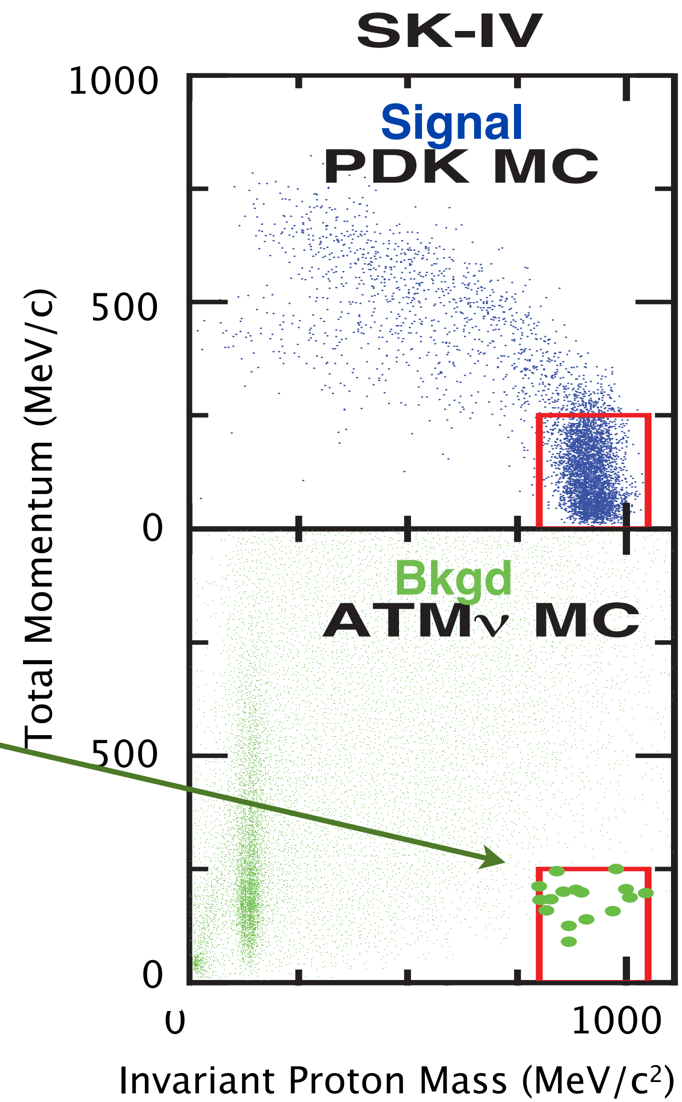


Motivation

Backgrounds come almost exclusively from atmospheric neutrino interactions

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



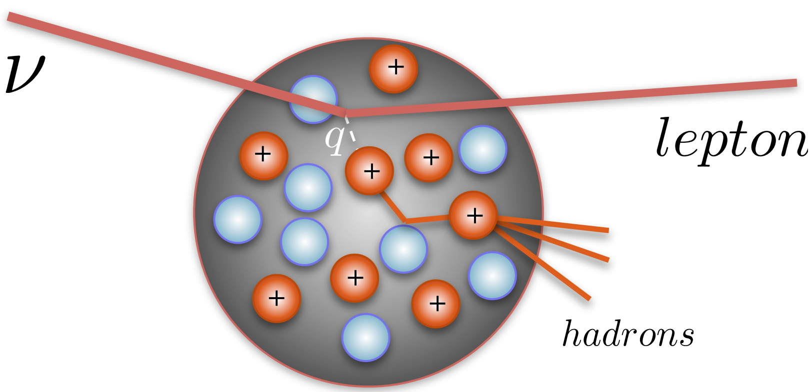


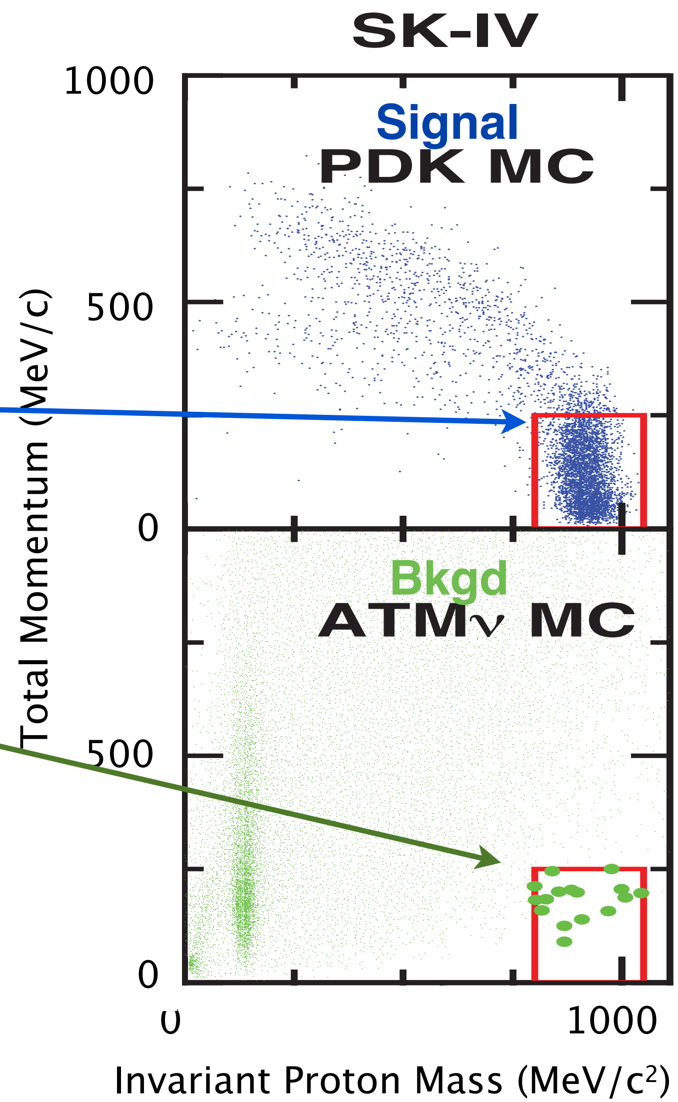
Motivation

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

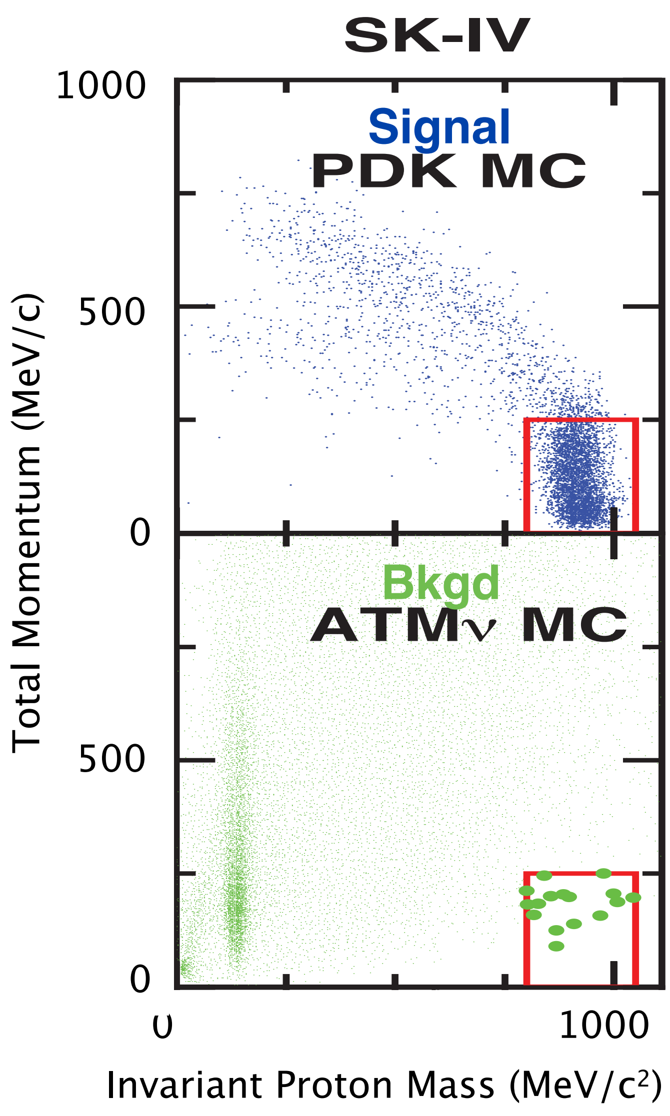
Backgrounds come almost exclusively from atmospheric neutrino interactions.

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

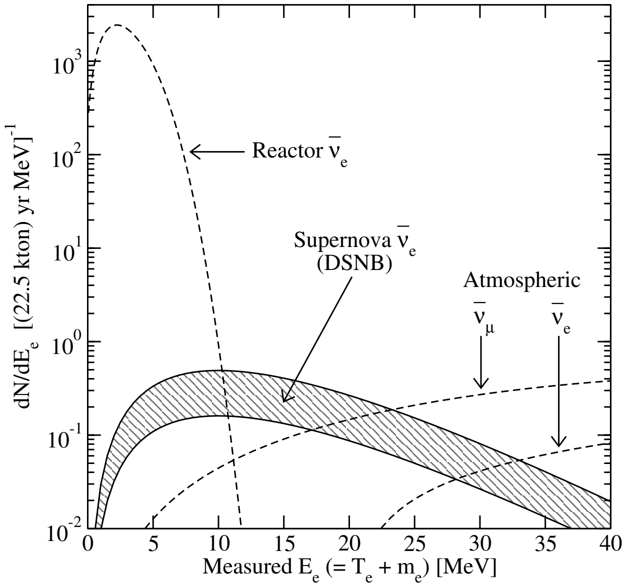
High energy neutrino interactions typically produce neutrons in the final state.

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.



Additional physics impact



SN neutrino detection

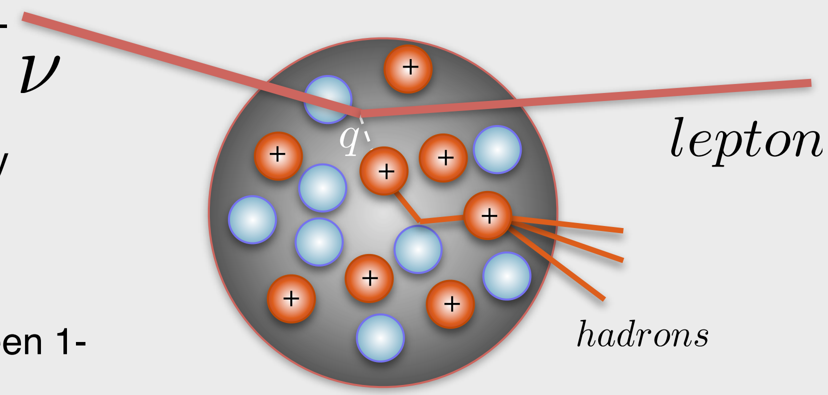
- Neutron tagging can be used to separate between diffuse supernova background (DSNB) neutrinos and various backgrounds.
- In core collapse Supernovae, the technique can be used to statistically discriminate between various flavors and fluxes.

Neutrino interaction Physics

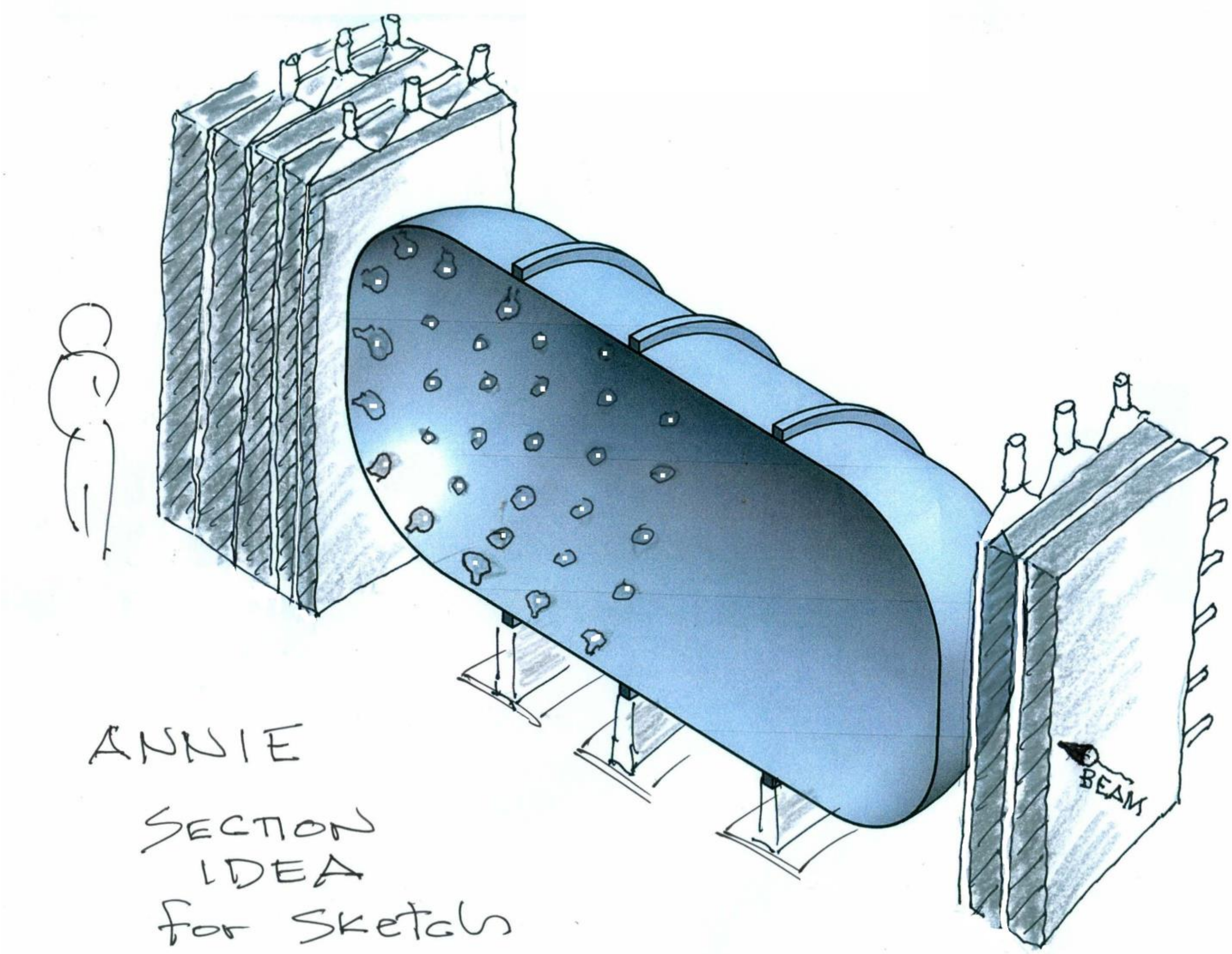
Nuclear models present the largest systematics in water-based oscillation experiments.

Neutron abundances may make it possible to statistically separate between neutral current and charged current interactions.

Neutron multiplicity is also sensitive to differences between 1-body and 2-body currents (where neutrinos scatter off of correlated pairs of nucleons).

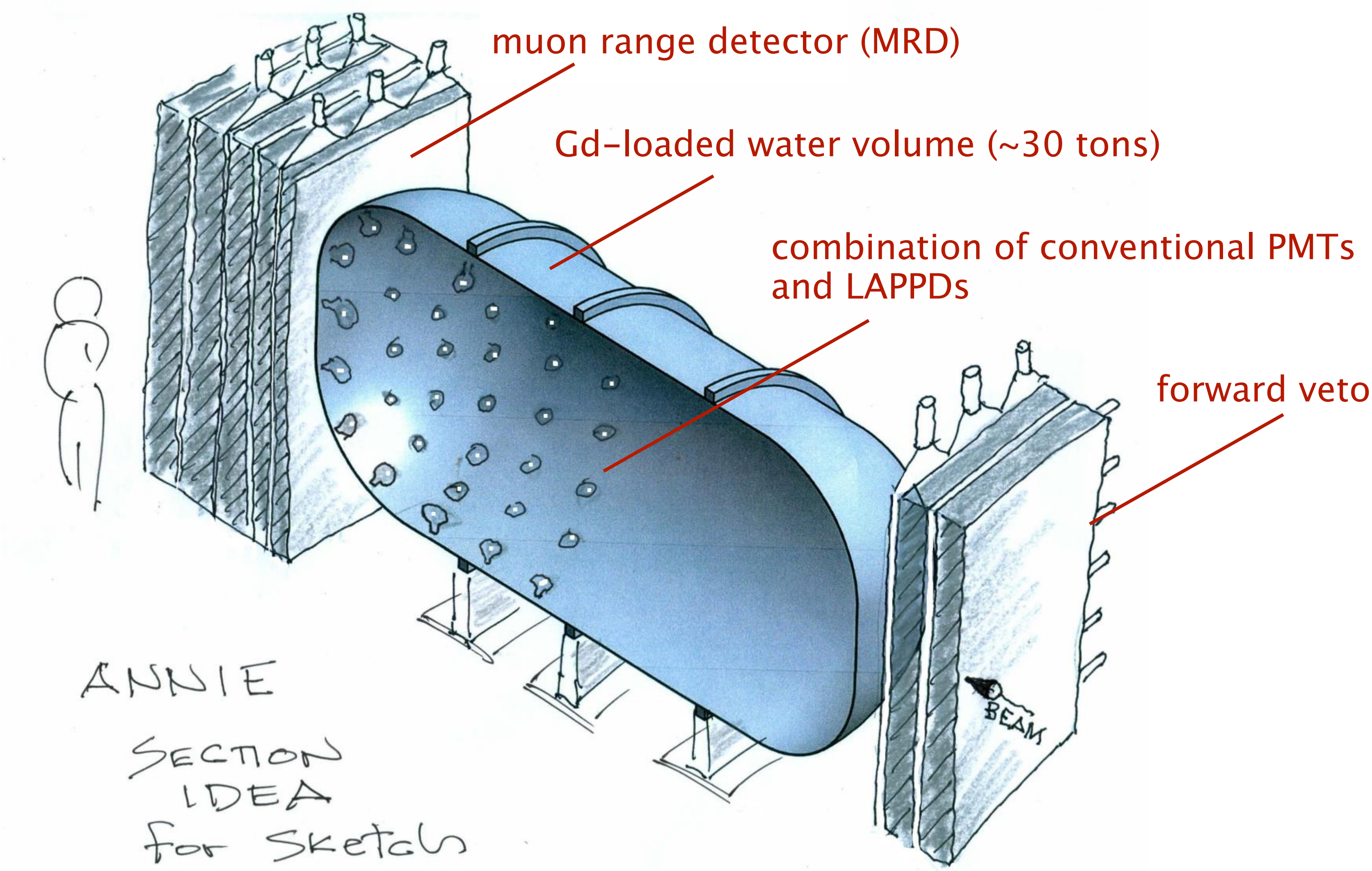


The ANNIE Detector System



R. Northrop

The ANNIE Detector System



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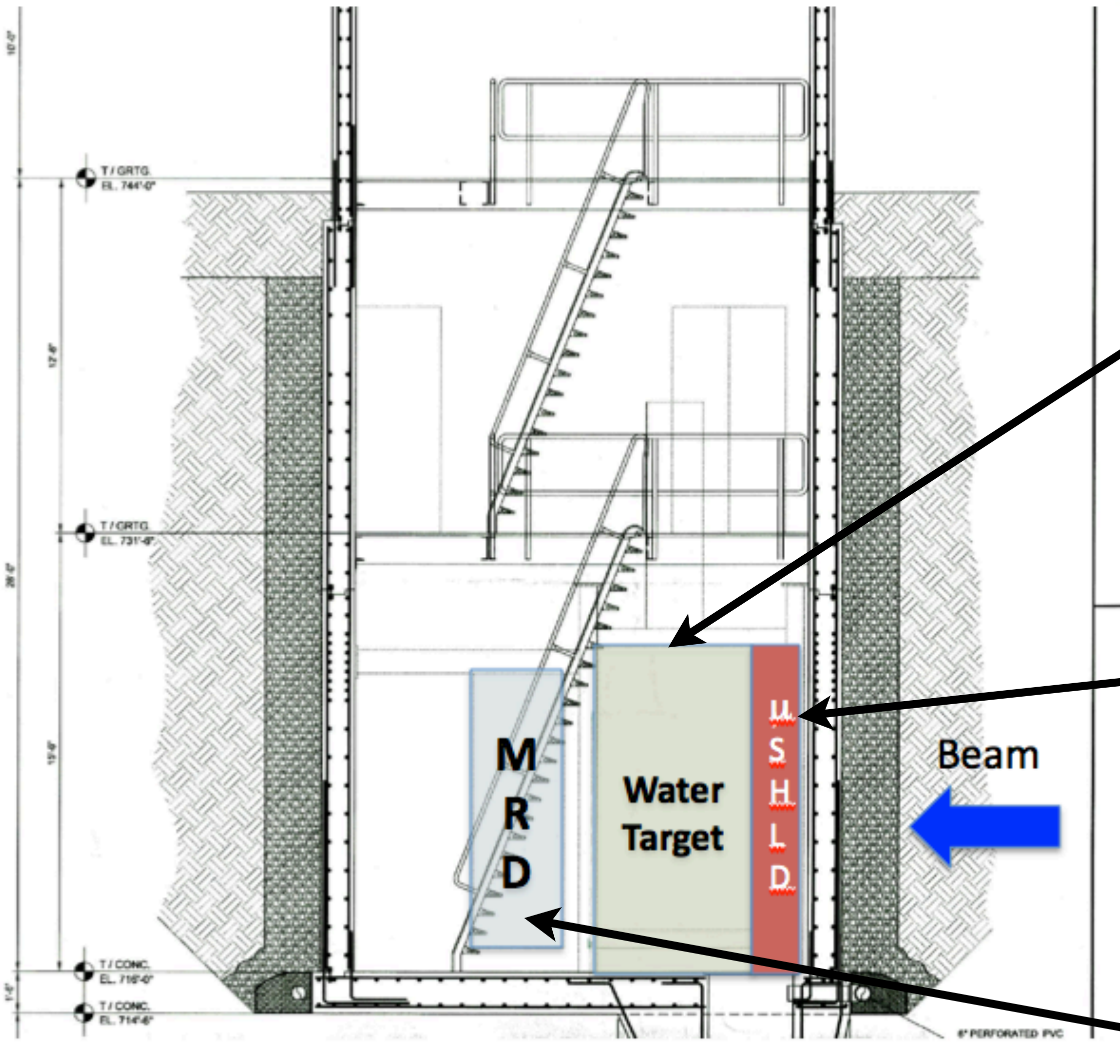


3m x 3m x 3m tank of Gd enhanced water instrumented with photosensors.

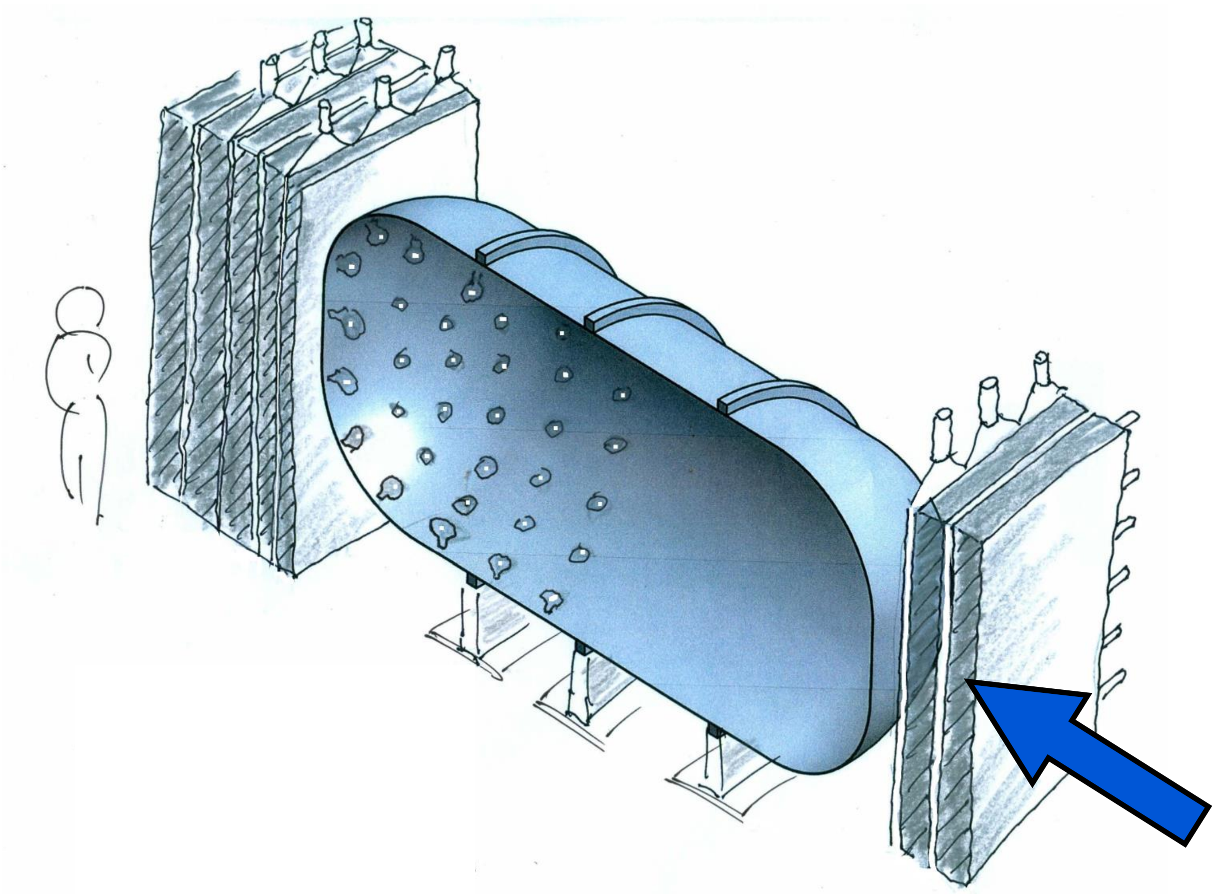
veto on muons produced upstream of the detector (FACC)

Existing Muon Range Detector (MRD)

“ANNIE Hall”

(formerly the SciBooNE pit)

ANNIE – basic concept



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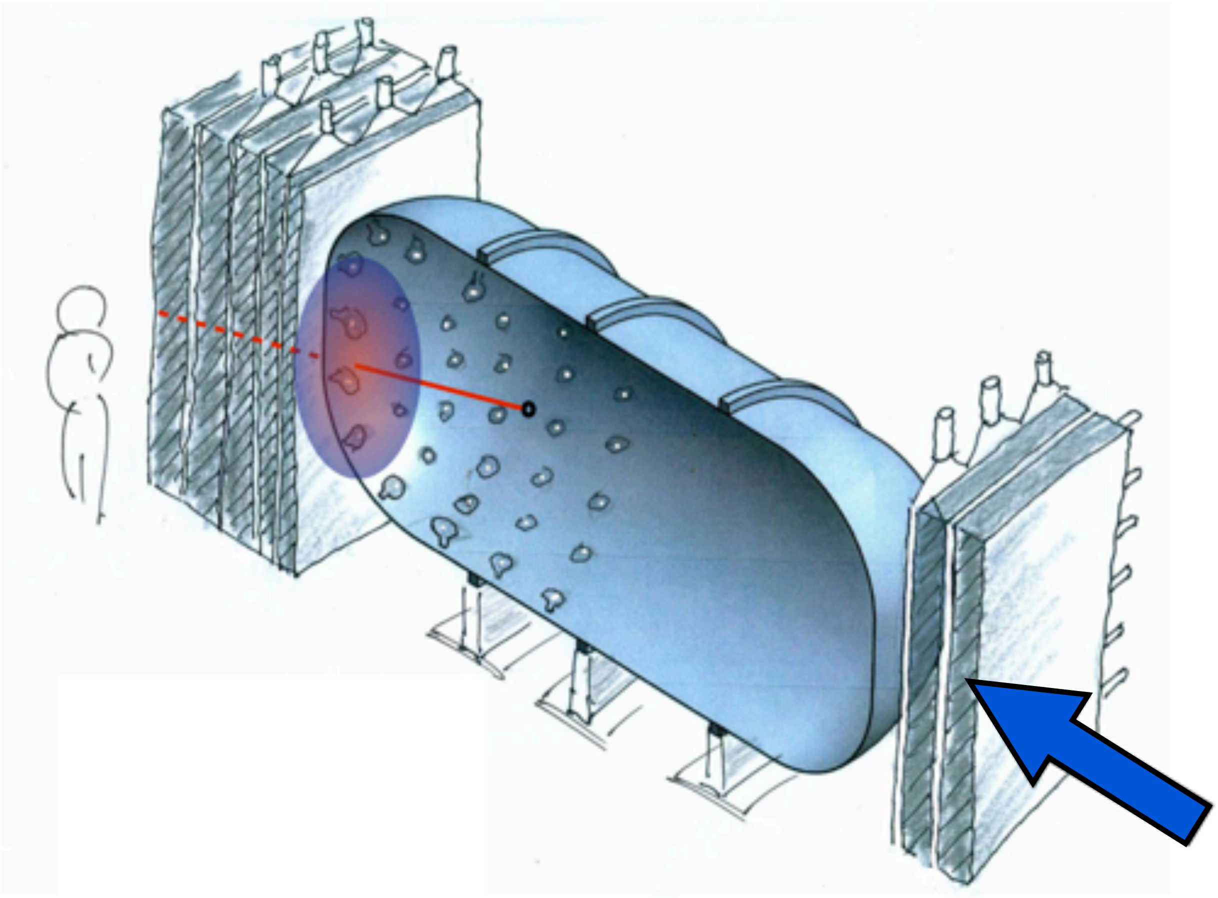

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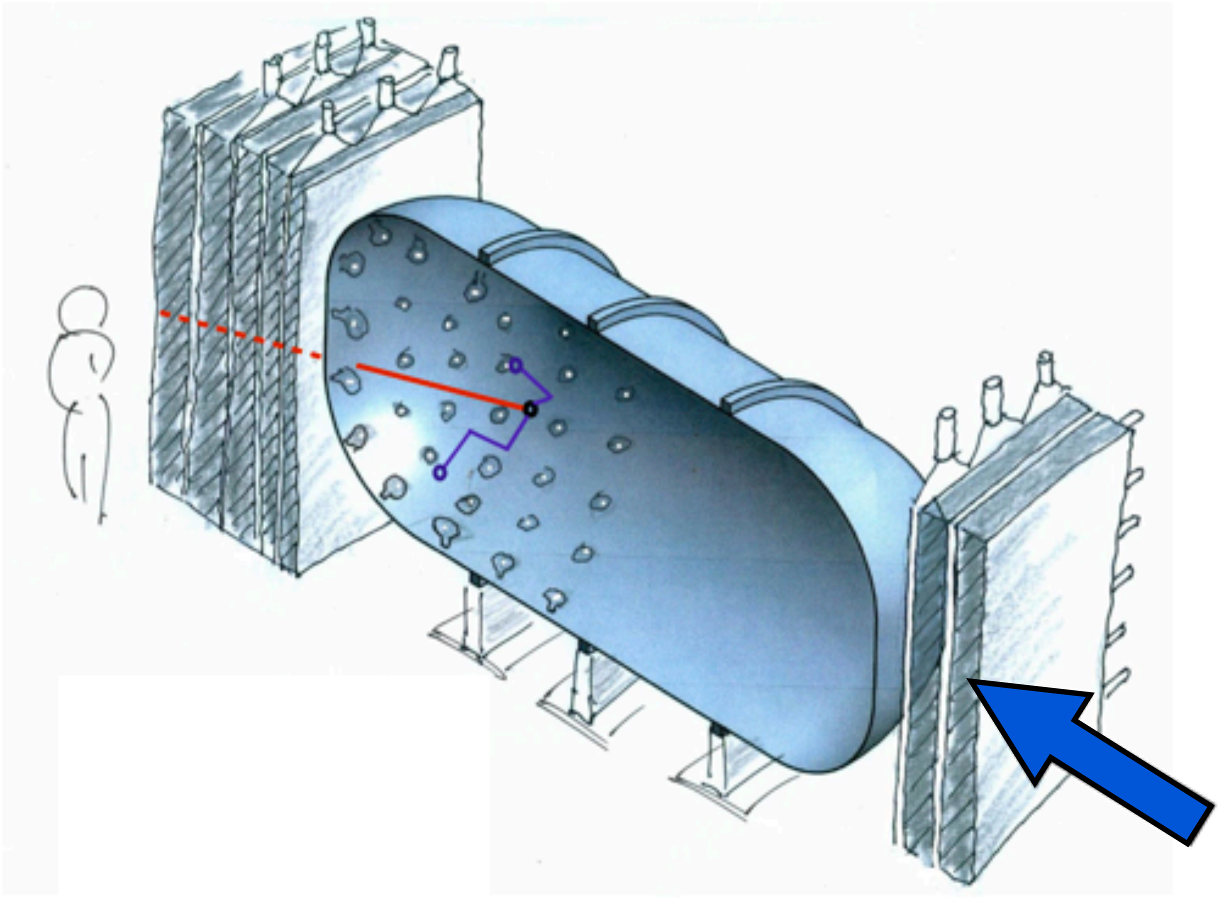
- A muon is produced and detected in the MRD.
- LAPPDs used to reconstruct vertex position based on arrival of Cherenkov light.

ANNIE – basic concept



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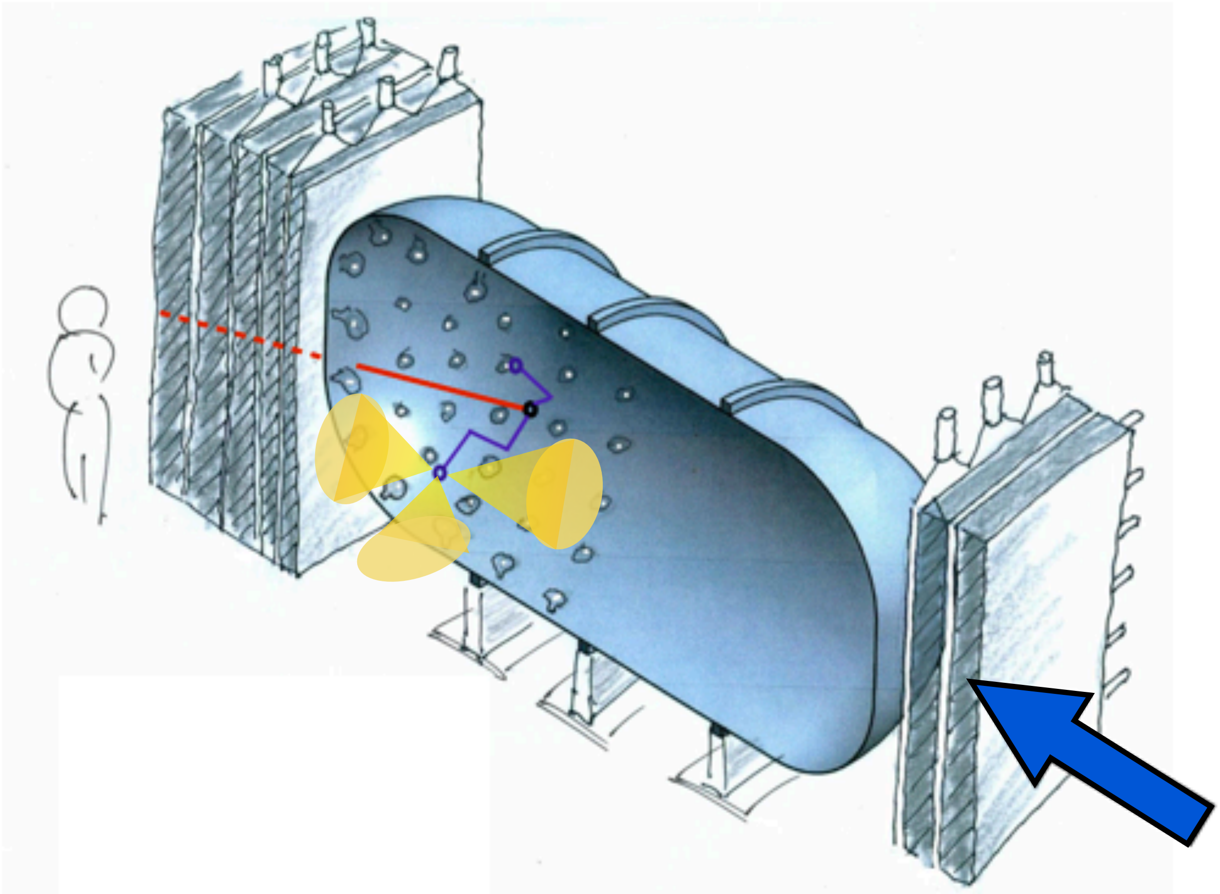

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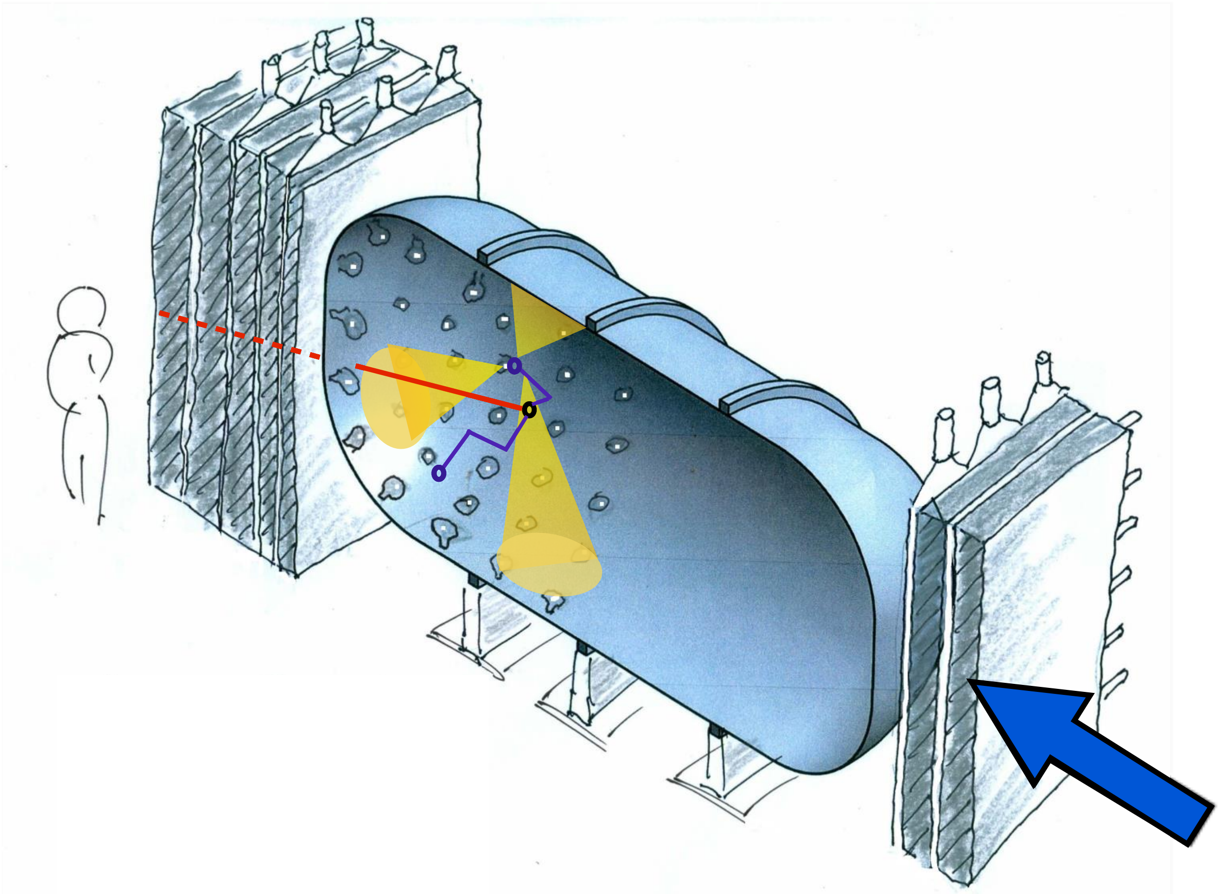

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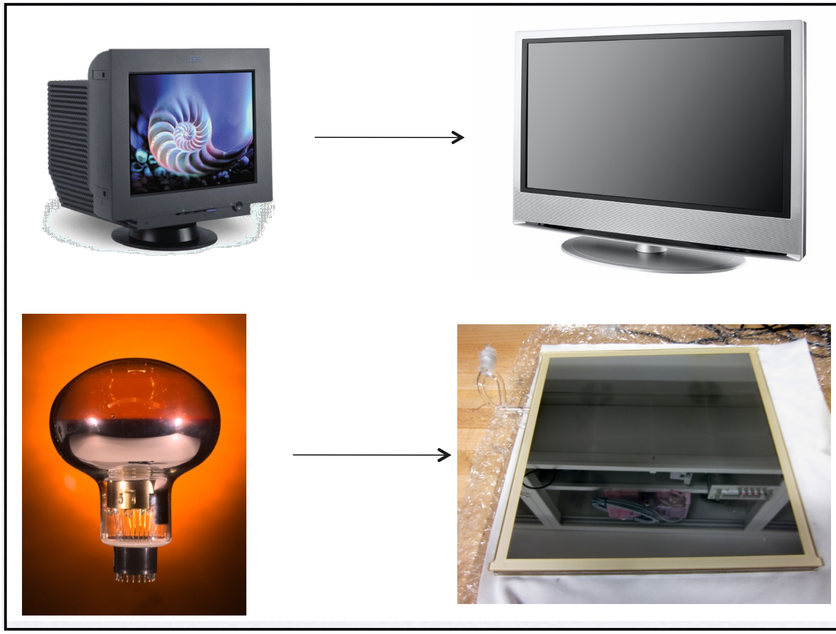
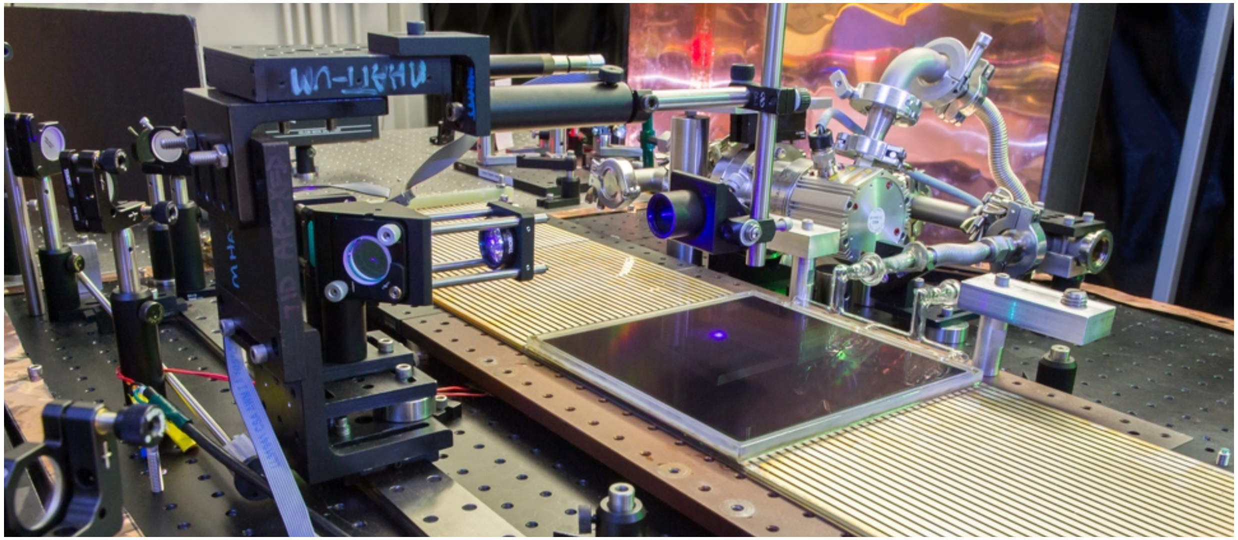
LAPPDs can provide the needed photodetector capabilities

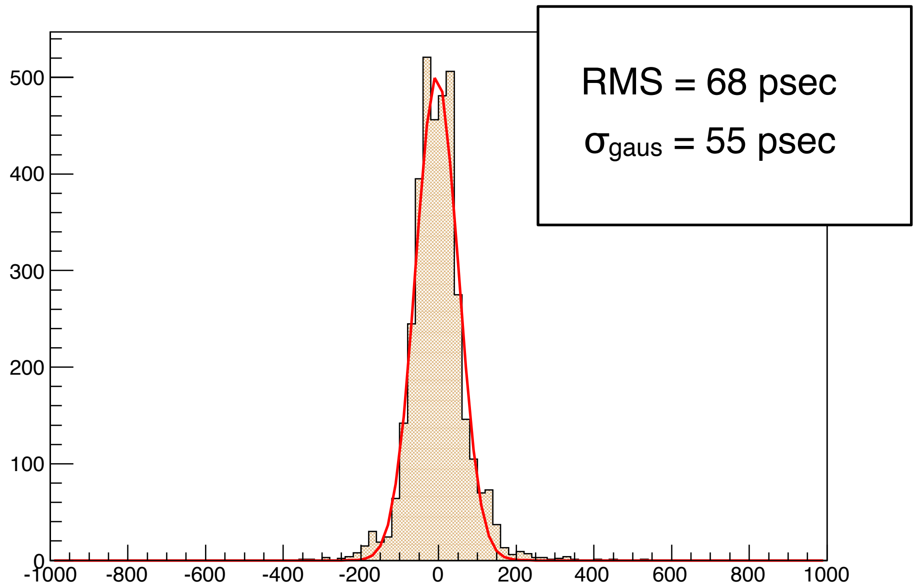
The Large Area Picosecond Photodetectors (LAPPD):

- large, flat-panel, MCP-based photosensors
- 50-100 psec time resolutions and <1cm spatial resolutions
- based on new, potentially economical industrial processes.
- LAPPD design includes a working readout system.



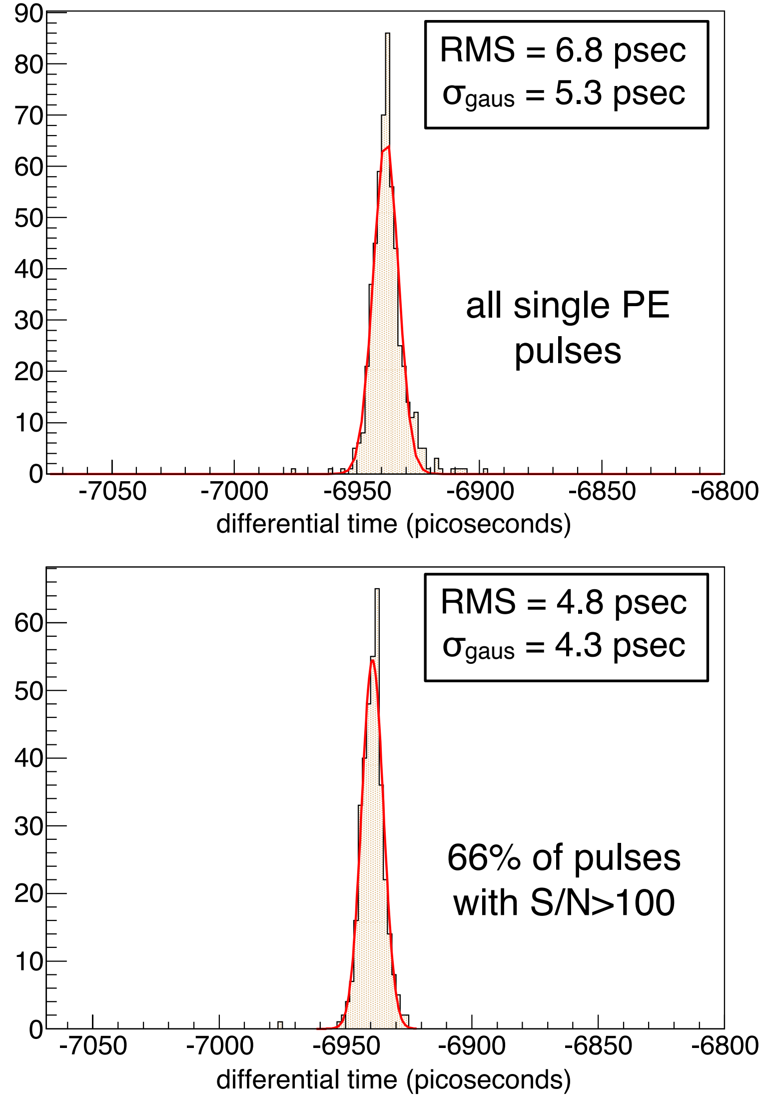


LAPPDs can provide the needed photodetector capabilities



single photoelectron absolute time resolution (psec)

differential time resolution between two ends of stripline



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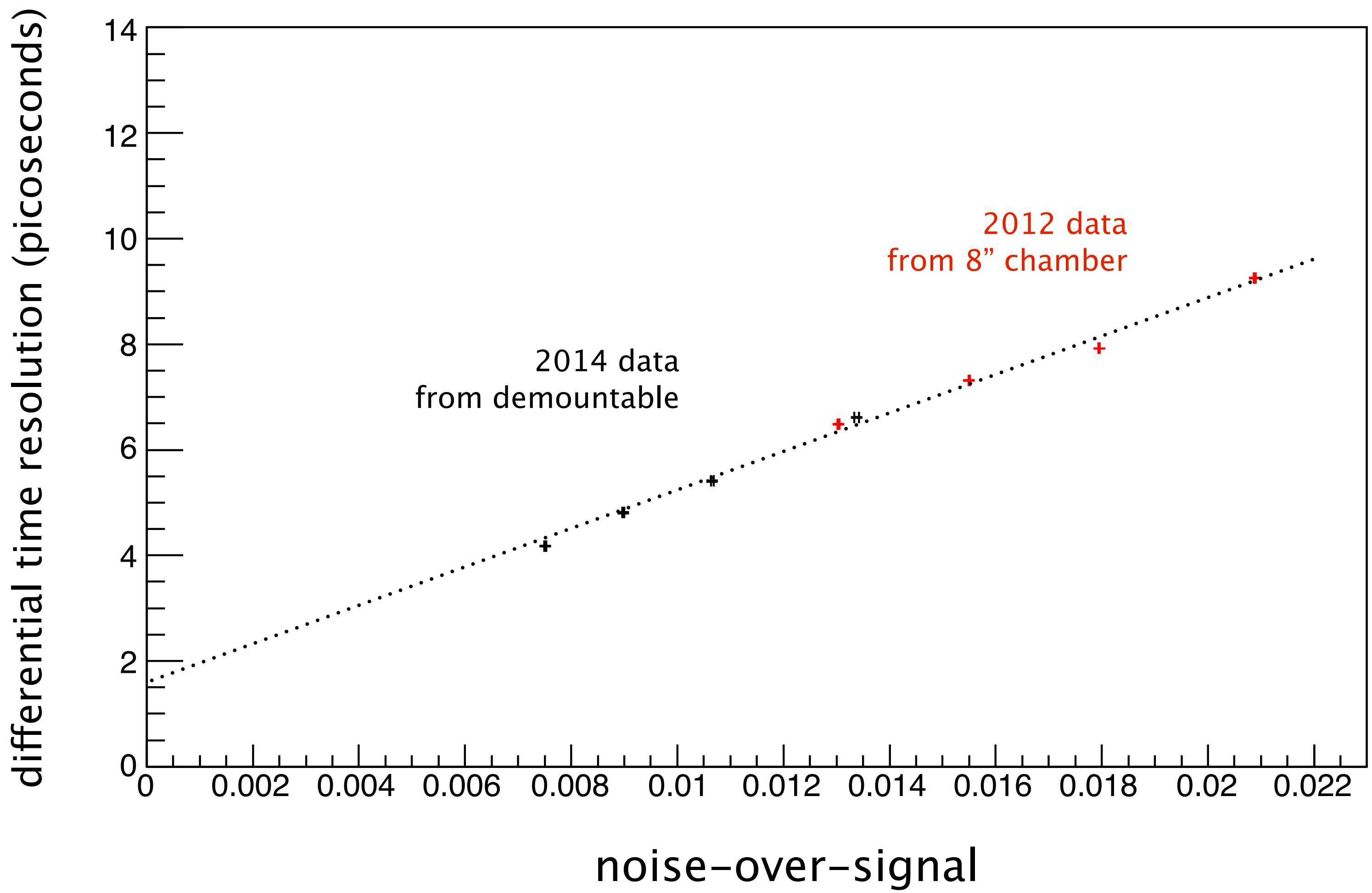
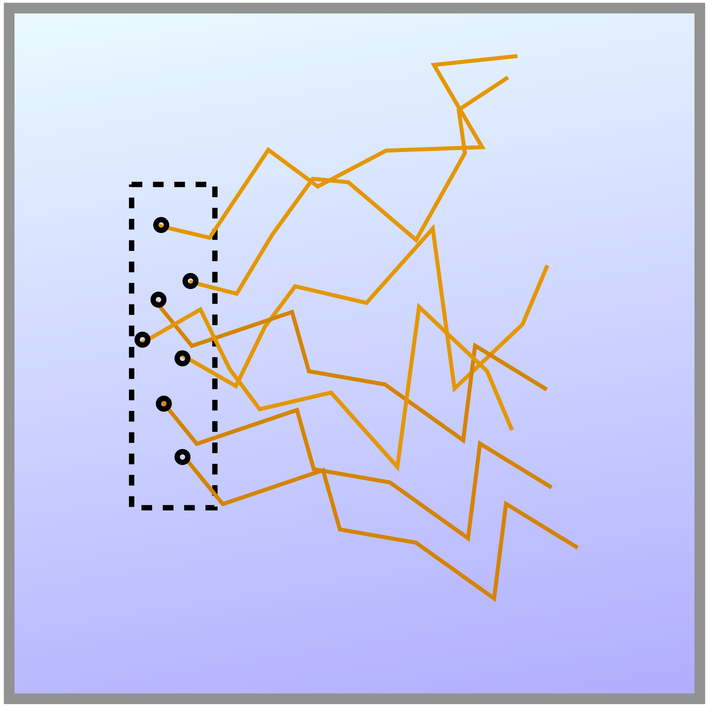


Timing-based vertex reconstruction is essential

Neutrons typically drift over a 2 meter distance.

- In the directions transverse to the beam, this 2-meter window is centered symmetrically about the interaction point.
- In the direction of the beam, it is mostly forward with respect to the interaction point.



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.

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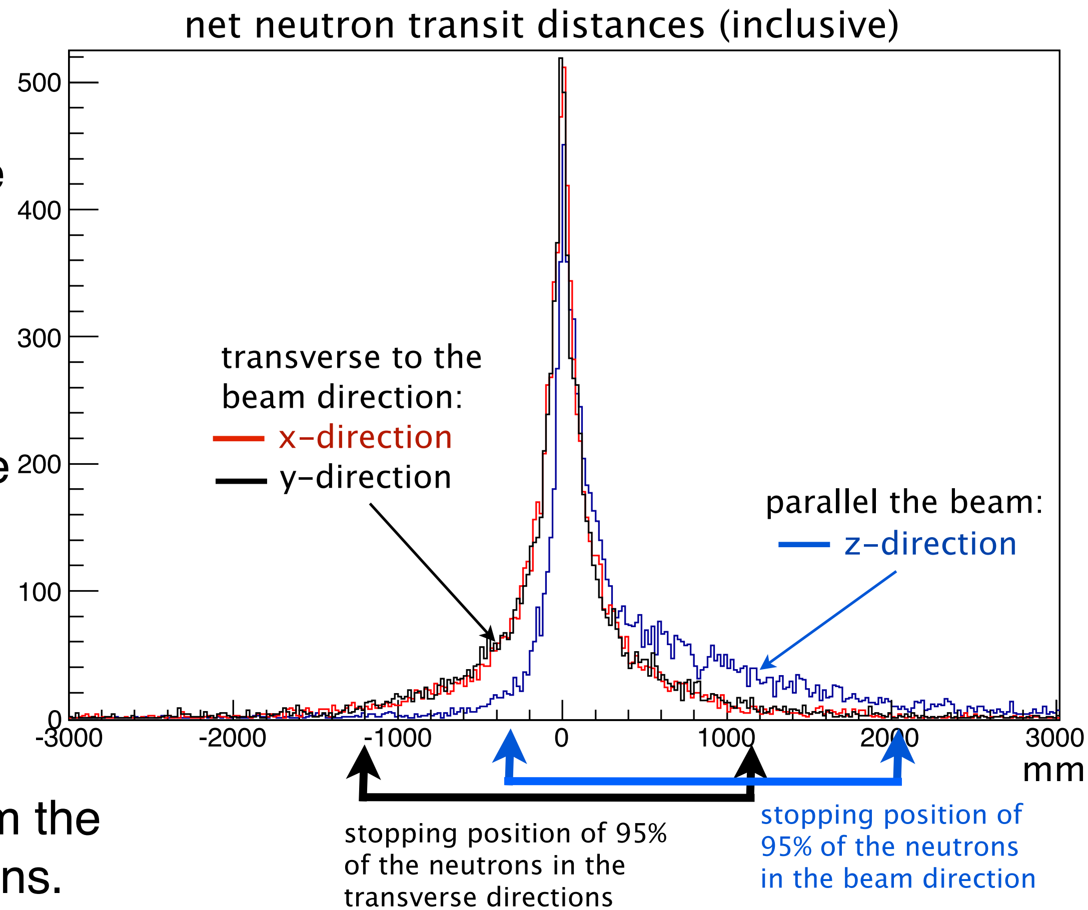

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Full Track Reconstruction: A TPC Using Optical Light?

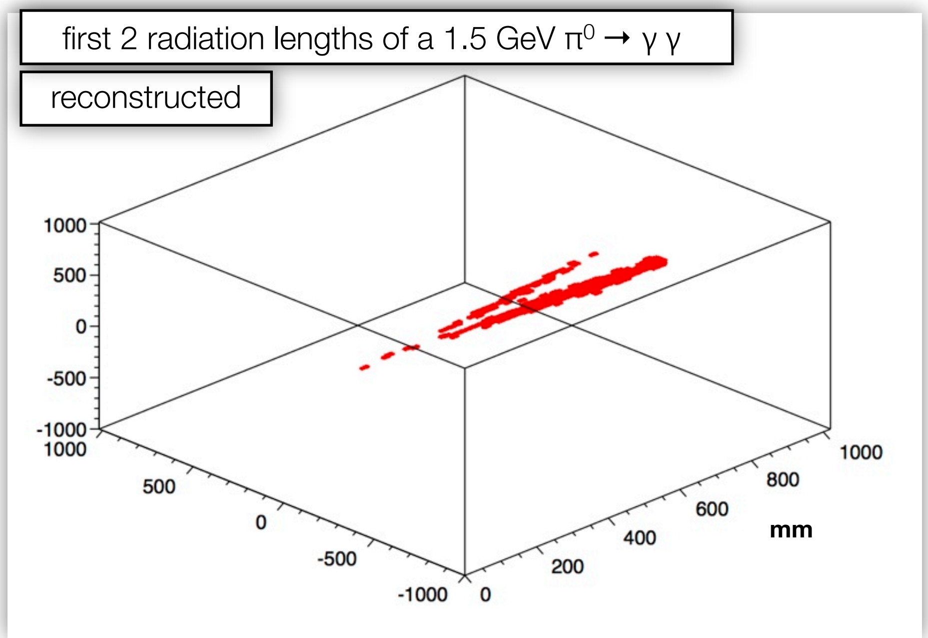
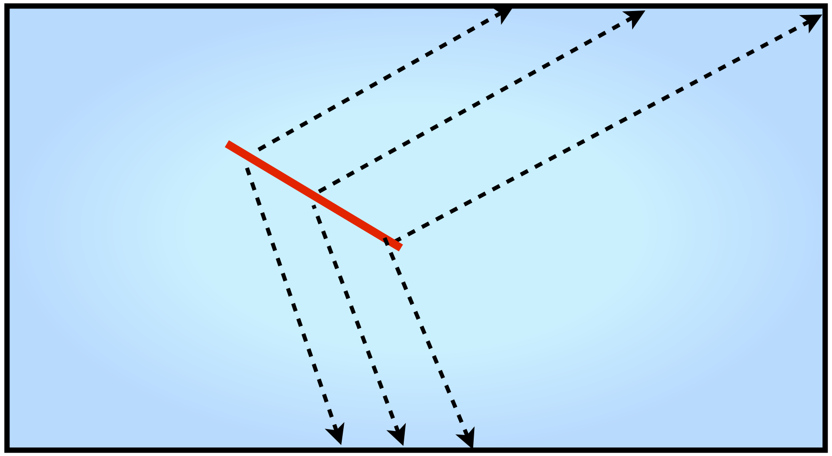


Image reconstruction, using a causal "Hough Transform" (isochron method)

“Drift time” of photons is fast compared to charge in a TPC!

~225,000mm/microsecond

Need fast timing and new algorithms

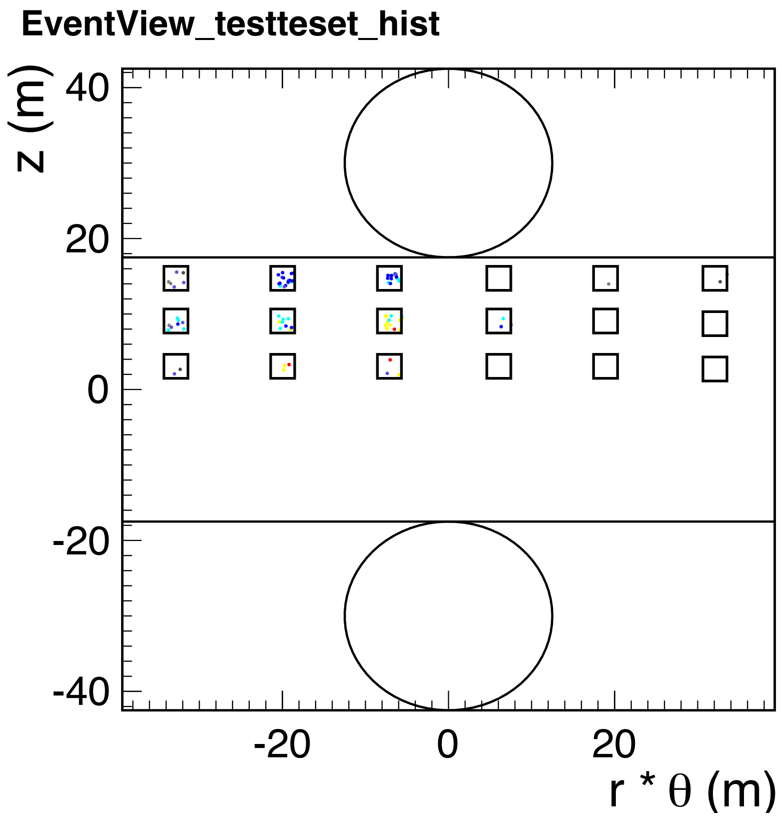


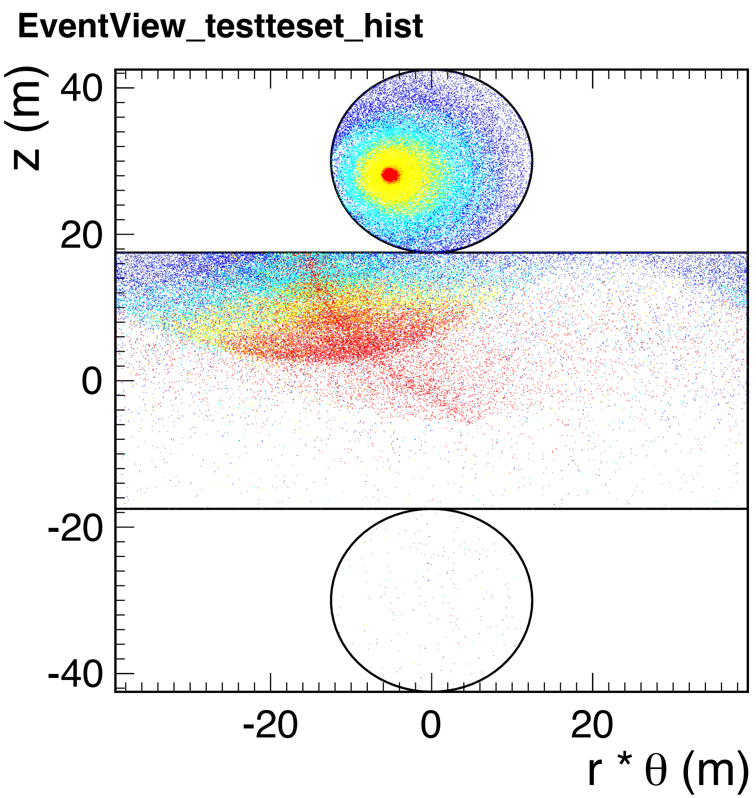
(see ANT13 LAPPD talk)

(see ANT13 mTC talk)

LAPPDs are imaging photosensors

- Given close proximity to the wall, and limited coverage, features of Cherenkov cones could not be resolved by single pixel detectors
- Often, the edge of a Cherenkov cone will be captured by a single module.
- LAPPDs can resolve individual hits within a single module. This means one can potentially reconstruct track parameters from light on a single tile.

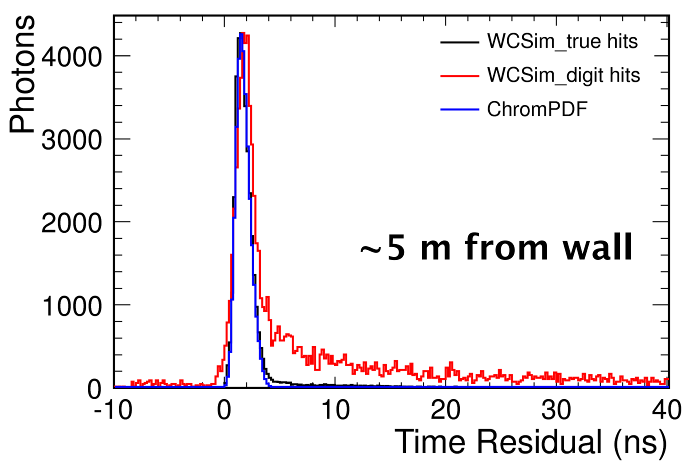


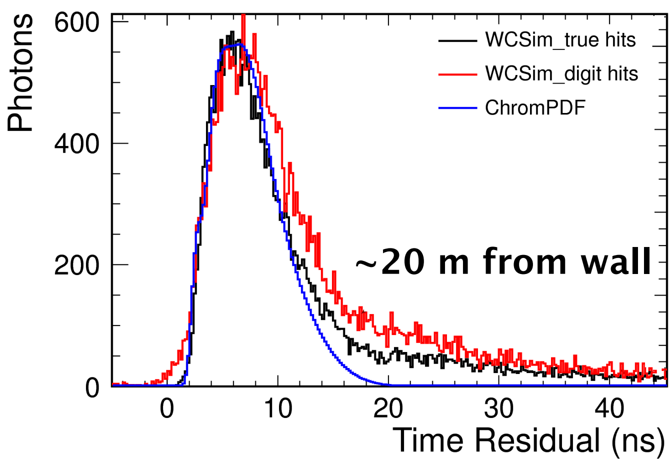


Why ANNIE is an ideal first implementation of LAPPDs

- ANNIE is small enough that limited batches of LAPPDs can feasibly meet the physics needs of the experiment.

- Chromatic dispersion is negligible

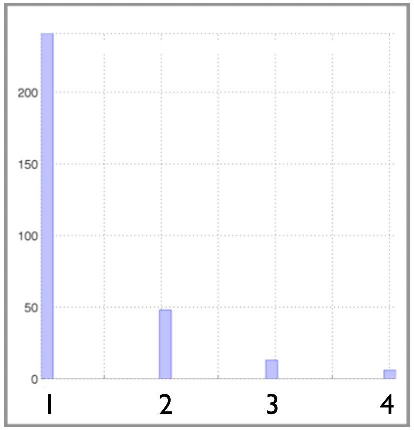




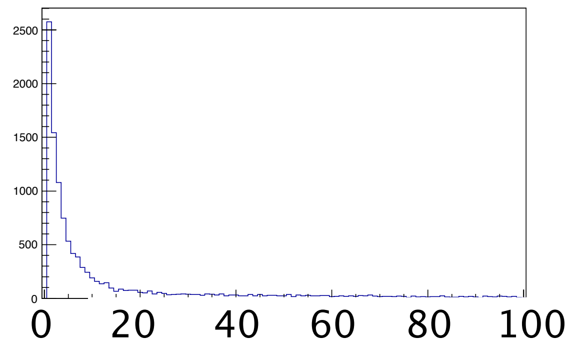
Why ANNIE is an ideal first implementation of LAPPDs

- Simplicity in Cherenkov-only light production
- low light yields

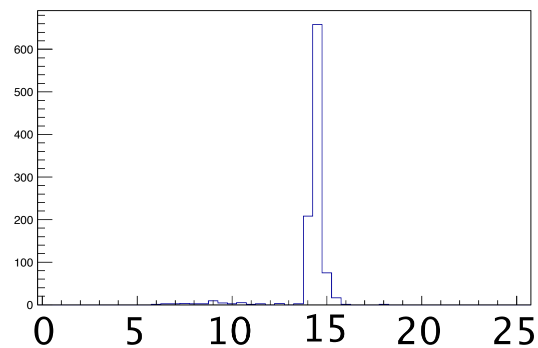
Number of hits per channel
(single event)

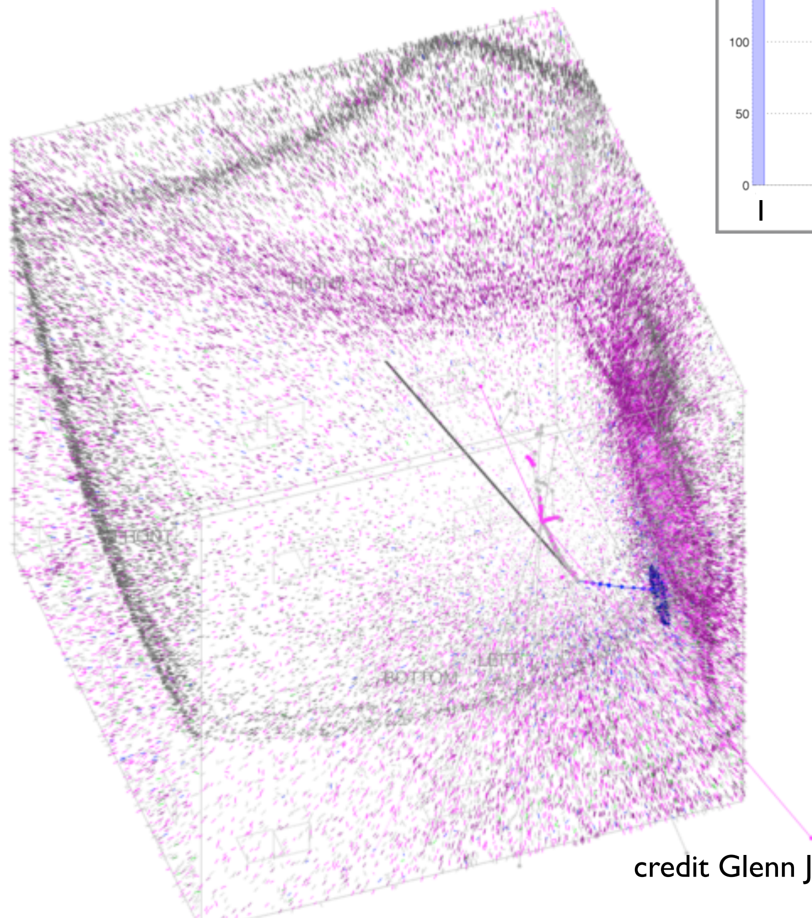


Number of hits per LAPPD (1000 evts)



Percentage of LAPPDs with more than 30 hits



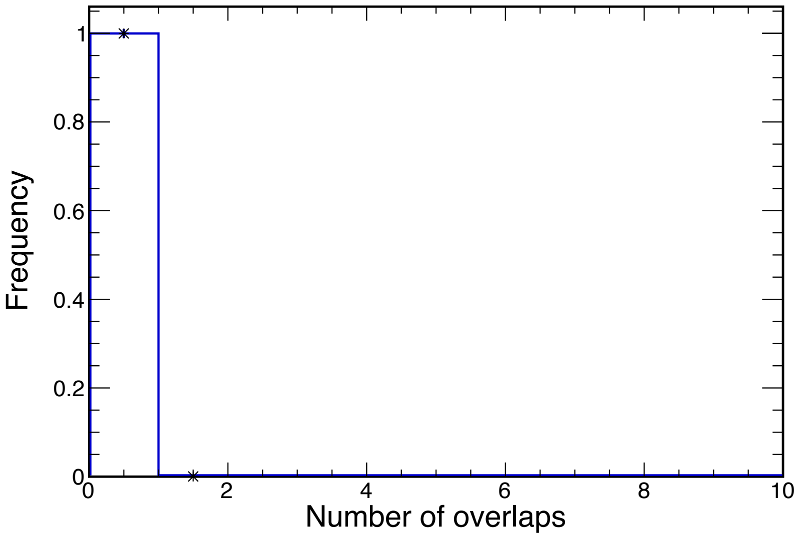


credit Glenn Jocher

Why ANNIE is an ideal first implementation of LAPPDs

- Manageable beam structure

30 ton water detector (=100 ns event length);
SciBooNE hall & Booster beam (=0.04 ev per spill)

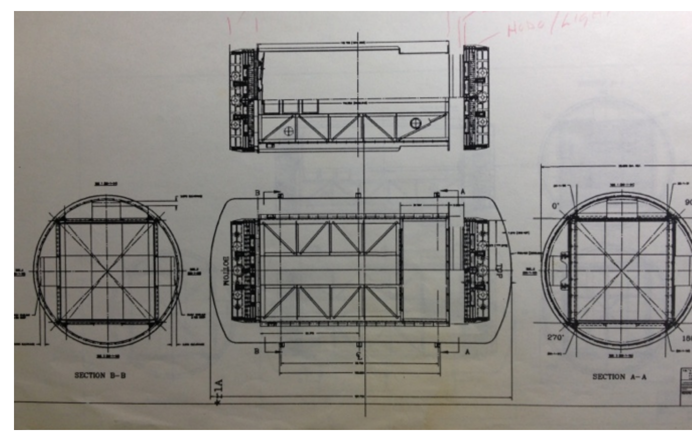


As expected, with $\ll 1$ event/spill, we get ~ 0 overlaps. Similar result even if factor of 1 order of magnitude in number of events has been made.

credit: E Catano-Mur

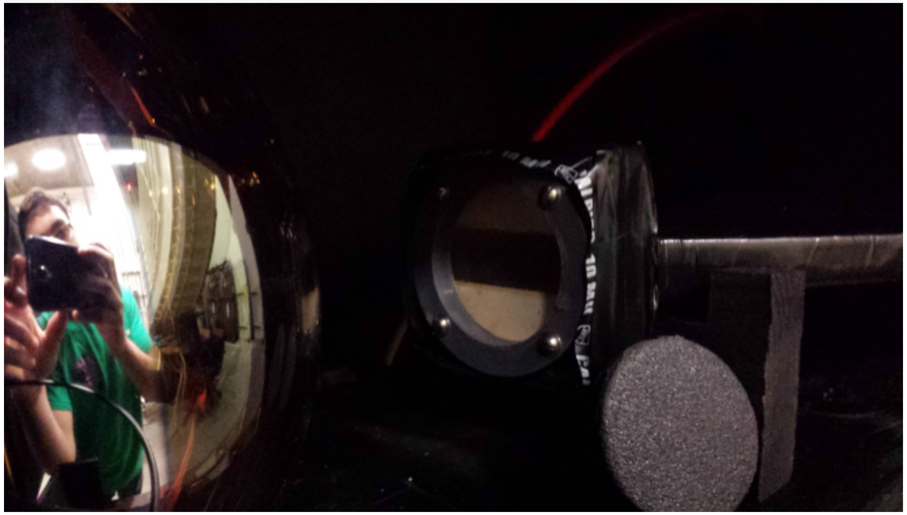
ANNIE technical developments – Water Volume

- U Chicago has an aluminum pressure tank used in cosmic ray balloon measurements
- It isn't exactly our chosen aspect ratio, but it's very close
- Richard Northrop (UC engineer) has begun work and is pretty confident it can hold it's volume in water.
- We may be able to build the supports and test it with a water fill, just in time for the next FNAL PAC meeting.



ANNIE technical developments – PMTs

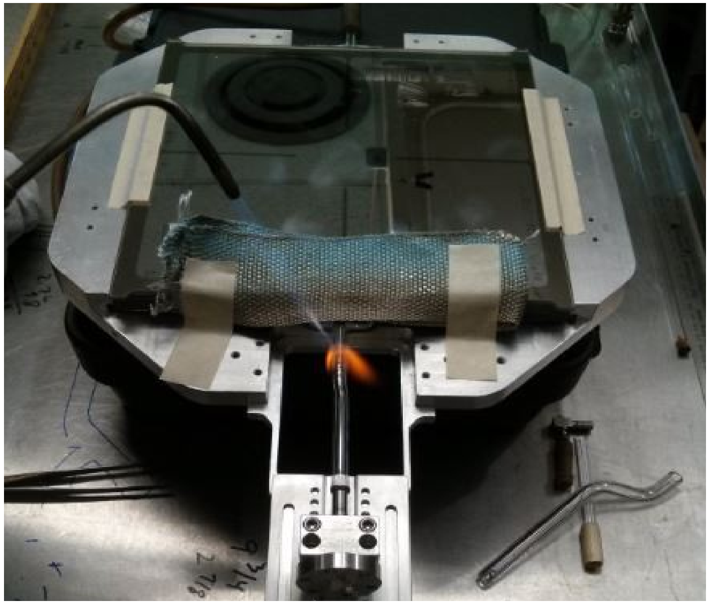
- UC Irivine has >100 spare 8" Hammamatsu PMTs
  - ~80 with good HV bases, ready for use
  - additional PMTs will need new bases
- This summer, they finished systematic tests for dark rate, pulse height and stability



Rating	-1	0	1	2	3	Rating≥ 1	#PMTs to be Analyzed
TYPE S (1)	11	4	36	21	6	63	7
TYPE I (2)	76	2	18	16	9	43	67

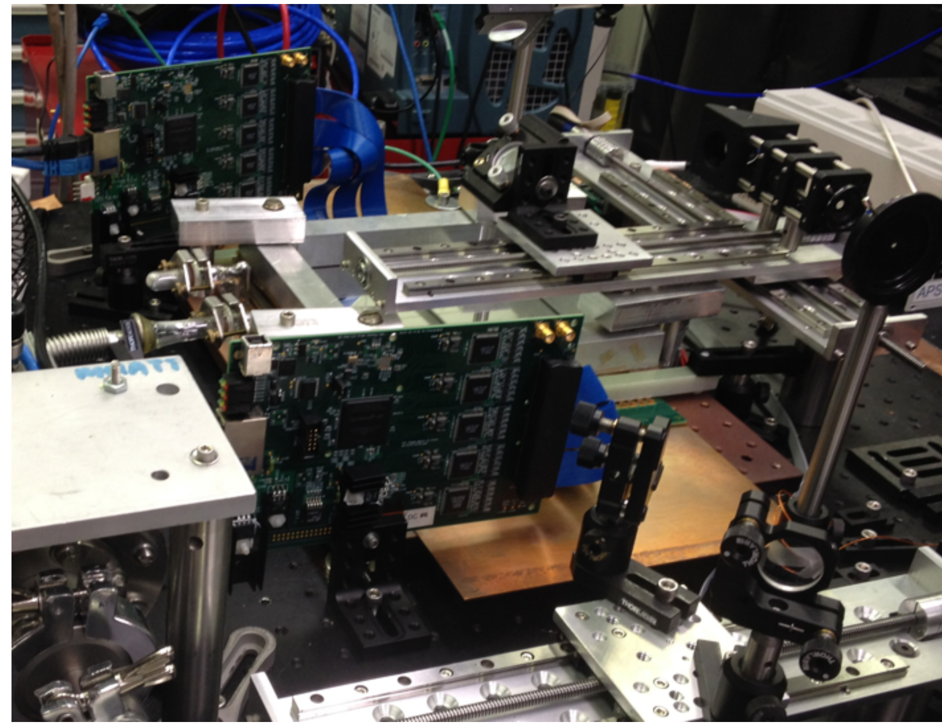
ANNIE technical developments – LAPPDs

- $3 M in STTR funding has been provided to Incom to begin commercialization of LAPPDs.
  - already into year 1 of 3-year process
  - closely integrated with Berkeley and ANL
- Ossy Siegmund (Berkeley SSL) has the parts and is awaiting the funding to begin sealing several trial LAPPDs very soon
- U Chicago is developing an advanced fabrication facility, based on in situ photocathode synthesis - could change the cost and throughput for LAPPDs and fast-track some more sealed tiles. System already being commissioned.
- Argonne has made a small-format glass tiles (6x6 cm), using a similar process as LAPPDs. These tiles can be used for development work.



ANNIE technical developments – electronics and HV

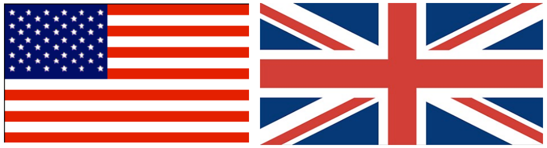
- Systematic studies of LAPPD performance under multi-photon pileup were performed using the PSEC4 electronics this summer. PSEC electronics worked very well. To be published soon.
- Work is ongoing to fund the development of the PSEC5.
- Eric Oberla (UC) is continuing development of the PSEC4 firmware. Some development work on the triggering capabilities may come through work with the WATCHMAN collaboration.
- One technical task is to develop a method for hi-pot'ing in water. An electrical functional, hermetically sealed small tile has been made available to do some demonstration work with HV in water.



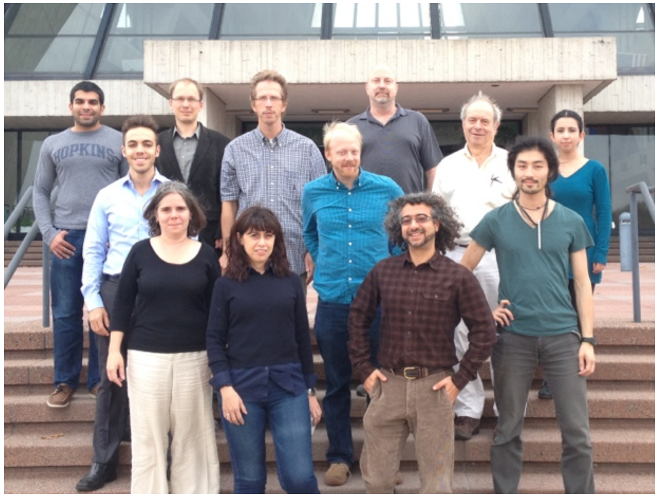
The Collaboration

30 collaborators

15 Institutions



- Argonne National Laboratory
- Brookhaven National Laboratory
- Fermi National Accelerator Laboratory
- Imperial College of London
- Iowa State University
- Johns Hopkins University
- National Geospatial-Intelligence Agency
- Ohio State University
- Ultralytics, LLC
- University of California at Davis
- University of California at Irvine
- University of California at Los Angeles
- University of Chicago, Enrico Fermi Institute
- University of Hawaii
- Queen Mary University of London



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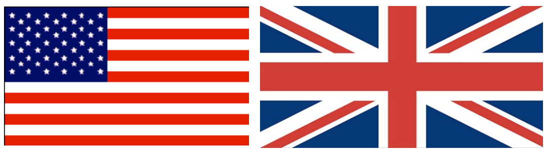

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- University of California at Davis
- University of California at Irvine
- University of California at Los Angeles
- University of Chicago, Enrico Fermi Institute
- University of Hawaii
- Queen Mary University of London

our mascot

Timeline

Preparation

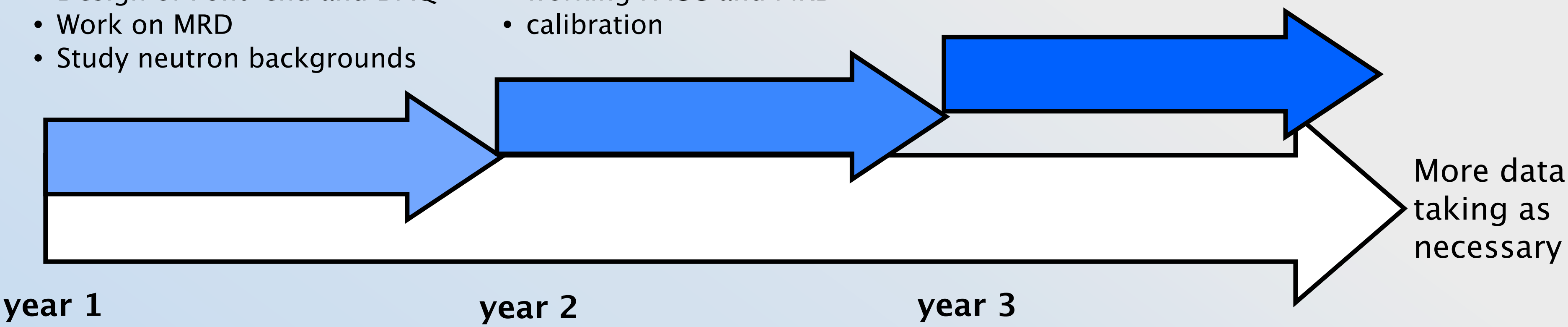
- Monte Carlo Studies
- Install Water Volume and PMTs
- Optimize Photosensor Coverage
- Design of Font-end and DAQ
- Work on MRD
- Study neutron backgrounds

Commissioning

- Tests with small numbers of LAPPDs
- Preliminary measurements
- working FACC and MRD
- calibration

First Data

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



Timeline

Preparation

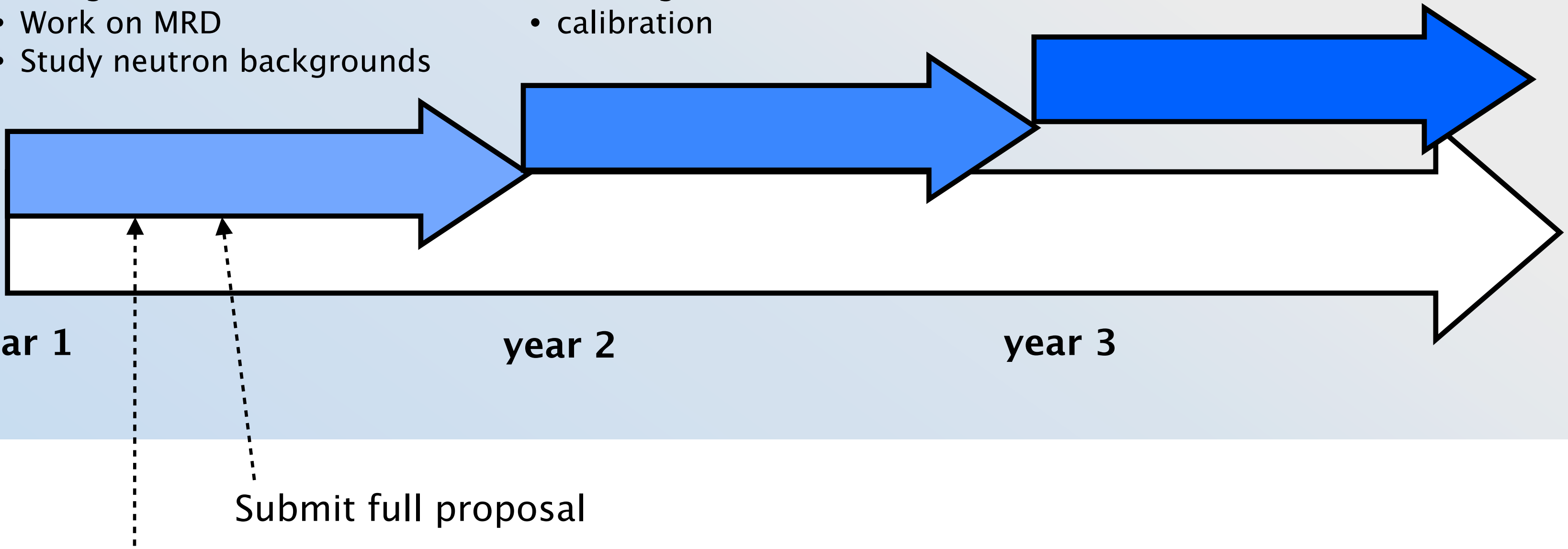
- Monte Carlo Studies
- Install Water Volume and PMTs
- Optimize Photosensor Coverage
- Design of Font-end and DAQ
- Work on MRD
- Study neutron backgrounds

Commissioning

- Tests with small numbers of LAPPDs
- Preliminary measurements
- working FACC and MRD
- calibration

First Data

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



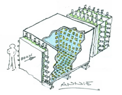
Preparatory work is already under way and moving quickly

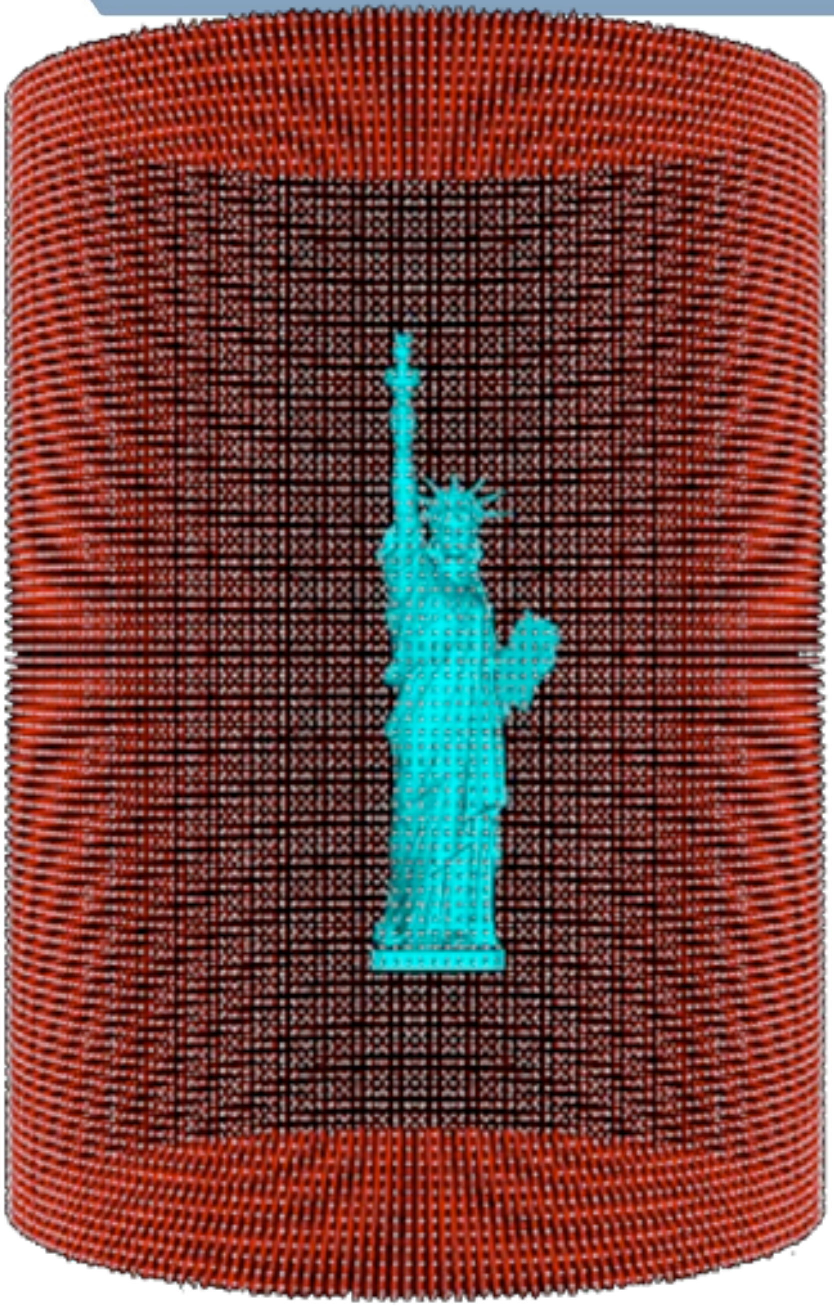
Then Onto Bigger Things?

ANNIE

WATCHMAN

200 kton?



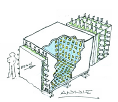


Then Onto Bigger Things?

Advanced Scintillator Detector Concept (ASDC): A Concept Paper on the Physics Potential of Water-Based Liquid Scintillator

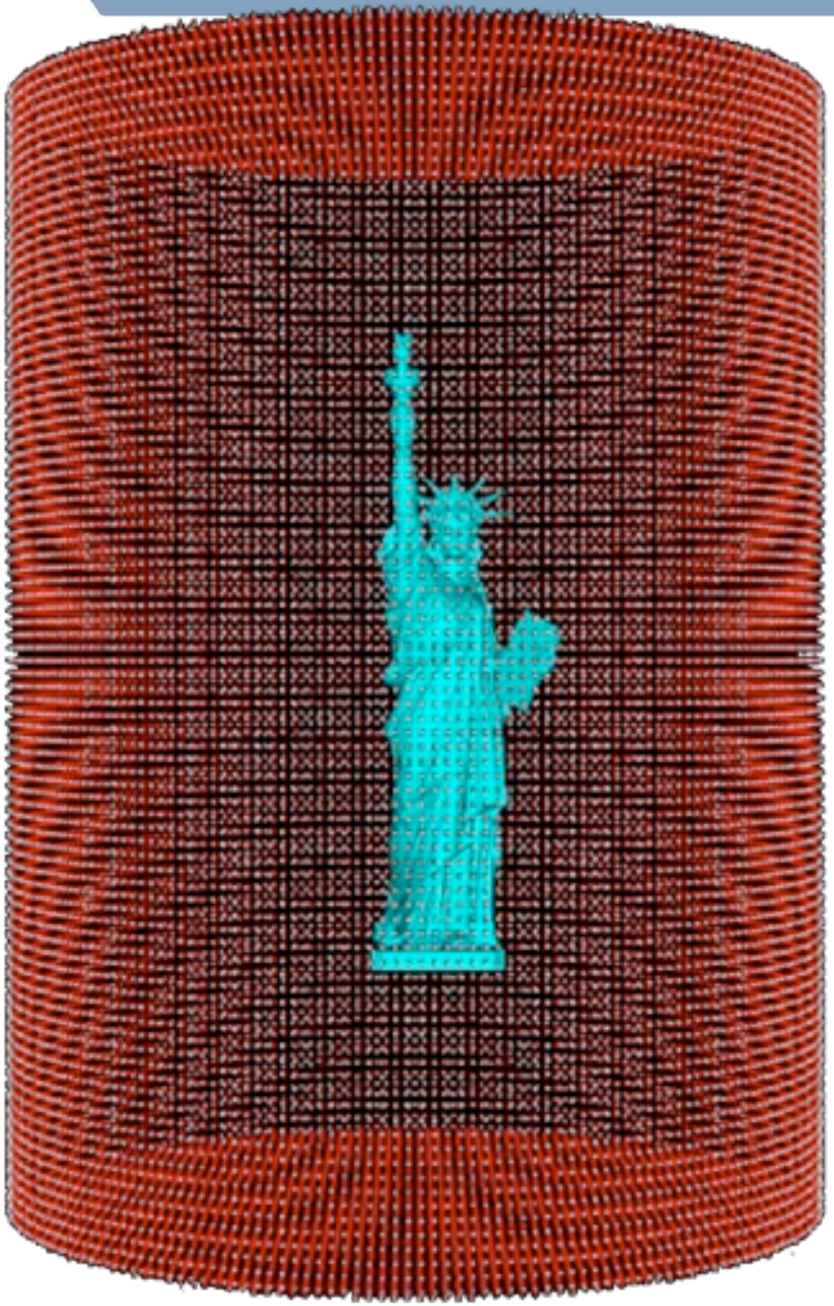
arXiv:1409.5864

ANNIE



WATCHMAN

200 kton?



Building a Successful Long Baseline Program

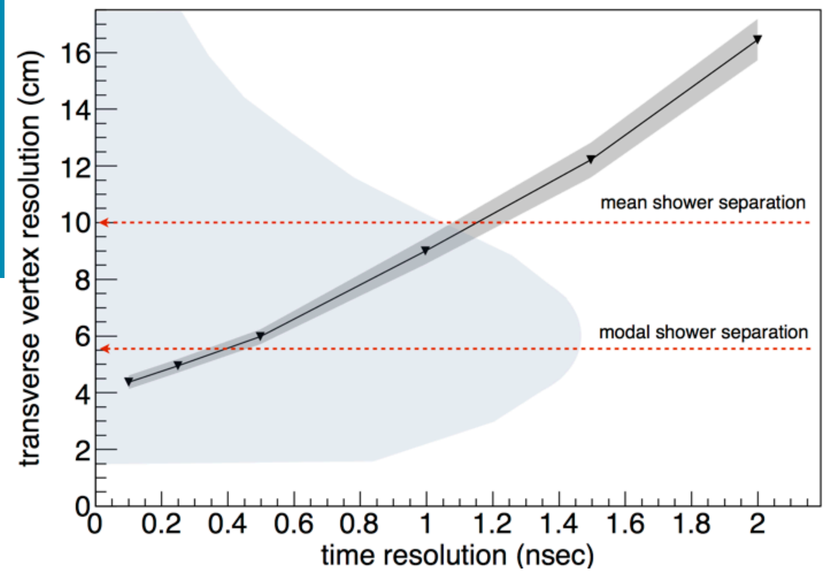
LBNF is a major opportunity and a flagship of US particle physics.

We need to build detectors that will fully exploit this beam and deliver home-runs over a broad range of physics

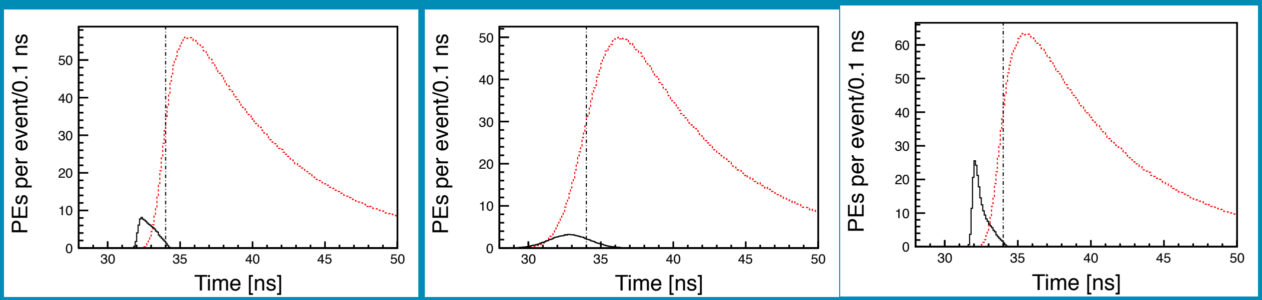
LAr detectors are (and should be) a major component

...but the addition of an Advanced Scintillator Detector would provide strong complementarity and much needed scale

Timing to reduce Pi0 backgrounds



Timing to separate between Cherenkov and scintillation light



(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;

arXiv:1307.5813

Conclusion

ANNIE provides key physics measurements necessary to future Intensity Frontier priorities.

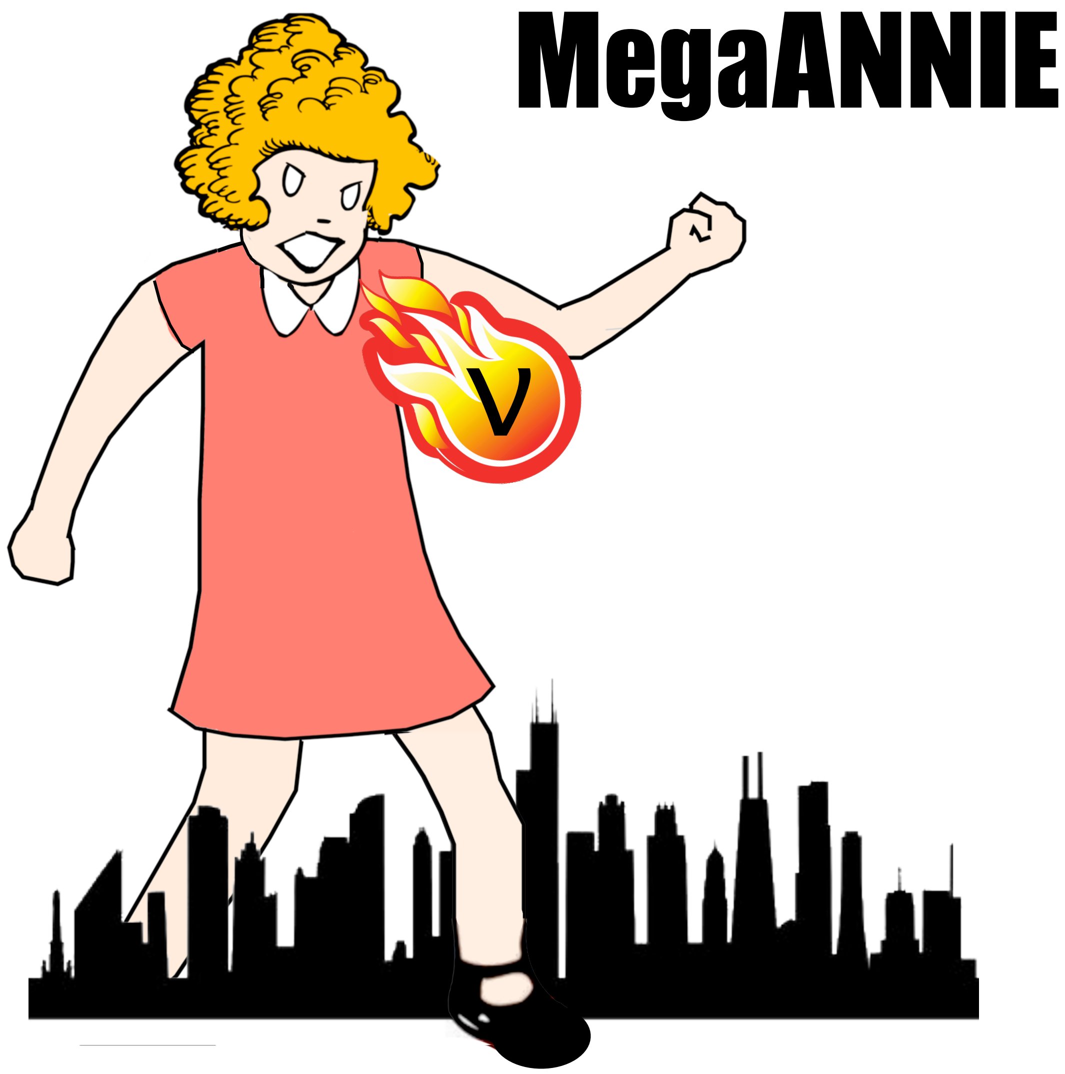
ANNIE is also a critical first demonstration of LAPPDs in a real WCh physics experiment

LAPPDs are ideal for the ANNIE physics program. ANNIE is an ideal early use for LAPPDs

This work has the opportunity to galvanize and bring together a large community of US and international collaborators with interest in next-generation WCh/LS detectors.

For more info, visit: annie.uchicago.edu

Summary



Thank You

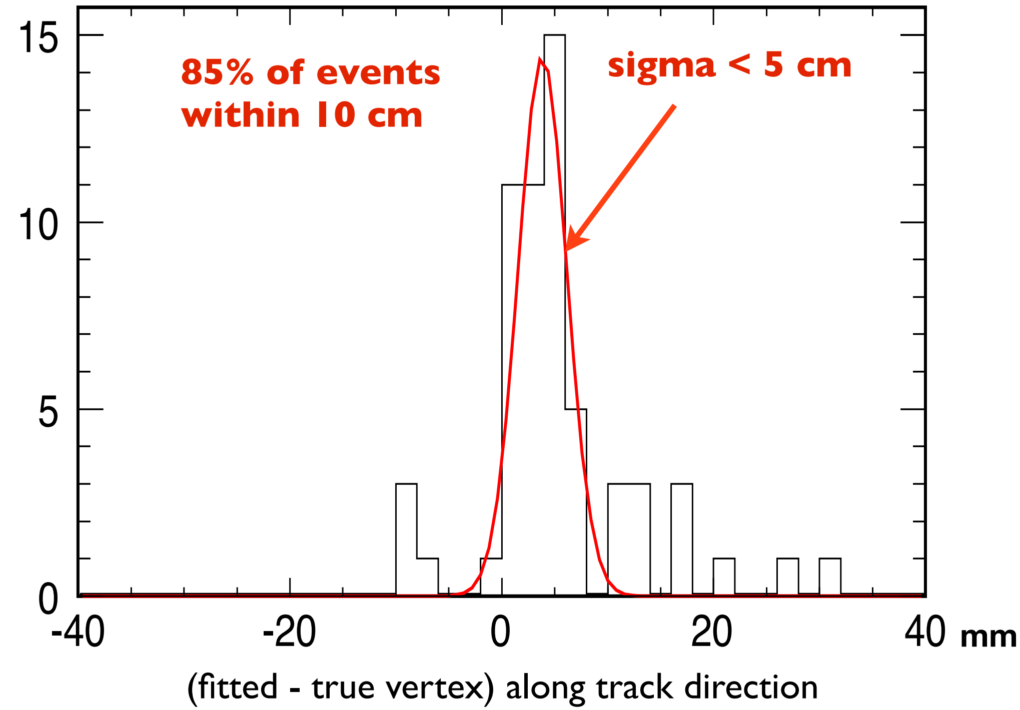
Backup Slides

Preliminary studies indicate that LAPPDs will meet our performance need

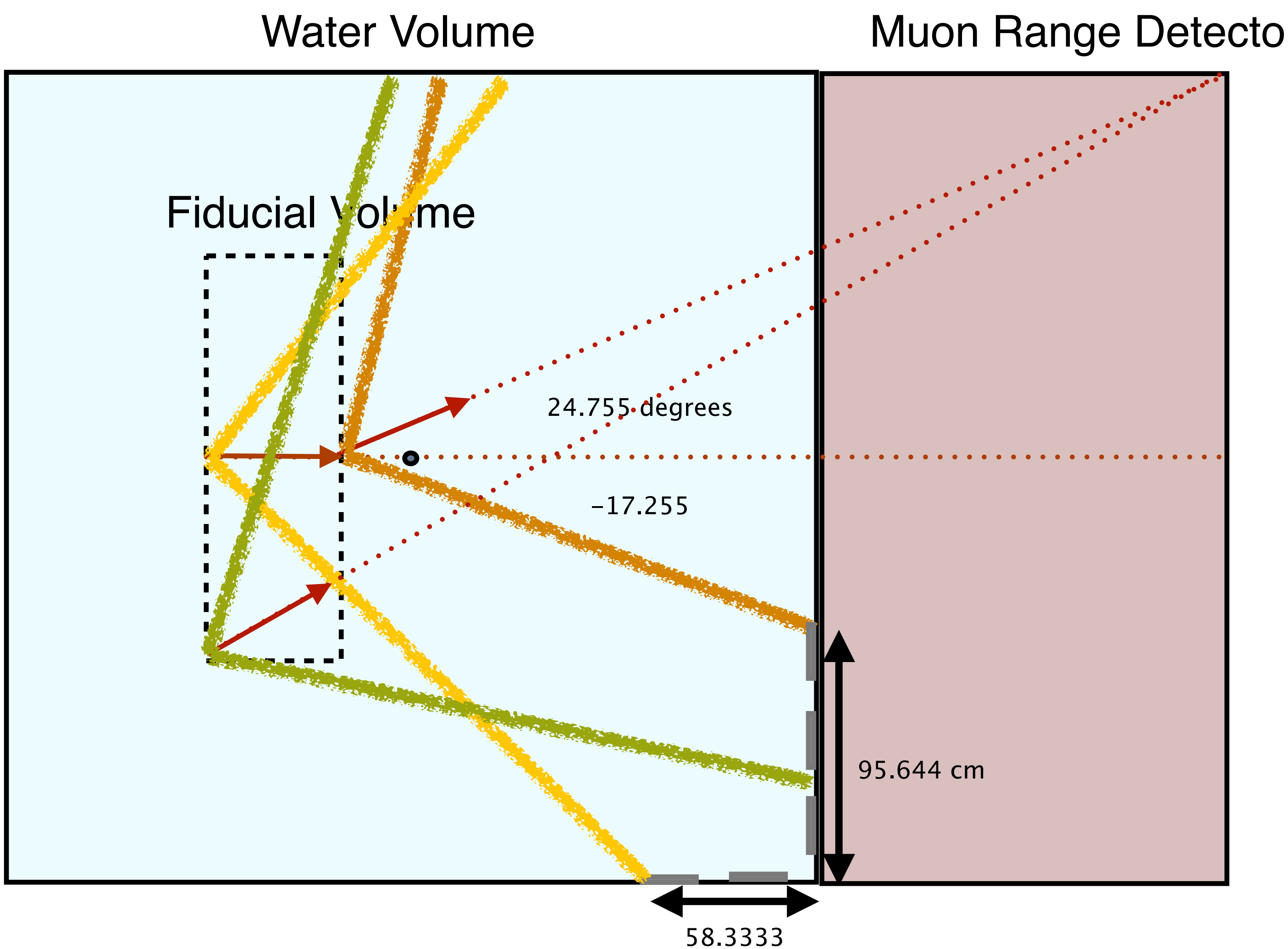
New technologies often require new reconstruction strategies.

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.


Water Volume
Muon Range Detector
Fiducial Volume
24.755 degrees
-17.255
95.644 cm
58.3333

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

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).

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**

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

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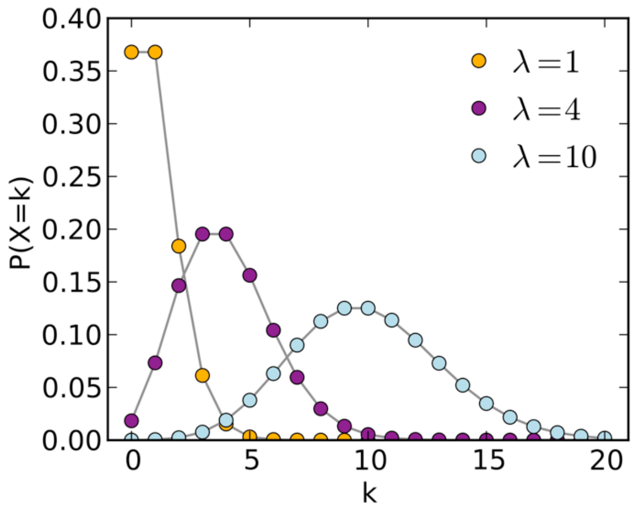
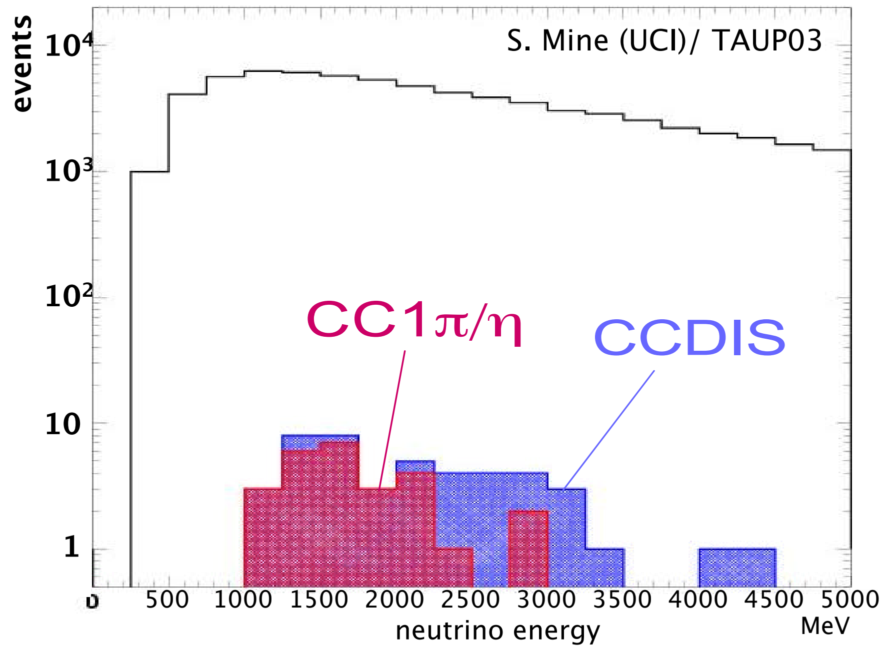


Did we see zero neutrons, given an expectation of 1 or 10? What is the number of expected neutrons? The spread?

The Booster Neutrino Beam Delivers The Needed Flux

- 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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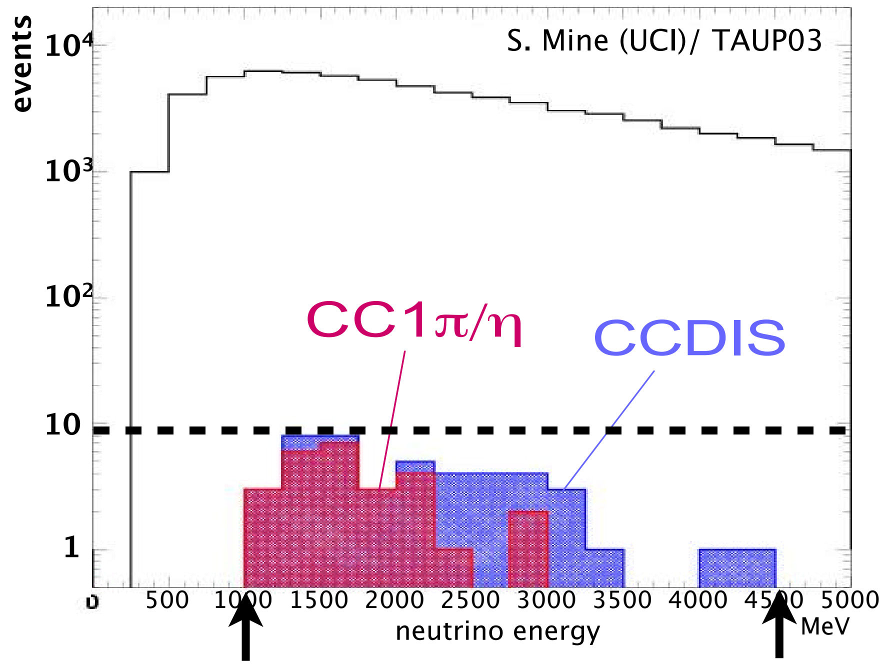

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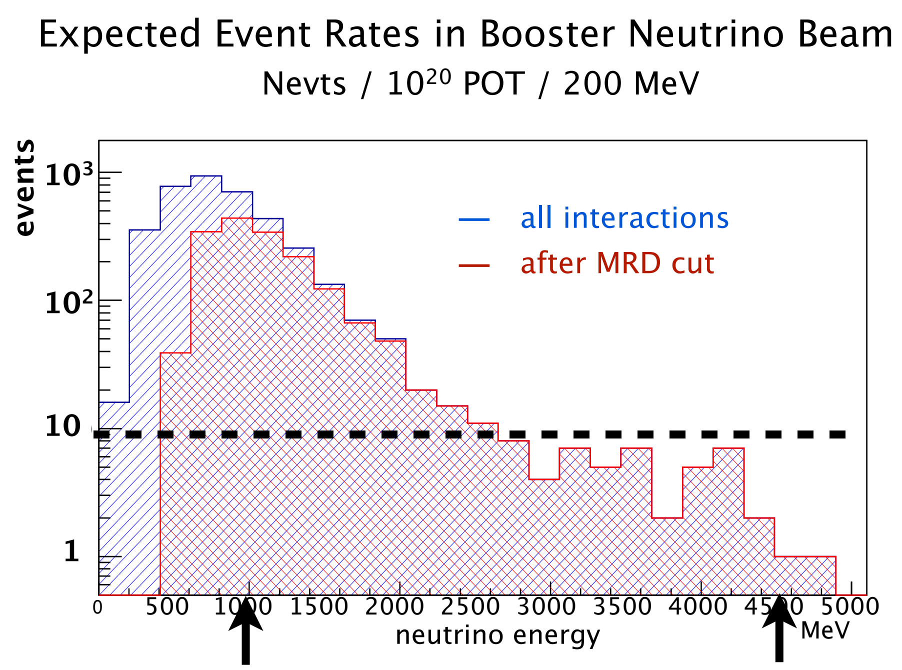
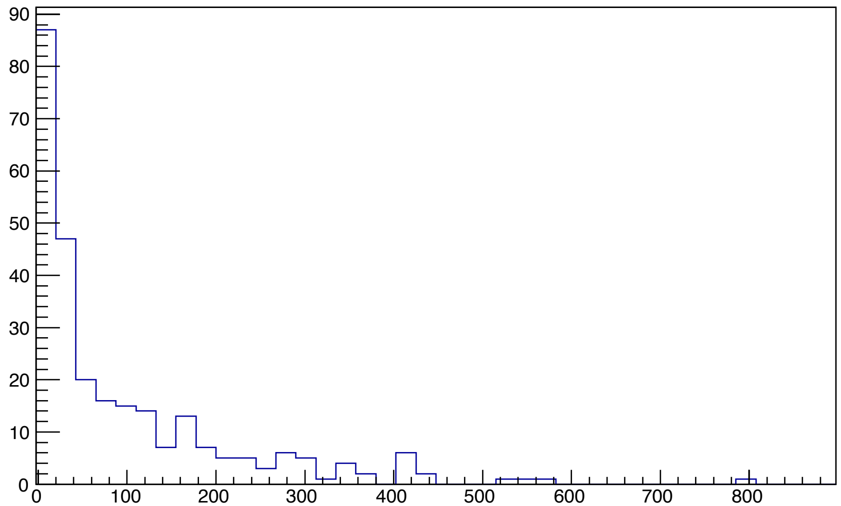
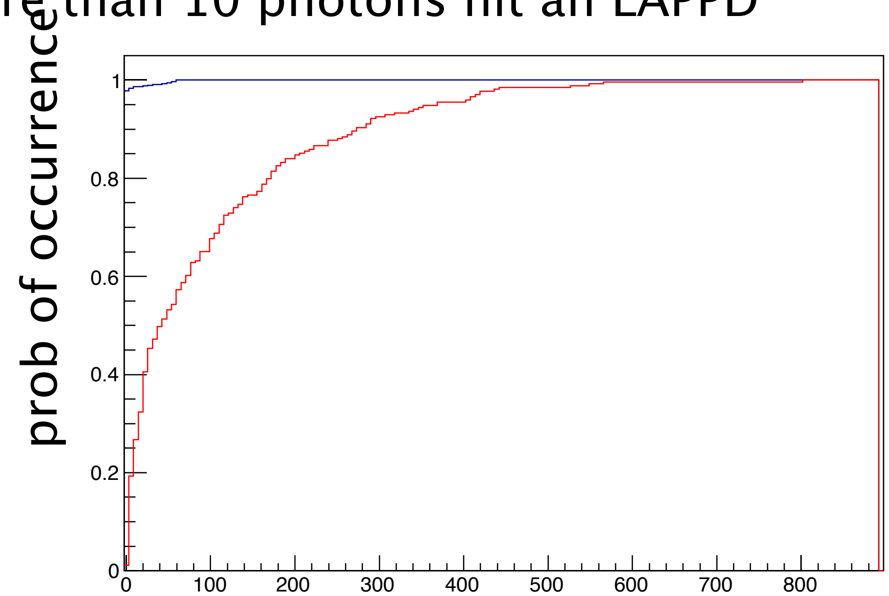




earliest point along a track where more than 10 photons hit an LAPPD

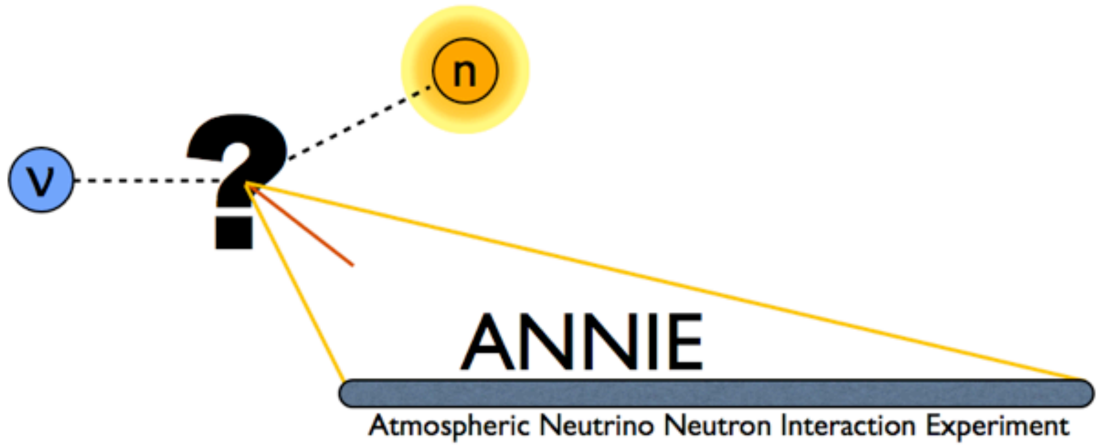


earliest point along a track where more than 10 photons hit an LAPPD

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).

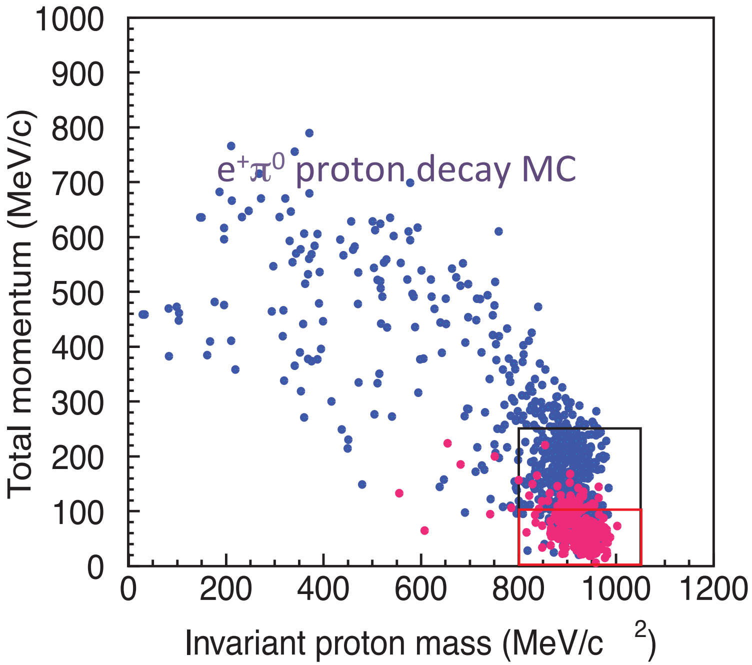
However, they also reduce the efficiency by a factor of 2

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?

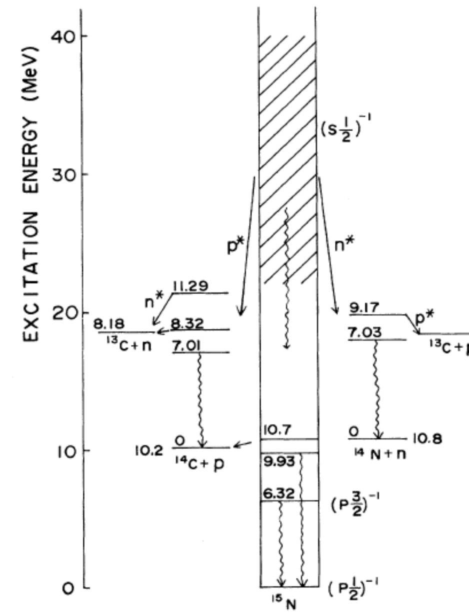
- For water, 20% of all protons are essentially free. If these decay, there is no neutron produced as the π^0 would decay before scattering in the water, and 400 MeV electrons rarely make hadronic showers that result in free neutrons.
- Oxygen is a doubly-magic light nucleus, and hence one can use a 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

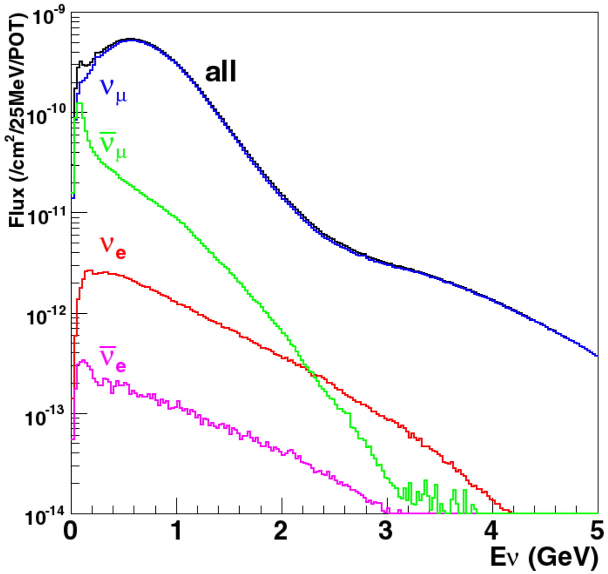
some gammas

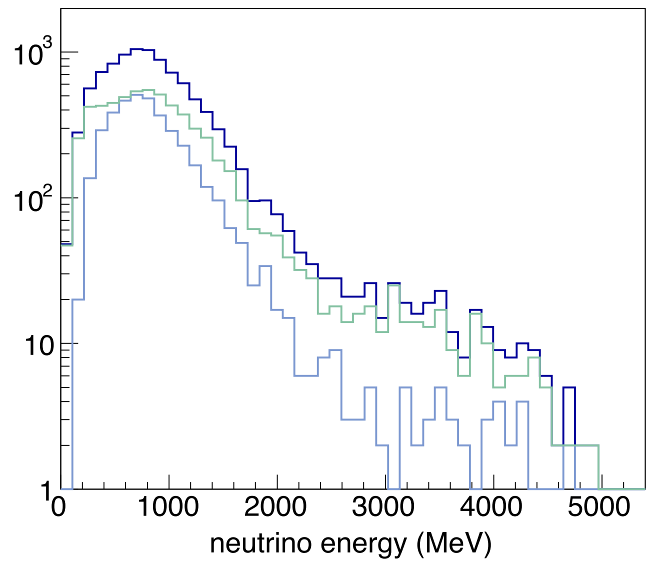
few neutrons

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 on Supernova Physics

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

events w/ neutron tag — events w/ NO neutron tag

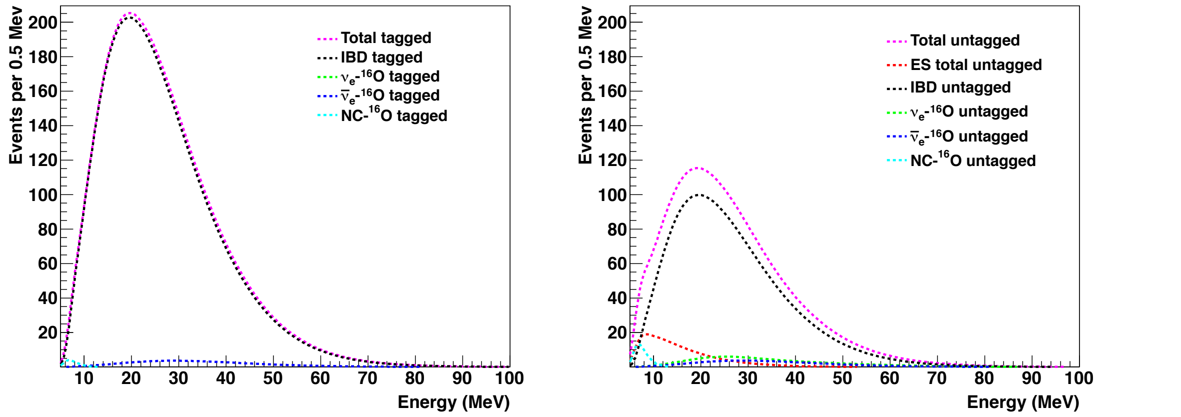


FIG. 46. Total events in WC showing contribution from the different interaction channels, for neutron-tagged (left) and untagged (right) events.

- 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.

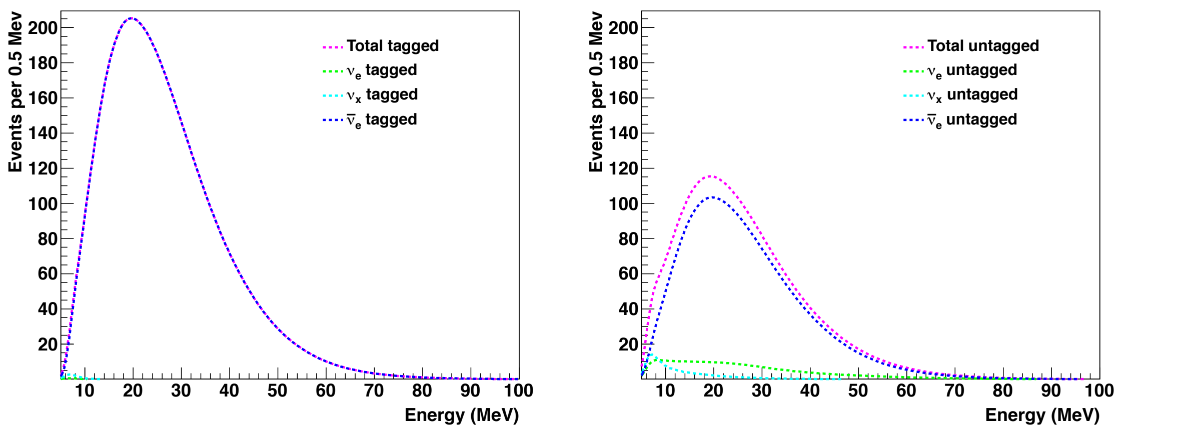
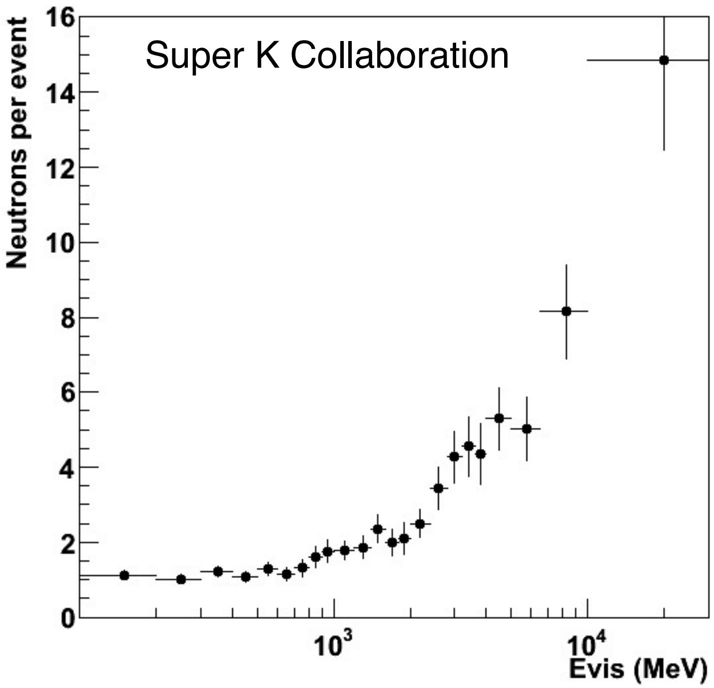


FIG. 47. Total events in WC showing contribution from the different flavors, for neutron-tagged (left) and untagged (right).

- 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, $\bar{\nu}_x$

Did Super Kamiokande Make This Measurement?

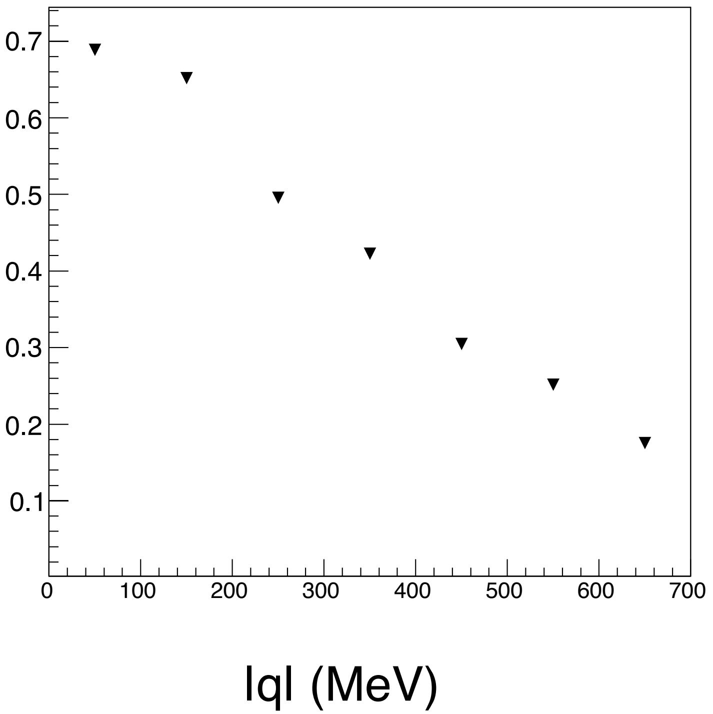


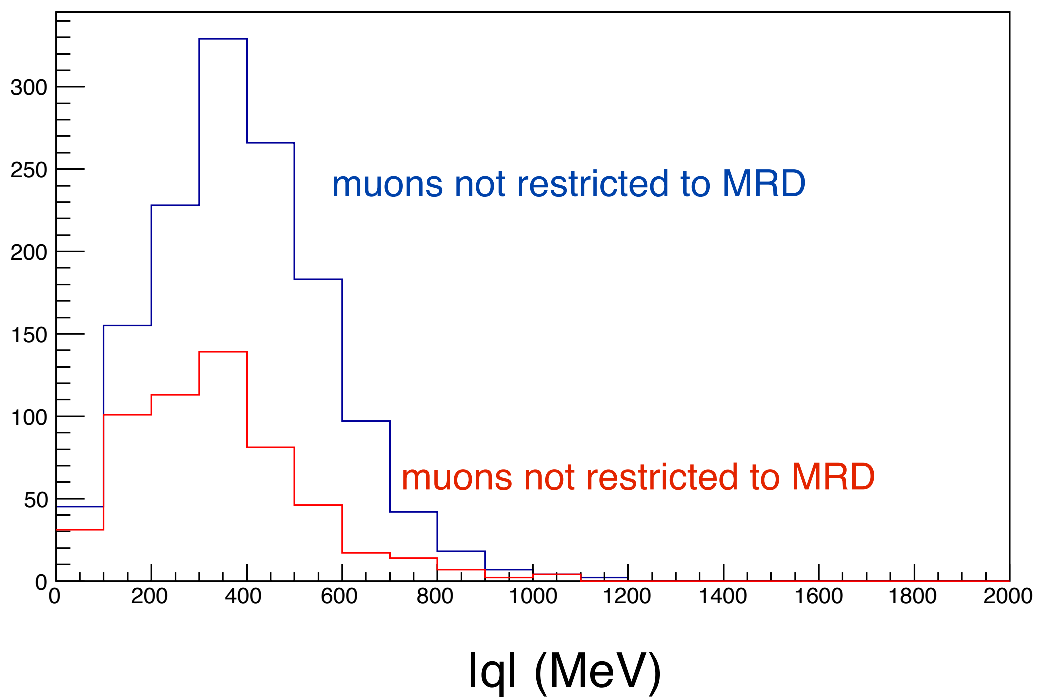
Yes, but not to an extent that they felt publishable:

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

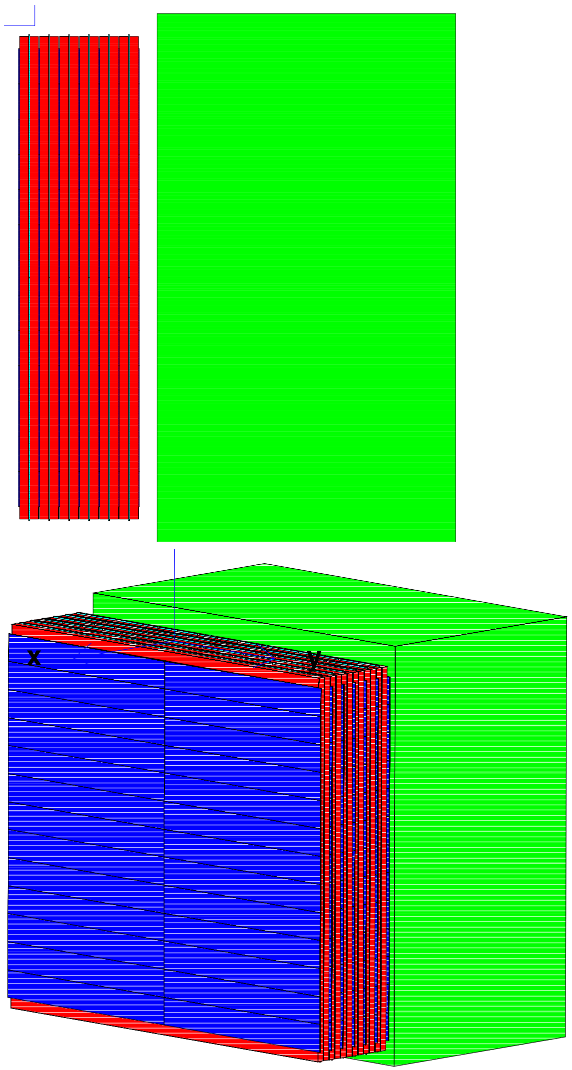
Nonetheless, this result is promising and strongly motivates a dedicated measurement.

efficiency for passing MRD cut





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.

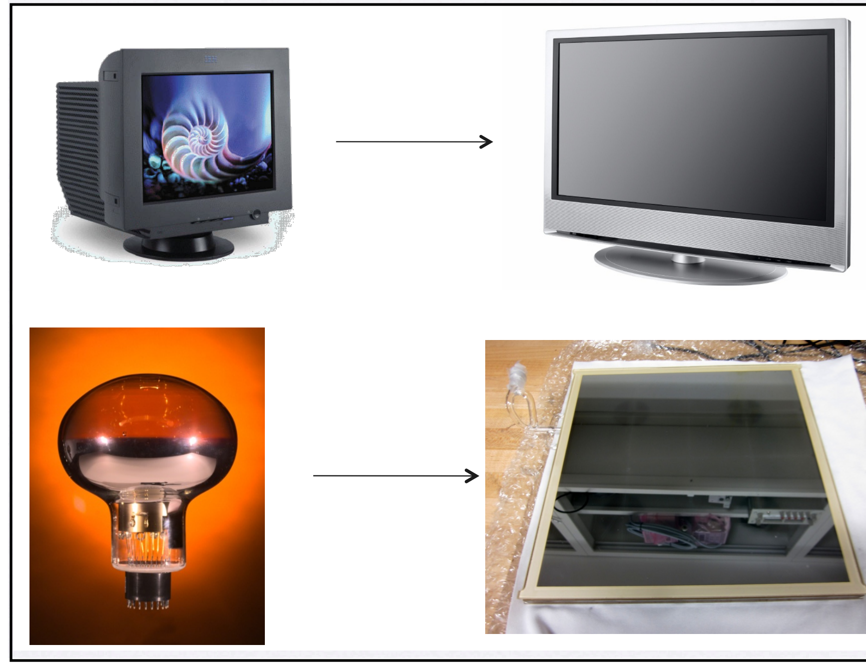
Price and availability?

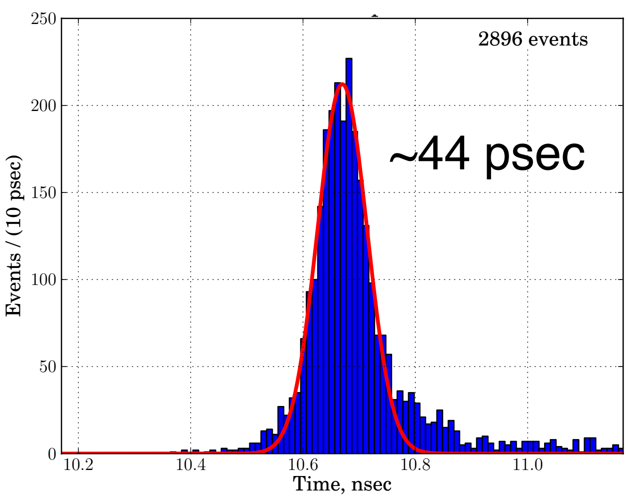
- Without a large market or economy of scale, we do not expect the first LAPPDs to be sold at what we hope the asymptotic price will be.
- Nonetheless, we expect them to be significantly cheaper per-unit-area than commercial MCPs
- We also hope, as early adopters, that Incom will be able to negotiate 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).

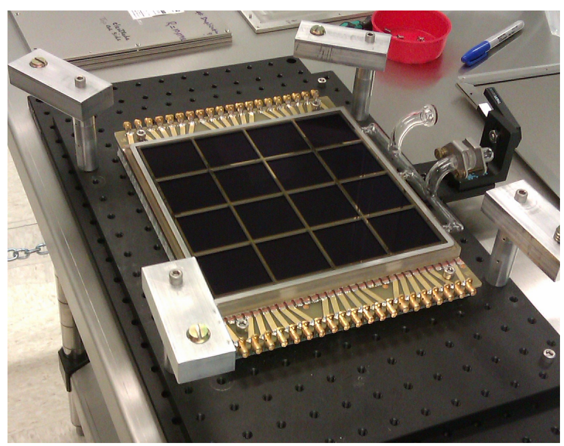
Adapting LAPPDs for Water Cherenkov Detectors

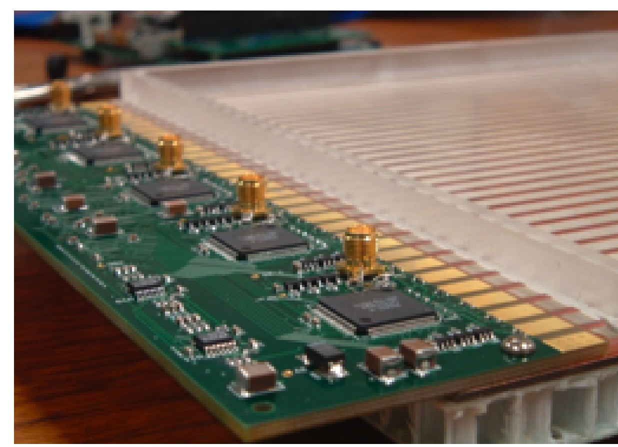
Subtasks:

- 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

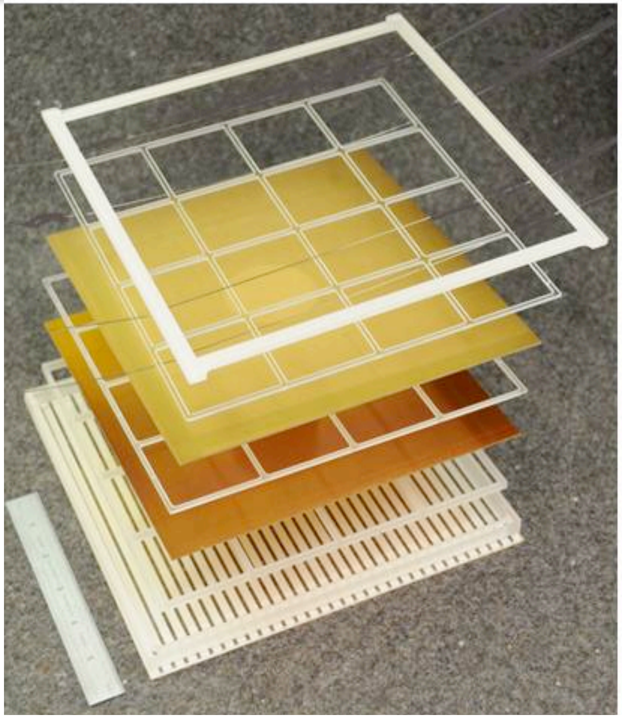


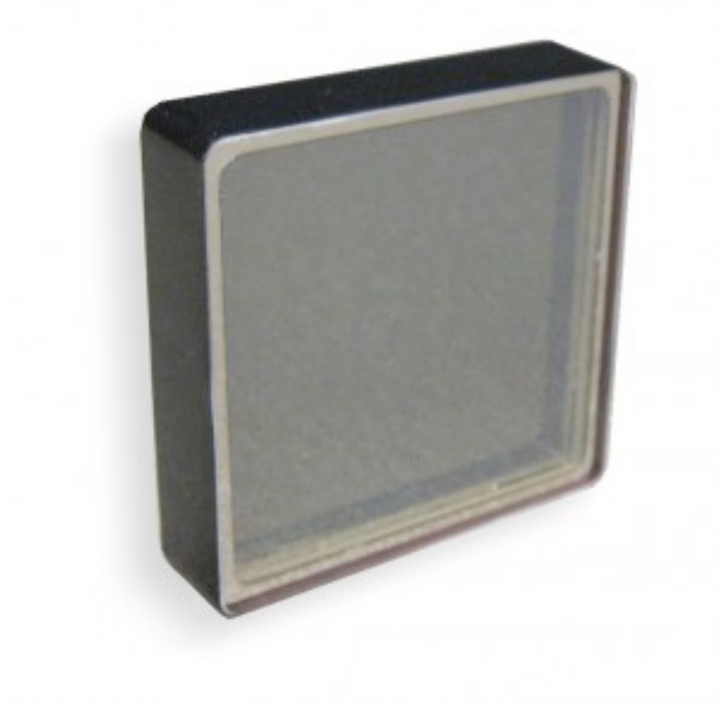






More on LAPPDs





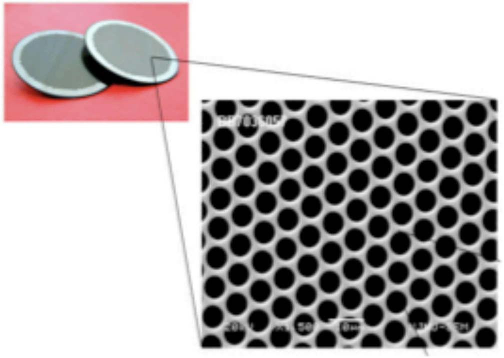
LAPPD detectors:

- 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

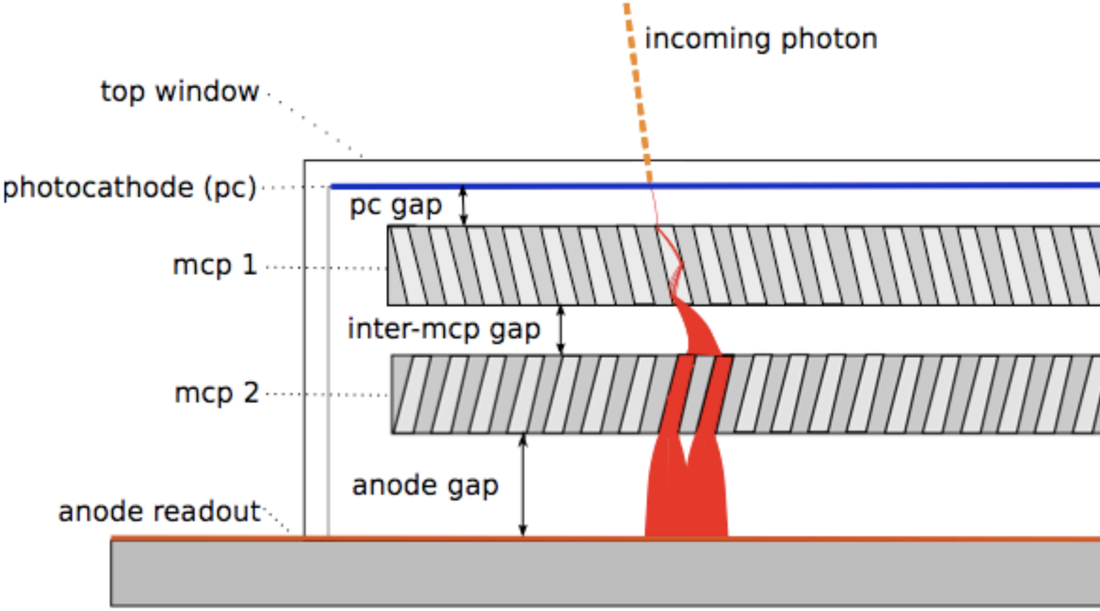
What is an MCP-PMT?



Microchannel Plate (MCP):

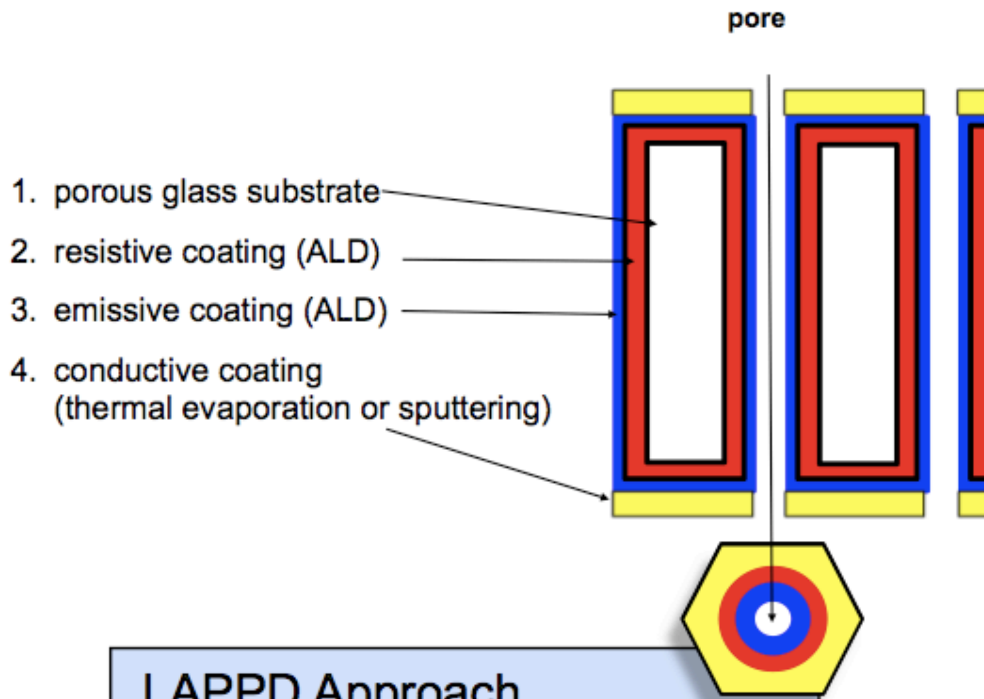
- a thin plate with microscopic (typically <50 μm) pores
- pores are optimized for secondary electron emission (SEE).
- Accelerating electrons accelerating across an electric potential strike the pore walls, initiating an avalanche of secondary electrons.

- 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



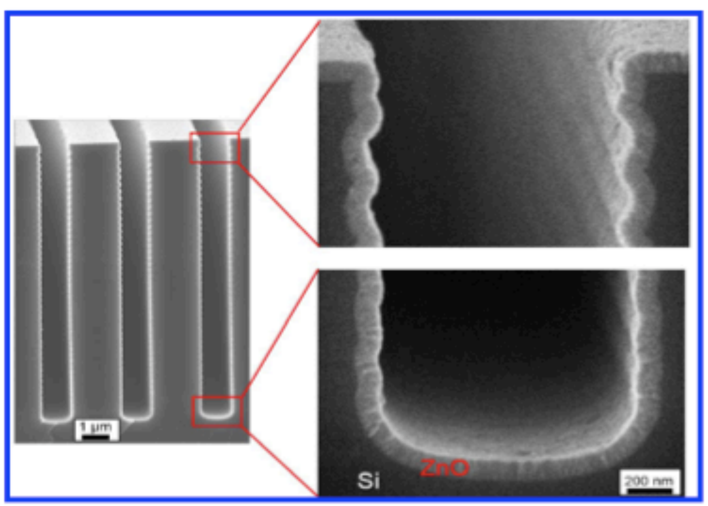
Our Approach

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).



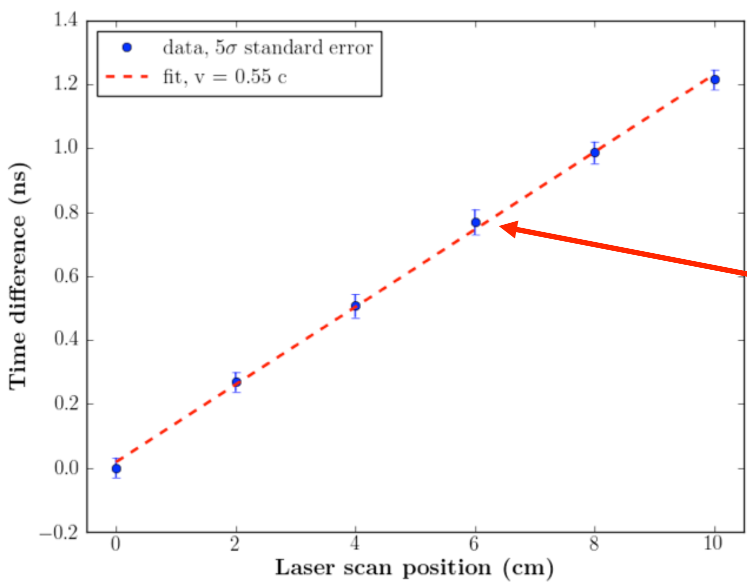
LAPPD Approach

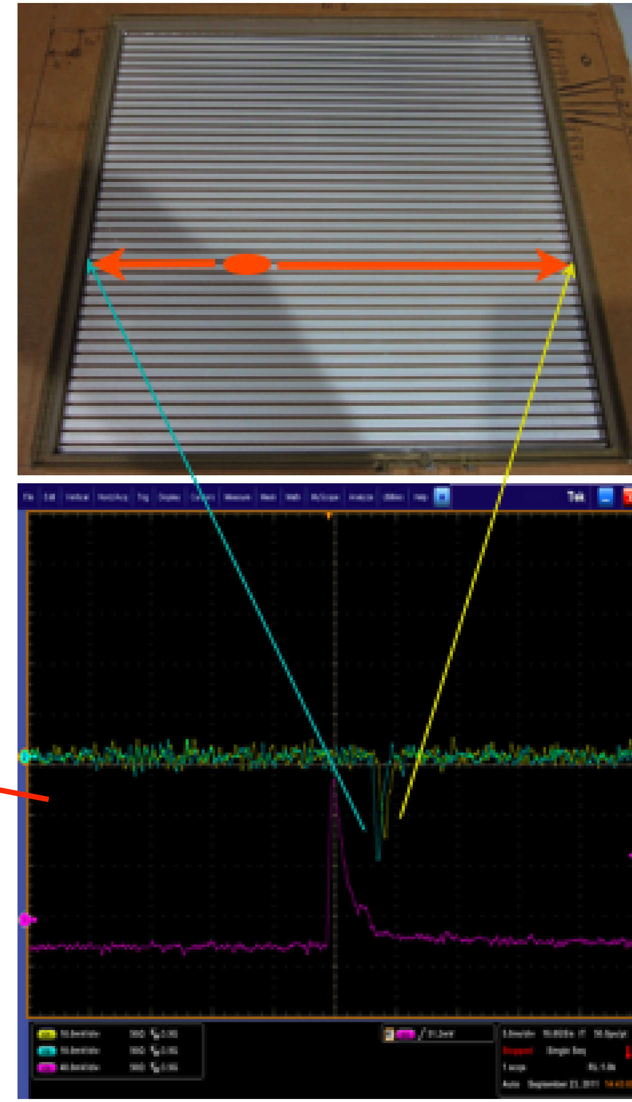
- Separate out the three functions
- Hand-pick materials to optimize performance.
- Use Atomic Layer Deposition (ALD): a cheap industrial batch method.
  - ALD is diffusive, conformal and allows application of material in single atomic monolayers

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



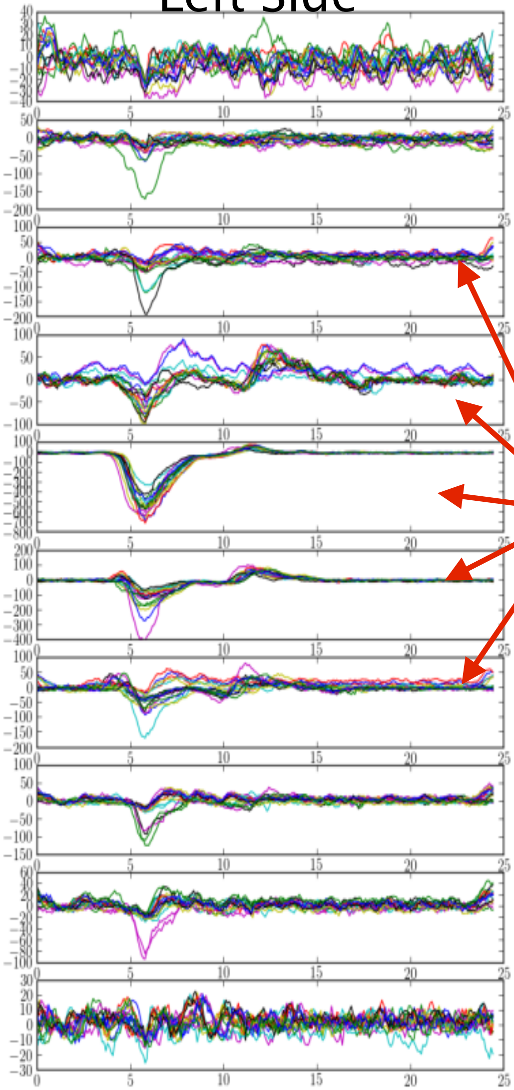


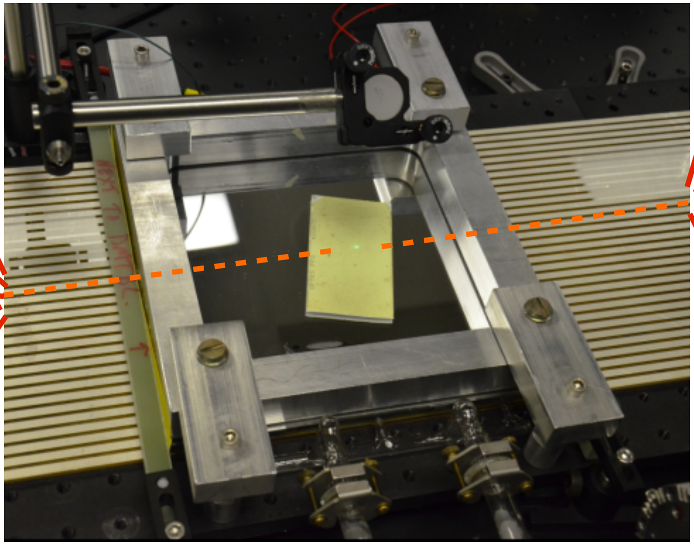
Slope corresponds to ~2/3 c propagations speed on the microstrip lines. RMS of 18 psec on the differential resolution between the two ends: equivalent to roughly 3 mm

Anode design

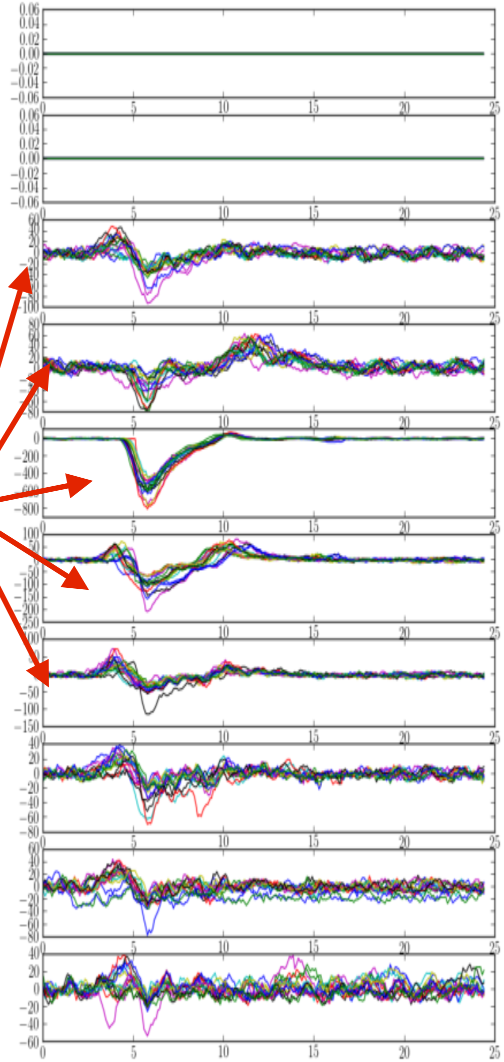
Transverse position is determined by centroid of integrated signal on a cluster of striplines.

Pulses on 10 striplines
Left Side





Credit: Eric Oberla

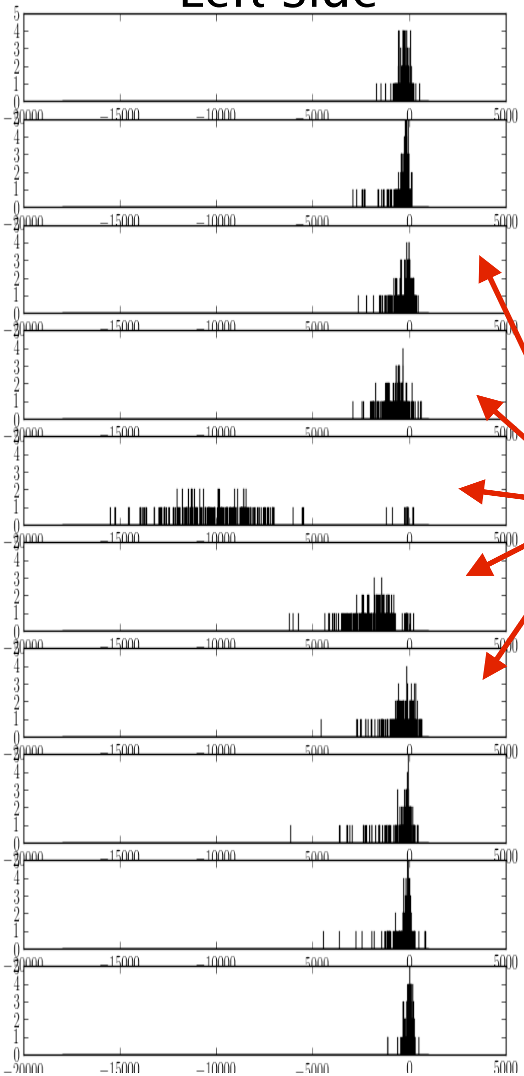


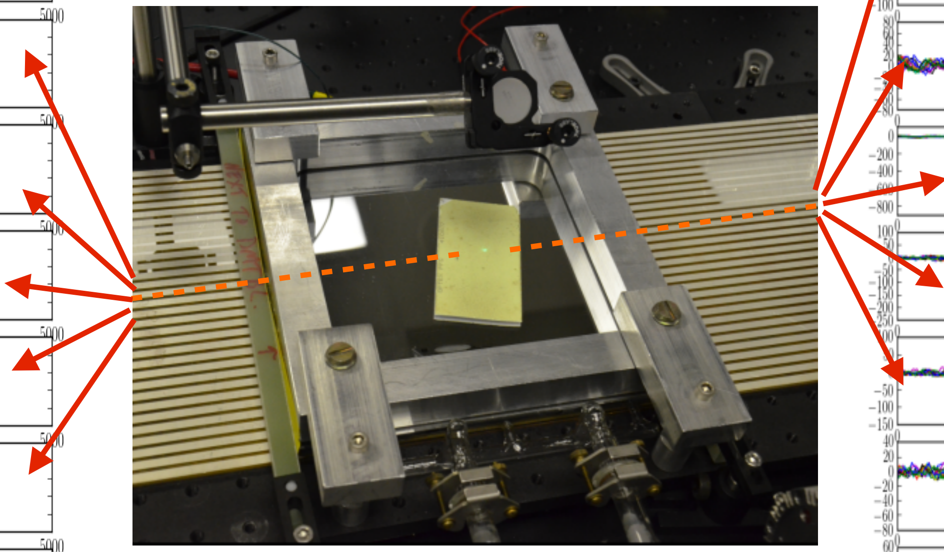
Right Side
Pulses on 10 striplines

Anode design

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

Pulse Heights (ADC counts)
Left Side





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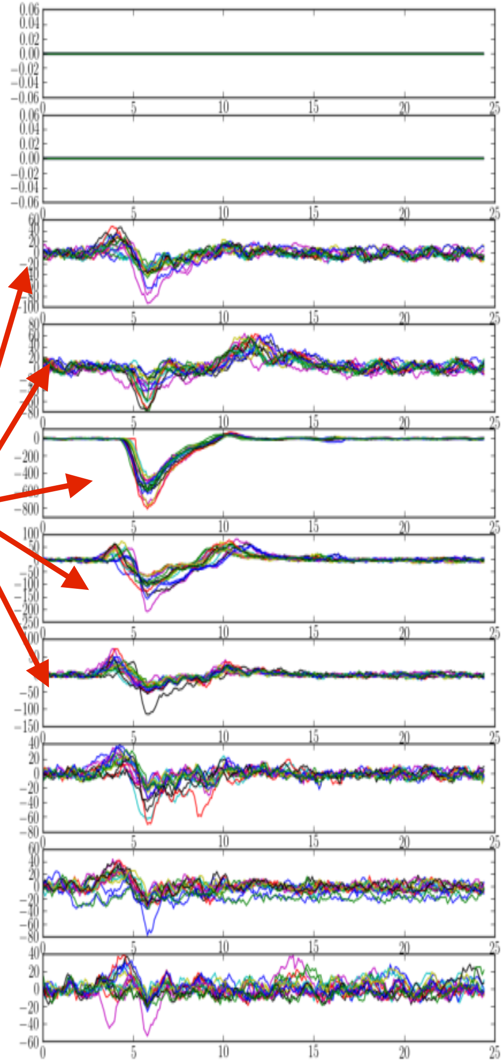
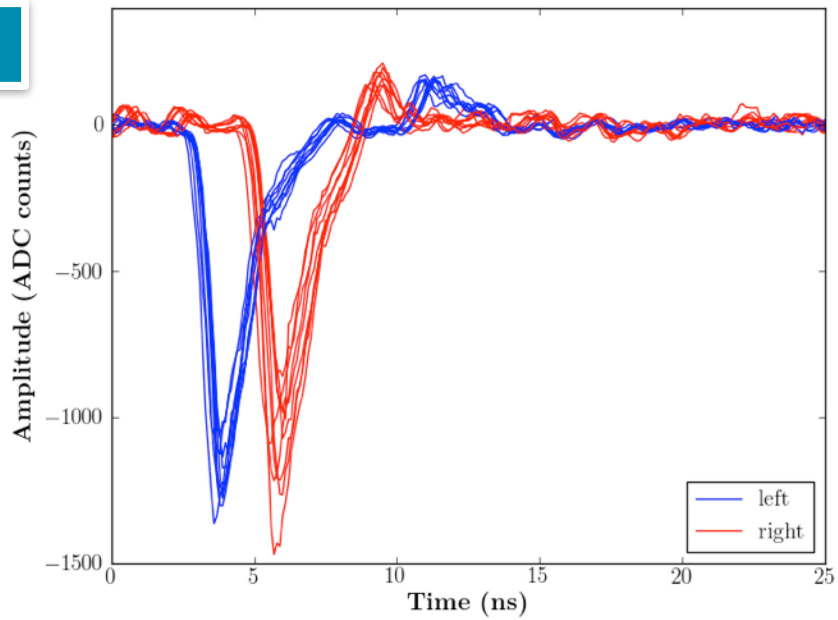
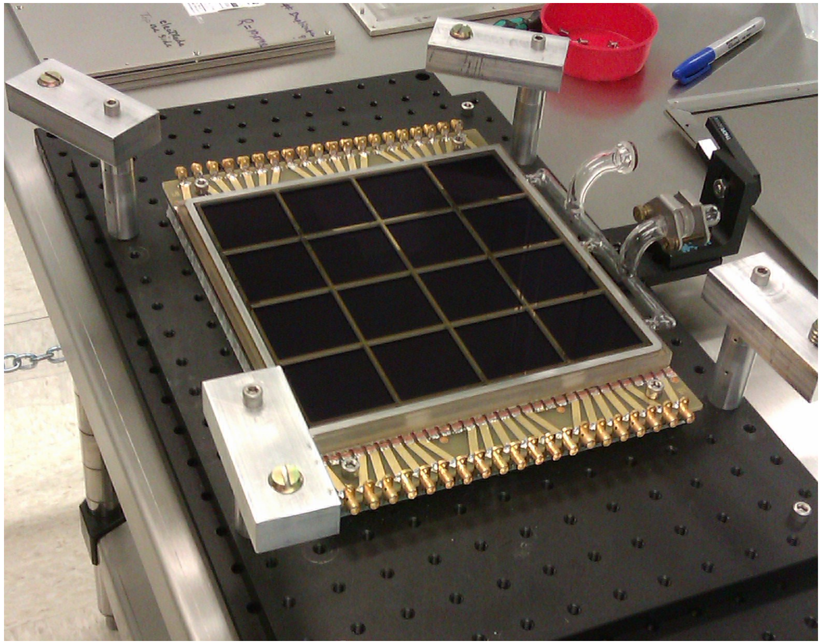
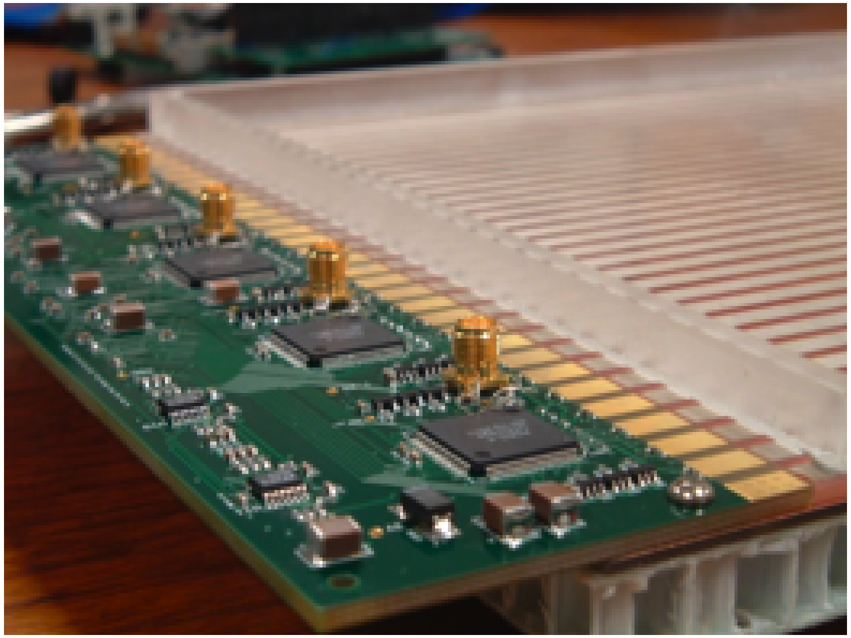


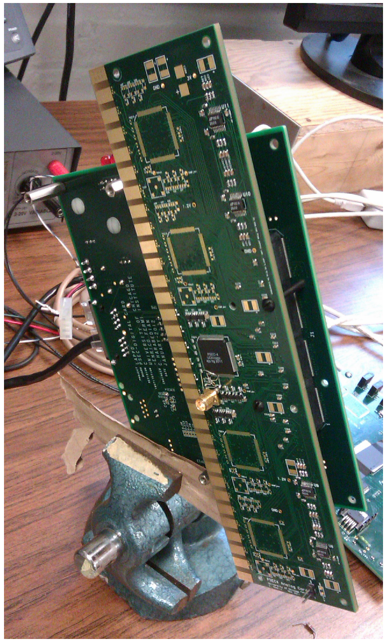
Right Side
Pulses on 10 striplines

LAPPD





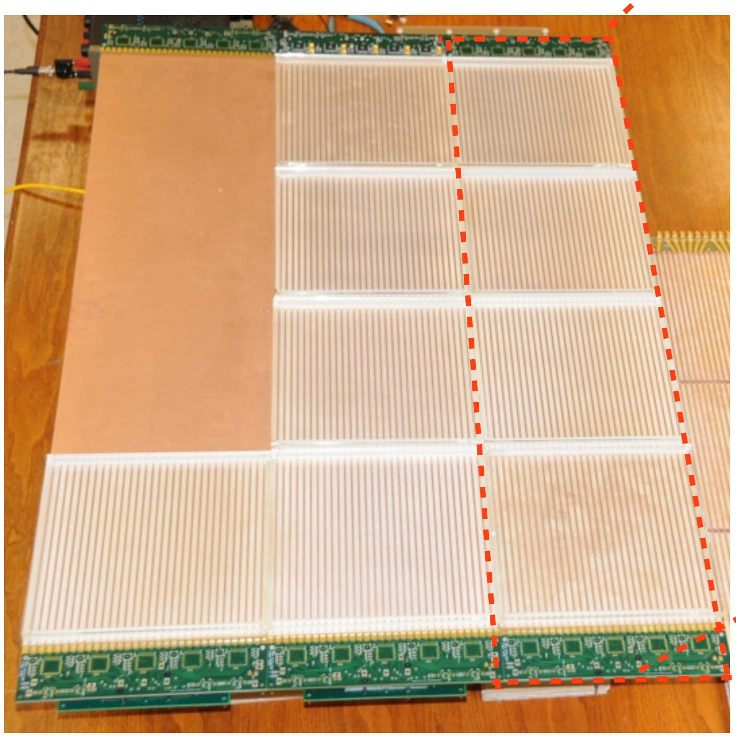


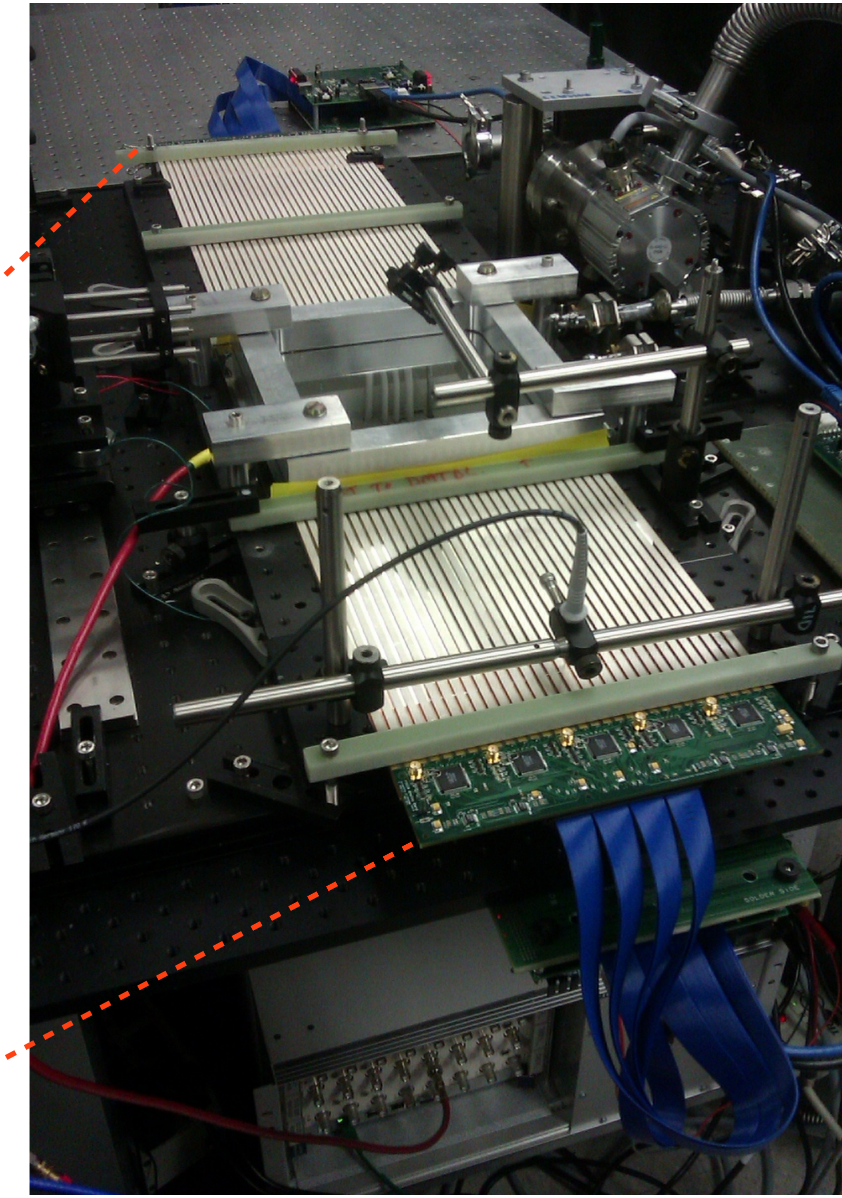


- LAPPD Goal of building a **complete detector system**, including even waveform sampling front-end electronics
- Now testing near-complete glass vacuum tubes ("demountable detectors") with resealable top window, robust aluminum photocathode

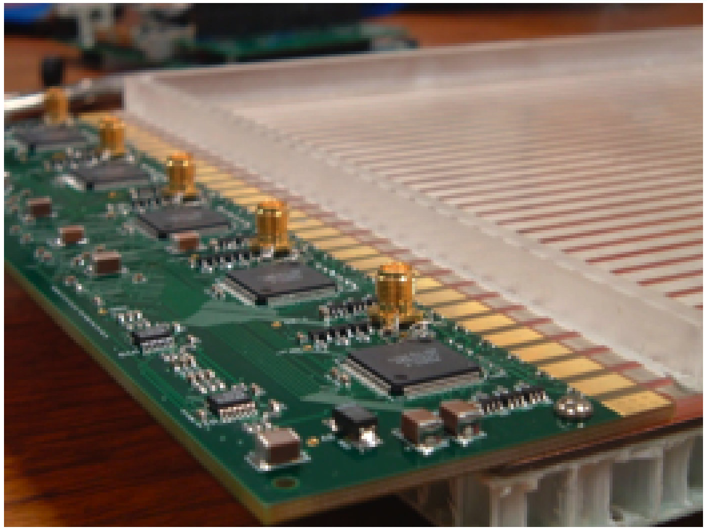
"SuMo Slice"

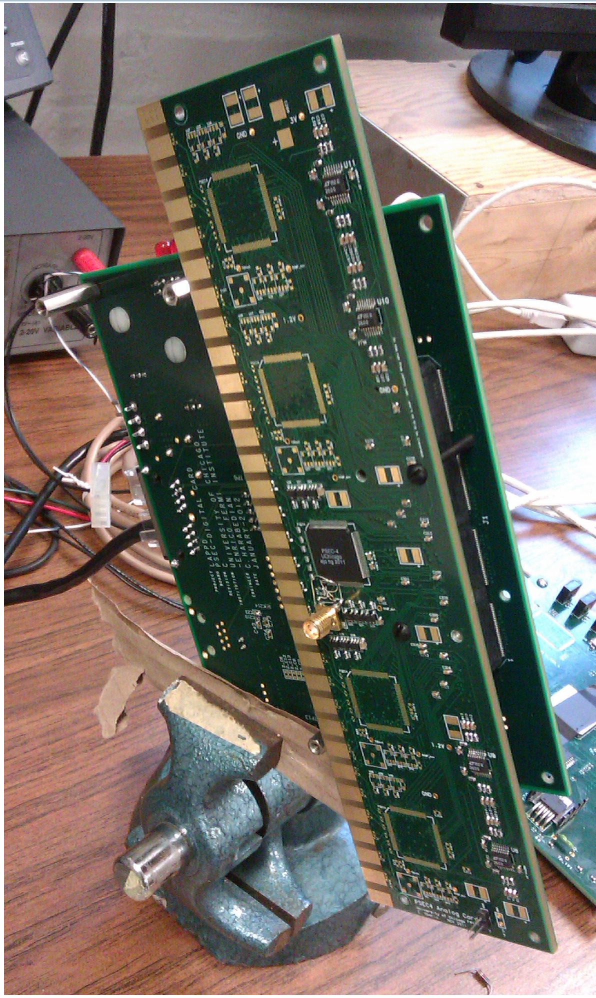
We are now testing a functional demountable detector with a complete 80 cm anode chain and full readout system ("SuMo slice").





Front-end Electronics





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

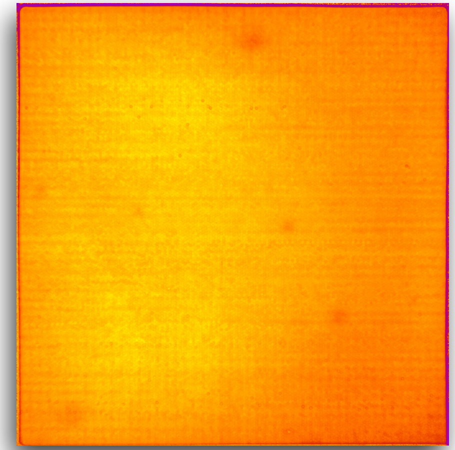
Analog Card:
- Readout for one side of 30-strip anode
- 5 psec chips per board
- Optimized for high analog bandwidth (>1 GHz)

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

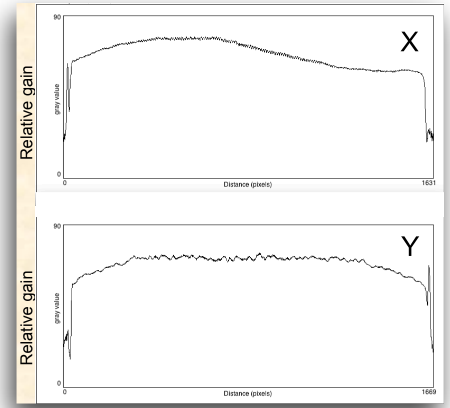
Central Card:
- Combines information from both ends of multiple striplines

We observe:

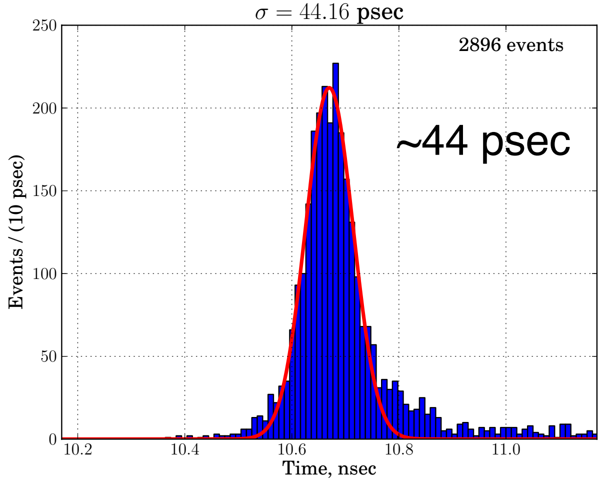
- Typical gains of $O(10^7)$
- Single photoelectron time resolutions of ~40 picoseconds.
- Timing in the many-photoelectron limit approaching single picoseconds

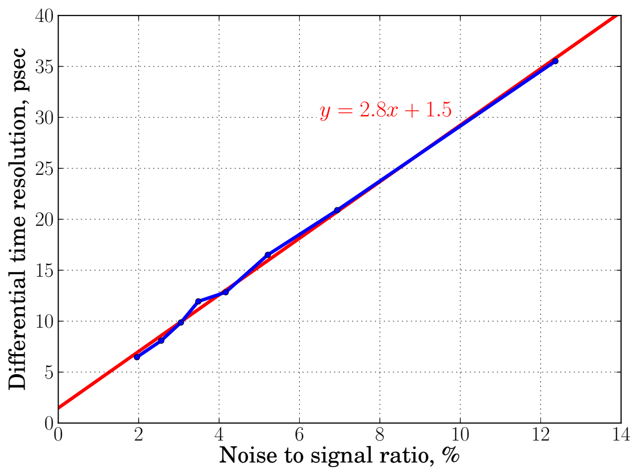


Berkeley SSL



ANL – MCP timing lab





Full Track Reconstruction: A TPC Using Optical Light?

1. Signal per unit length (before attenuation)

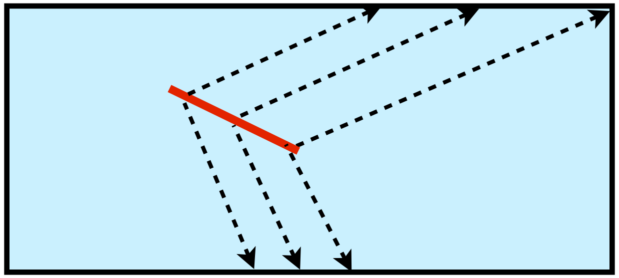
   ~20 photons/mm (Cherenkov)

2. "Drift time" (photon transit time)

   ~225,000mm/microsecond

3. Topology

   drift distances depend
   on track parameters



4. Optical Transport of light in water

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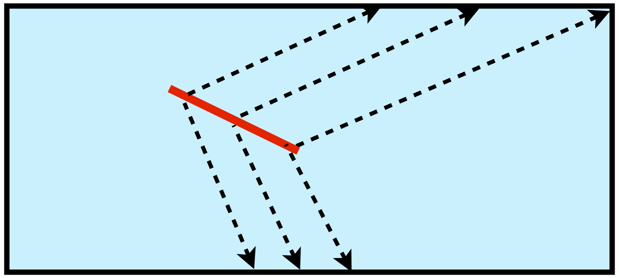


4. Optical Transport of light in water

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

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

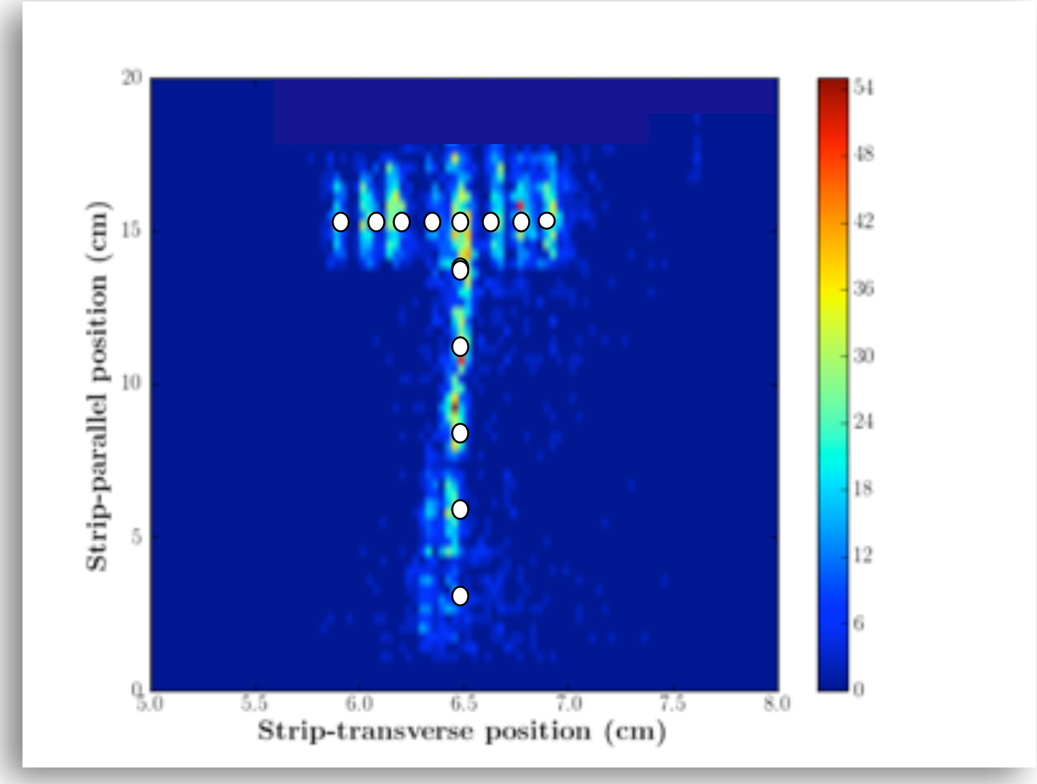
This presents some reconstruction challenges, but not unconquerable.

Appropriate reconstruction techniques are needed.

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

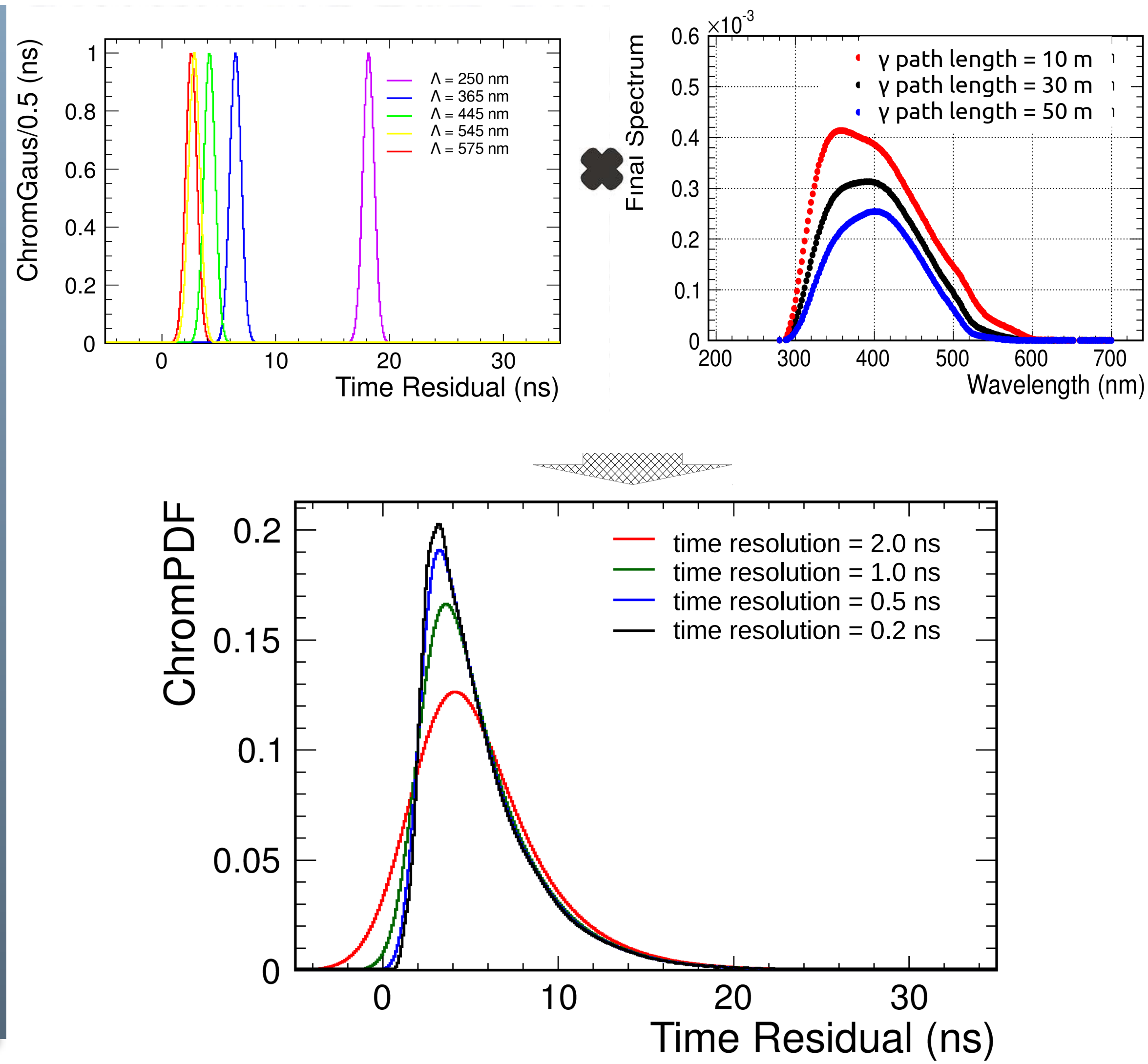
- Measure a single time-of-first-light and a multi-PE blob of charge
- Likelihood is factorized into separate time and charge fits
- History of the individual photons is washed out

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

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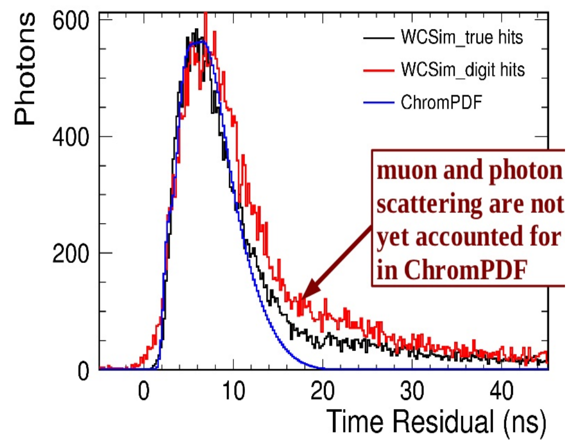
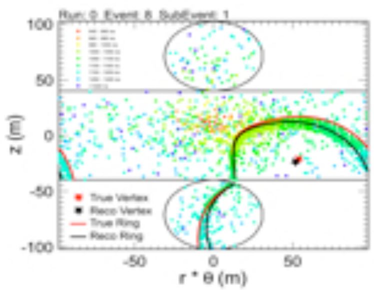
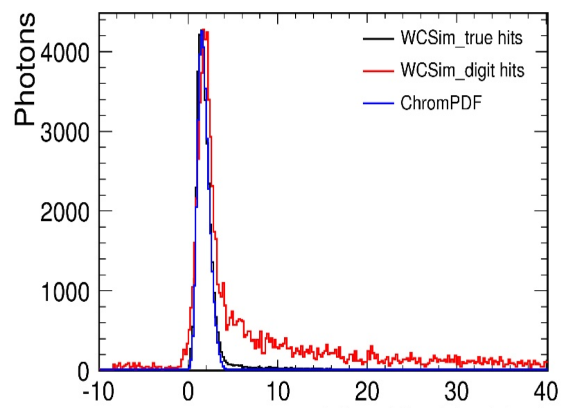
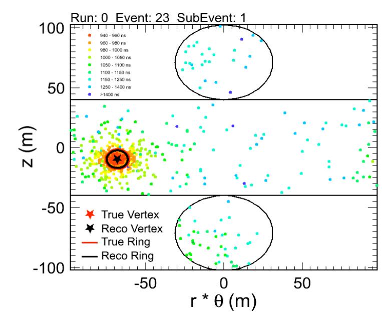






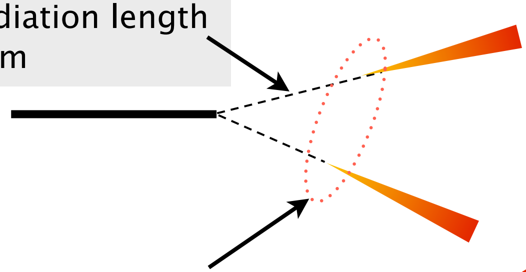


Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

Simple Vertex Reconstruction

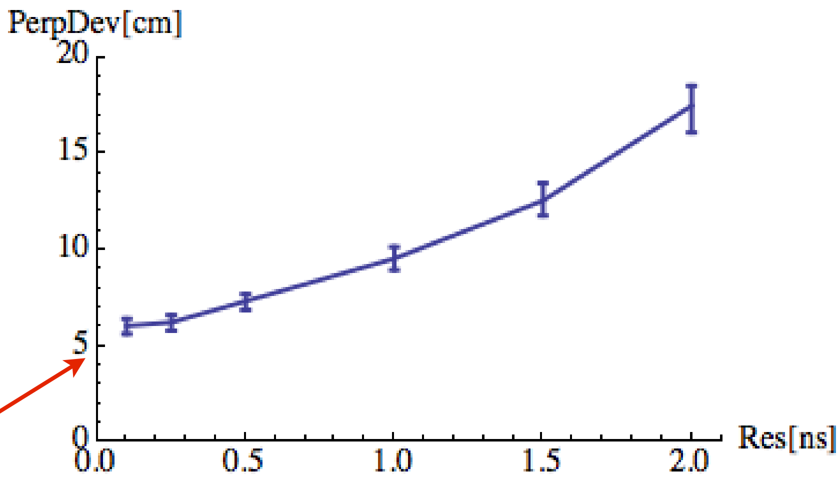
- Transverse component of the vertex (wrt to track direction) is most sensitive to pure timing since T0 is unknown.
- Separating between multiple vertices depends on differential timing (T0 is irrelevant)
- We study the relationship between vertex sensitivity and time resolution using GeV muons in water. 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

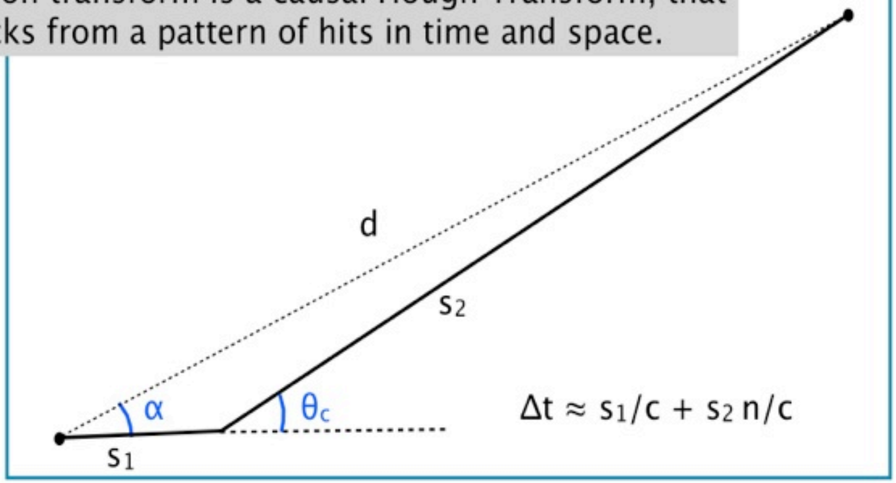
Optical TPCs are scalable to 100s of kilotons



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

Isochron

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



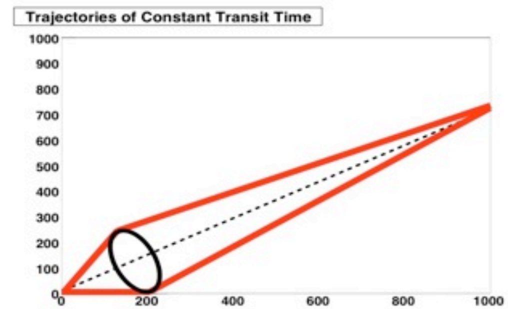
Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns:

s_1 and α

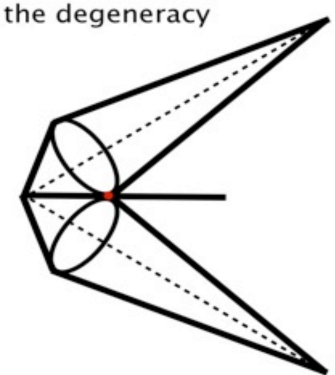
but there are two constraints:

$s_1 + s_1 = d$ 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

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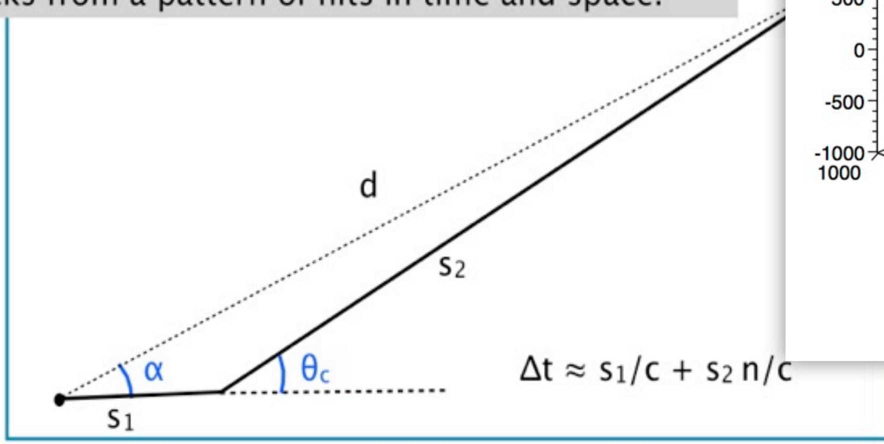

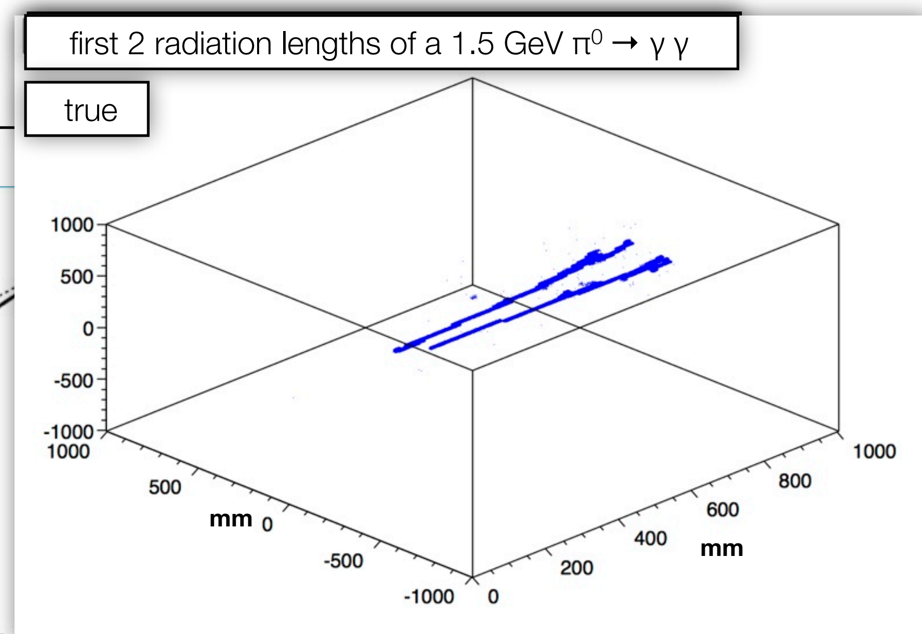

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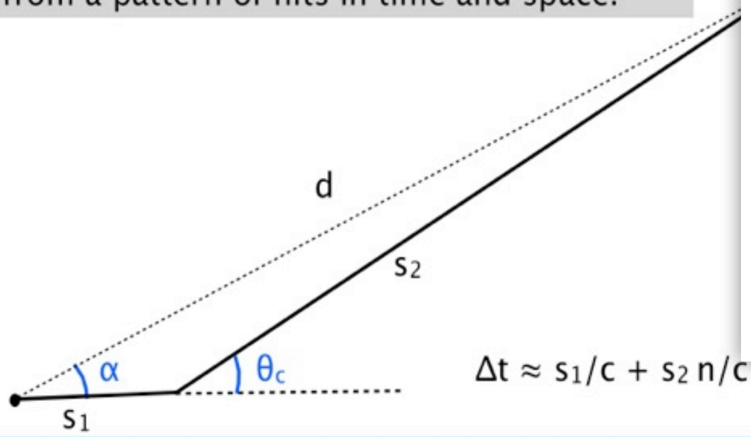

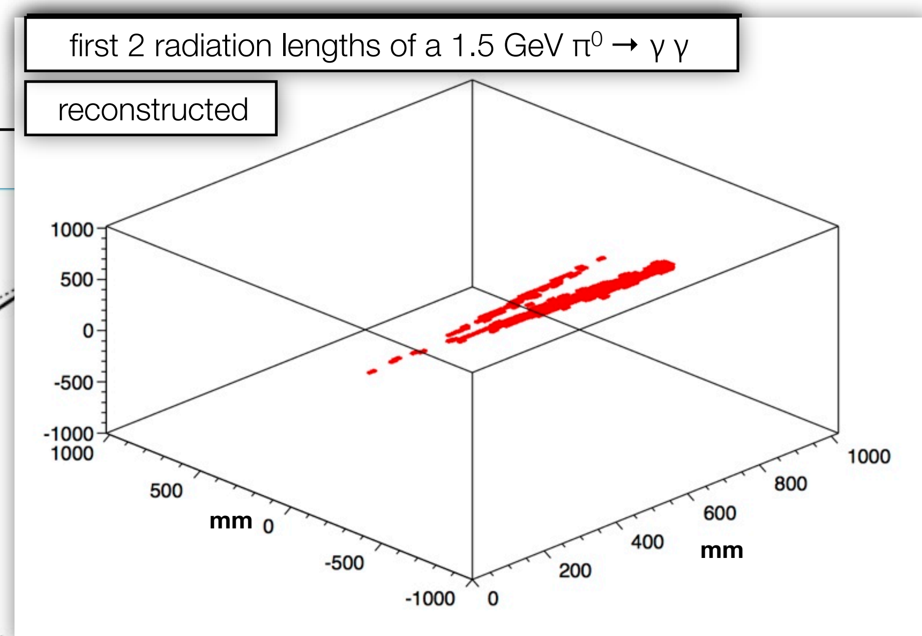

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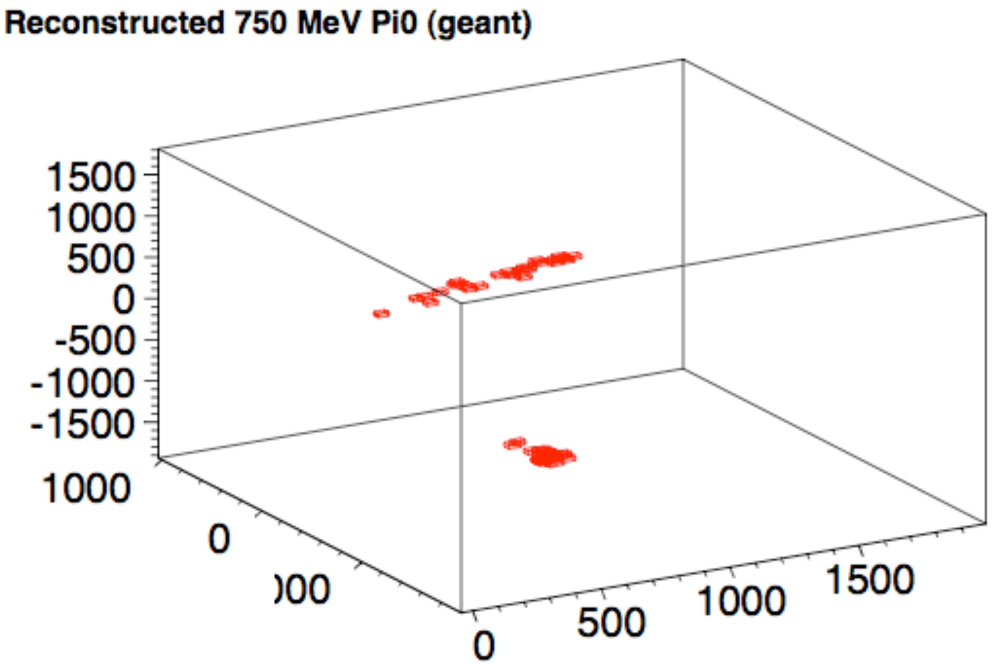
but there are two constraints:

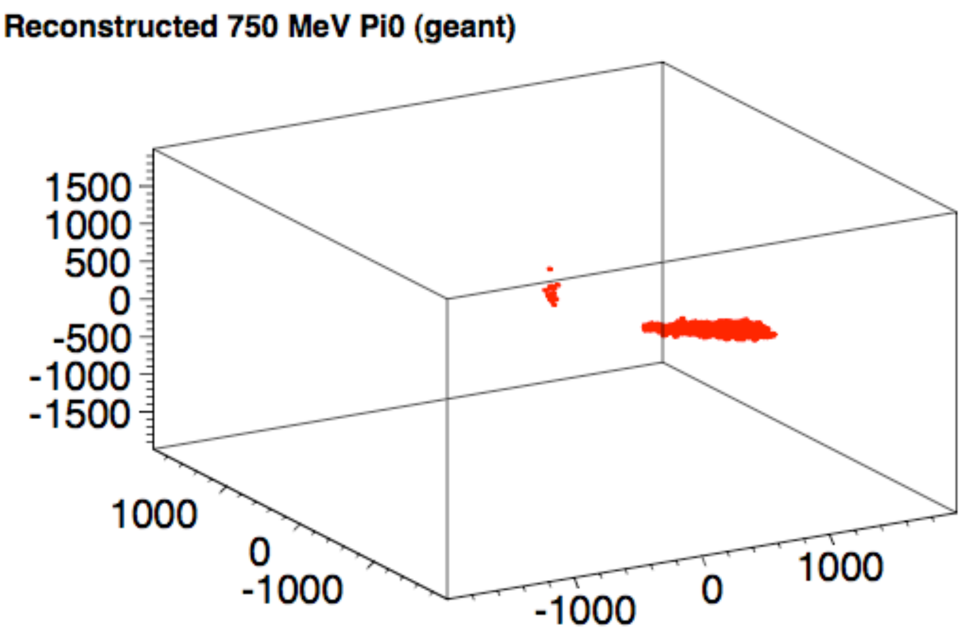
$s_1 + s_1 = d$ and $\Delta t_{measured} = s_1/c + s_2\, n/c$

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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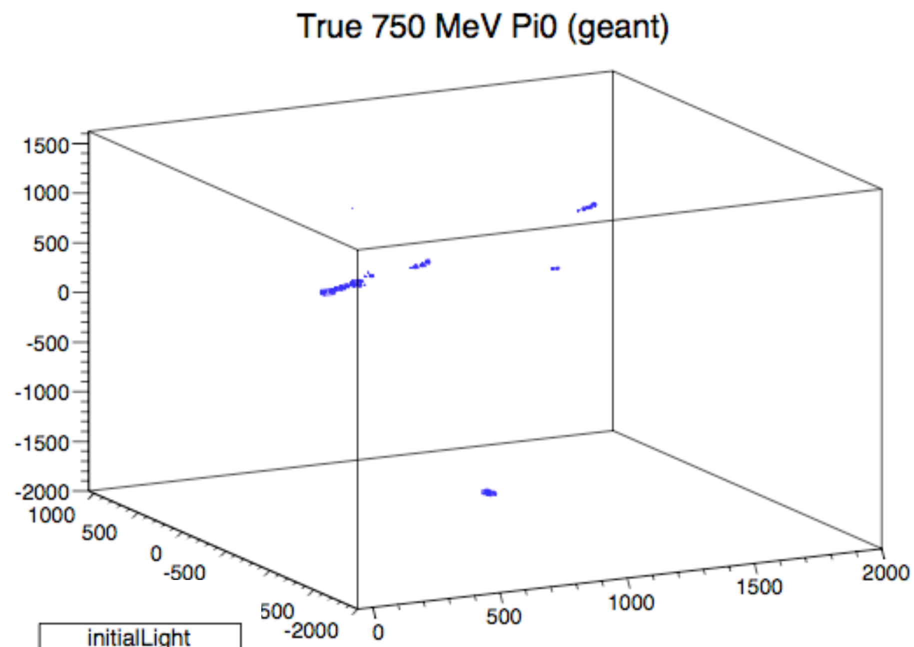
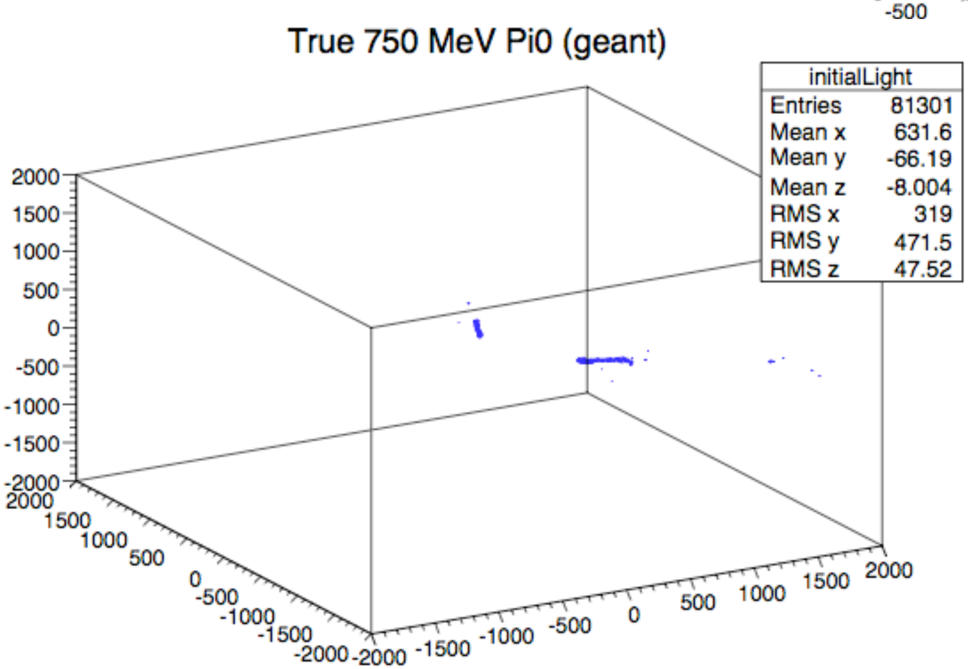
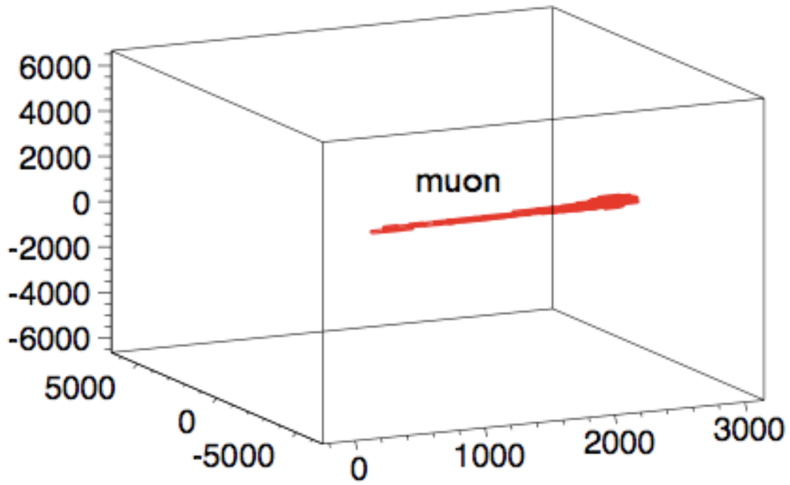
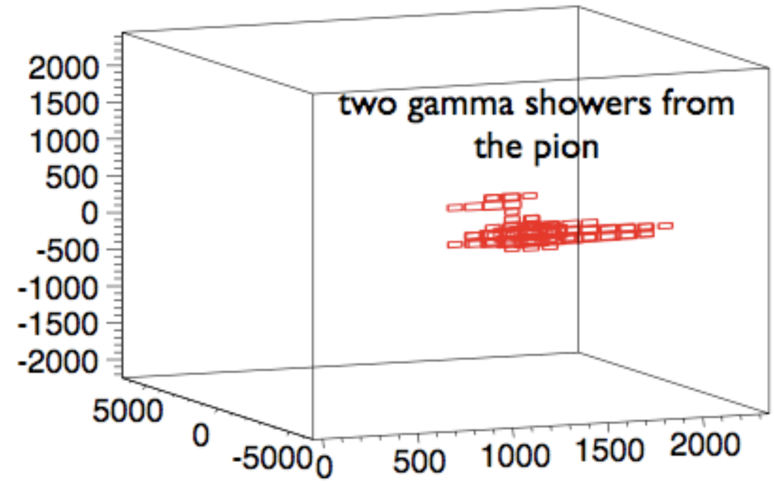
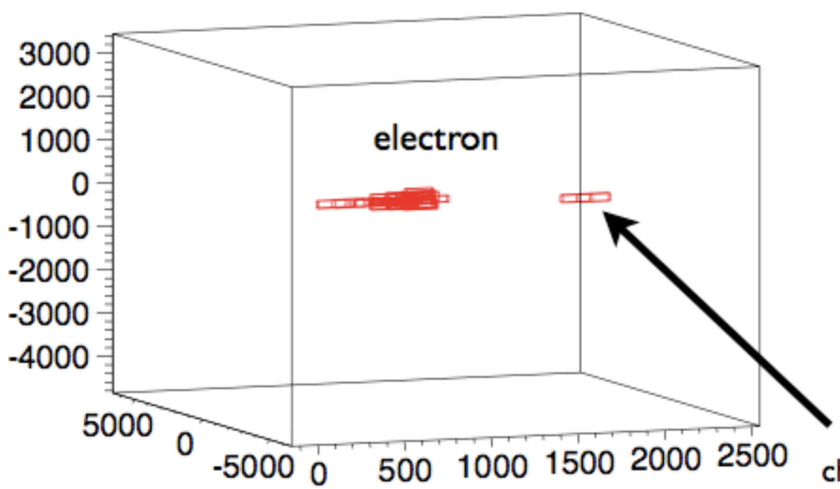




Reconstructing Geant Events







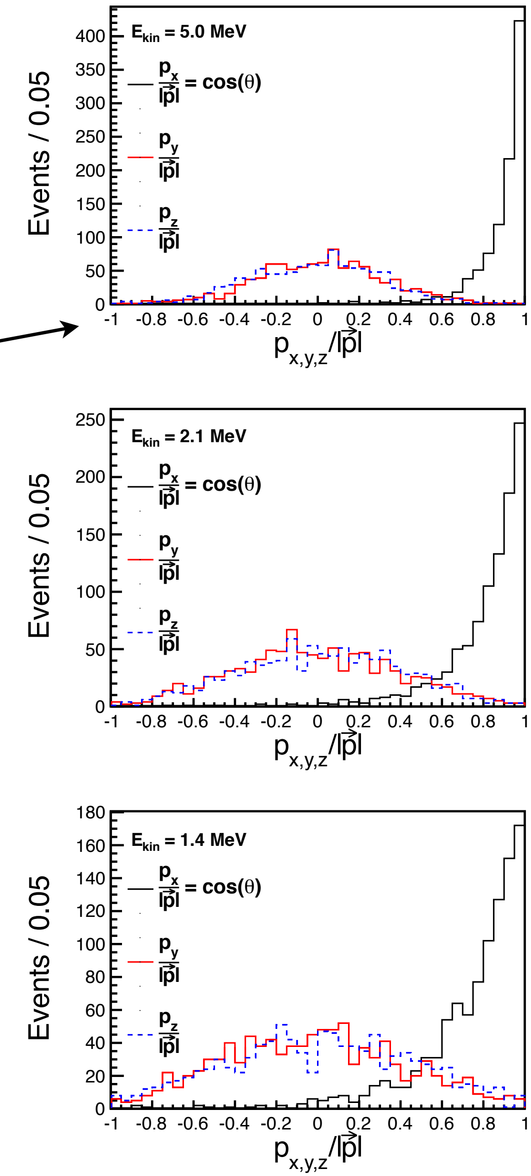
check out the detached shower from the bremstrahlung!!!

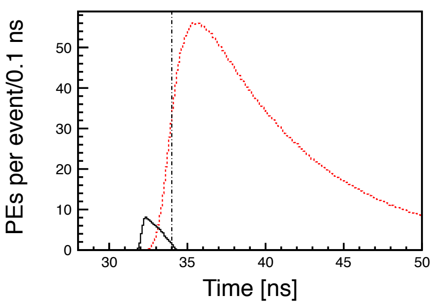
Optical TPC with scintillator

Optical TPC concept is more general than pure Cherenkov.

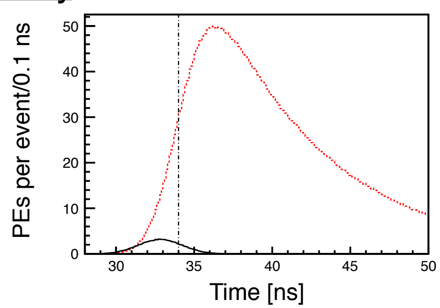
It may be possible to use timing to separate between Cherenkov and scintillation light in liquid scintillator volumes, capitalizing of the advantages of each separately.

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

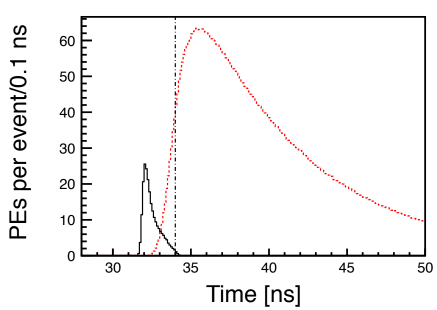




(a) Default simulation.



(b) Increased TTS (1.28 ns).



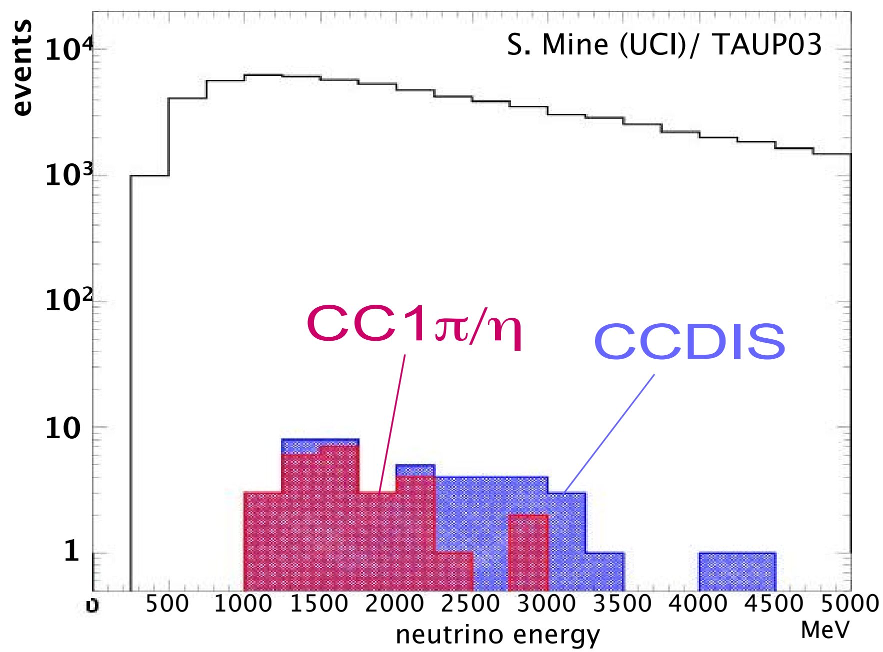
(c) Red-sensitive photocathode.

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

The Booster Neutrino Beam Delivers The Needed Flux

- 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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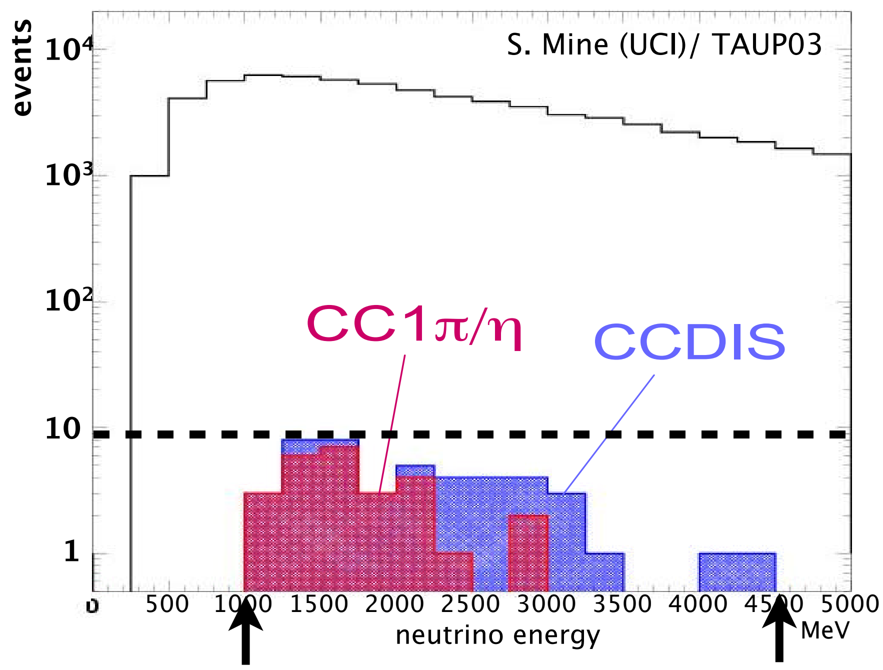

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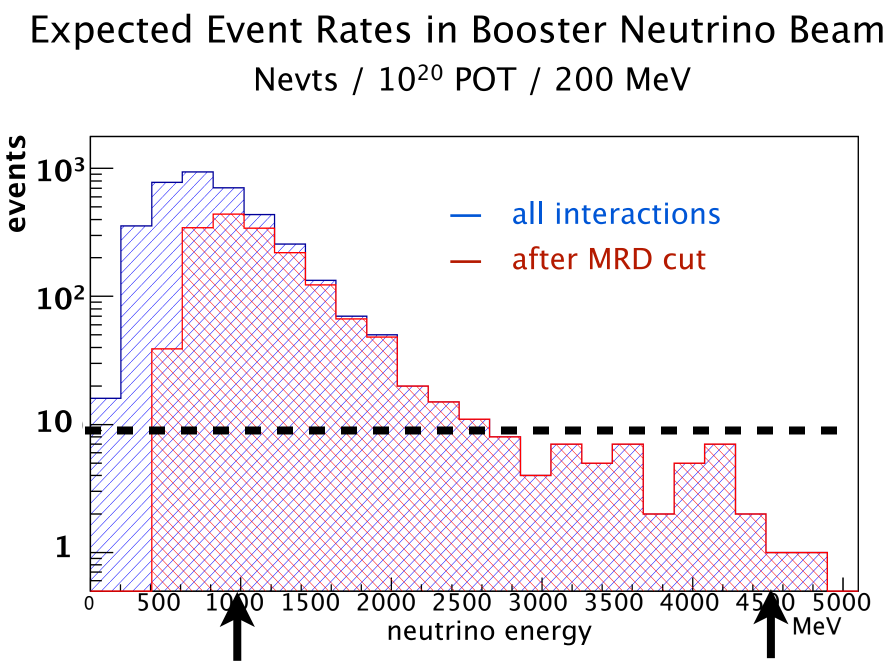
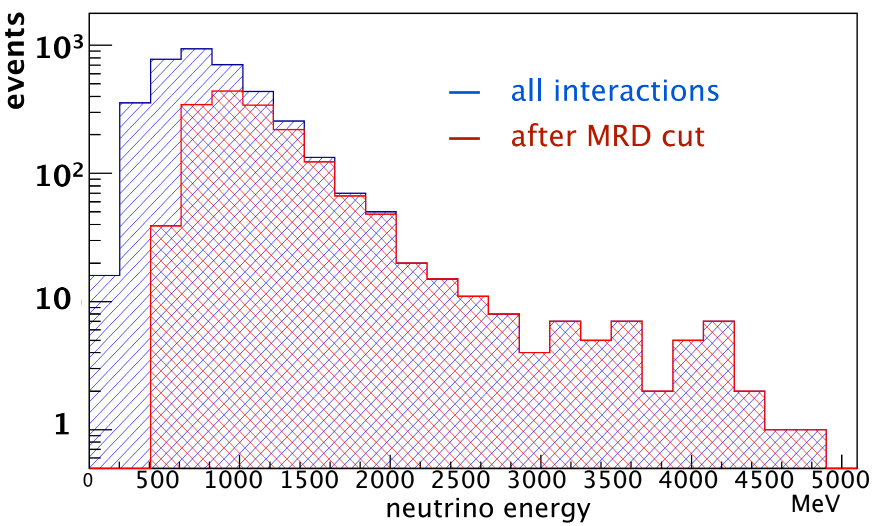


The Booster Neutrino Beam Delivers The Needed Flux

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

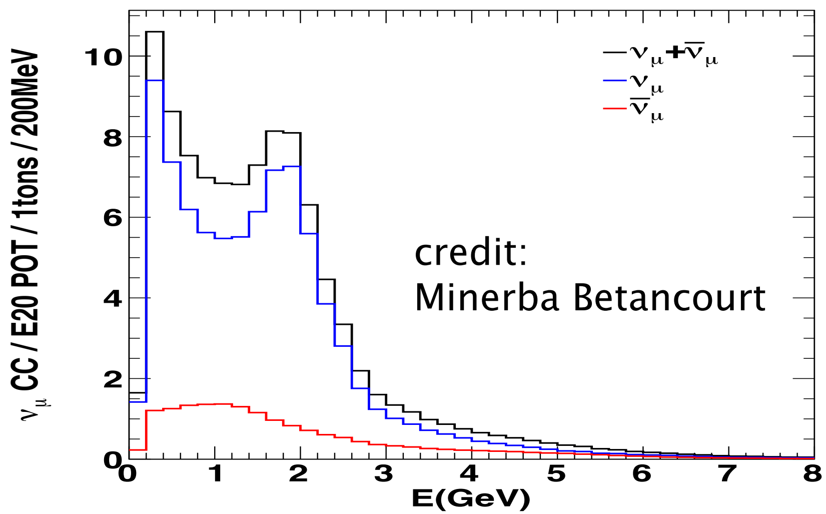


~500 events per ton/1e20 POT/200 MeV at 1 GeV

~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