Backup Slides

LAPPDs

FURTHER READING:
A Brief Technical History of the Large-Area Picosecond Photodetector (LAPPD) Collaboration

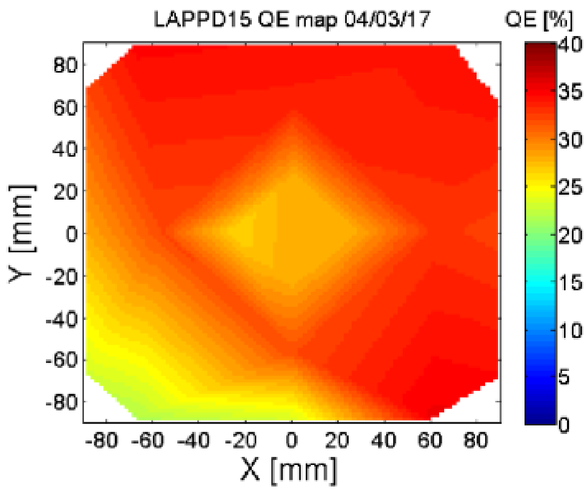
http://arxiv.org/abs/1603.01843

INCOM TILES

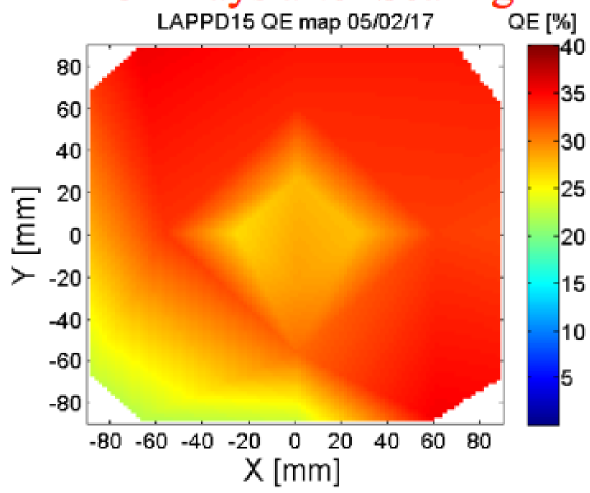
INCOM PERFORMANCES ACHIEVED	
TILE #9 – Sealed Sept 14, 2016 ○ No measurable deterioration in the vacuum seal since sealing*. ○ MCP IDs = C00089-003 & C00101-014 ○ MCP Gain 4E6 at 1000V/MCP, and 1.5E7 at 1100 V/MCP , tested on 8/16/2016; ○ MCP Spatial gain variation +- 30% of mean ○ QE = Typical for Aluminum ○ Noise rate at STP is less than 150 Hz integrated over the surface ○ Currently still being used for picosecond timing experiments	**TILE #12 – Sealed 12/21/2016** ○ No measurable deterioration in the vacuum seal since sealing* ○ MCP IDs = C000101-104 & C00089-002 10/24/2016, ○ MCP Gain 1.5E6 at 1000V/MCP and 1E7 at 1150 V/MCP (top end for LAPPD12), ○ MCP Spatial Gain Variation = +-5% of mean ○ QE Uniformity = ≥ 10% on average ○ QE (365nm Max/Avg/Min) = 16.5% /**11.1%** /6.7% ○ Noise rate at STP is less than 150 Hz integrated over the surface
TILE #10 – Sealed October 11, 2016 ○ No measurable deterioration in the vacuum seal since sealing*. ○ MCP IDs = C00043-050 & C00023-054 ○ MCP Gain = 3.7E6 at 1000V/MCP, and 1.1E7 at 1100 V/MCP , tested on 5/24/2016; ○ MCP Spatial gain variation +- 10% of mean ○ QE (365nm) = 0.9 – 2.3% initially à 4.2 - 6.5% following extensive HV scrub ○ MCP dark rate at STP is 200 cts/s at 1150 V/MCP, or 0.5 cts/s cm^2.	**TILE #15 – Sealed 03/31/2017** ○ No measurable deterioration in the vacuum seal since sealing*. ○ MCP IDs = C00023-047 & EX-125, ○ MCP Gain = 4.5E6 at 1,000 V / MCP, tested 2/3/17, ○ MCP Spatial Gain Variation= +- 20% of mean. ○ MCP Dark Rate = 64 cts/s, or 0.16 cts/s cm^2 ○ QE (365nm Max/Avg/Min) = 39.5% /**33.7%** /24.5% (4/5/2017) ○ QE Uniformity >60% ○ Stable HV Performance @1,100 V / MCP ○ Tile Dark Rate = 0.65 cts/s cm^2 @ 12mV threshold, 1,000V / MCPs, 5.5 cts/s cm^2 @ 12mV threshold, 1,030V / MCPs ○ Tile Gain = 2.8 X 10^6 @1030 V/MCP

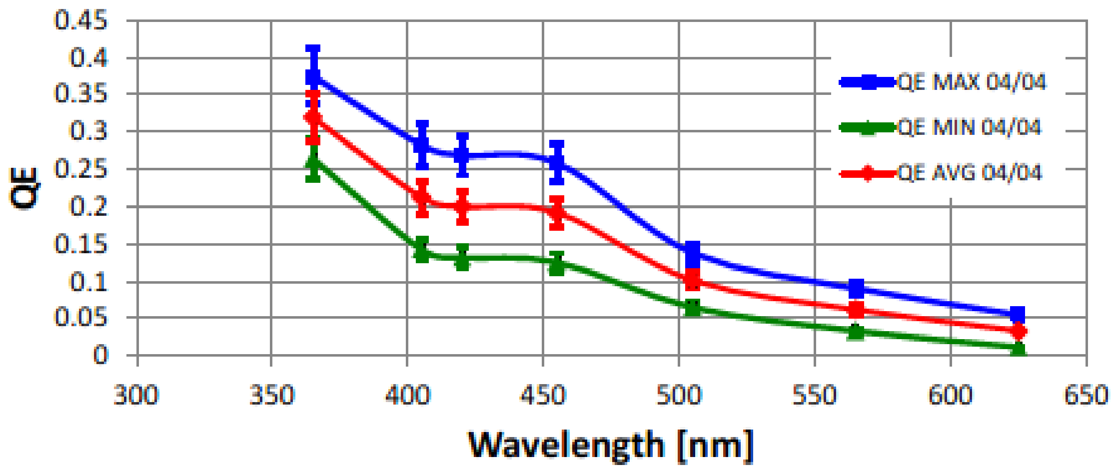
Tile #15

3 Days after Sealing



32 Days after Sealing

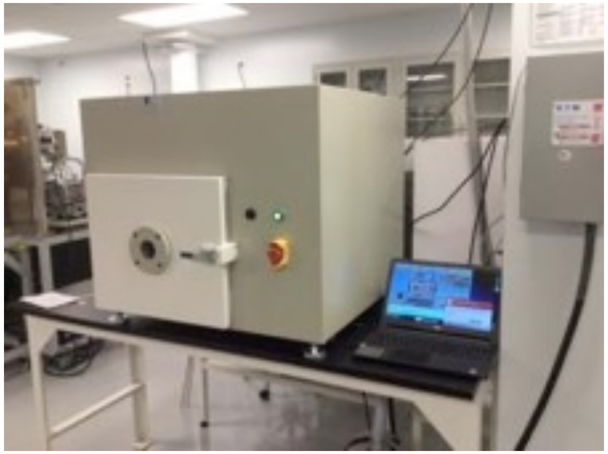




Commercialization Status (Incom)

Vacuum

LAPPD integration and sealing tank

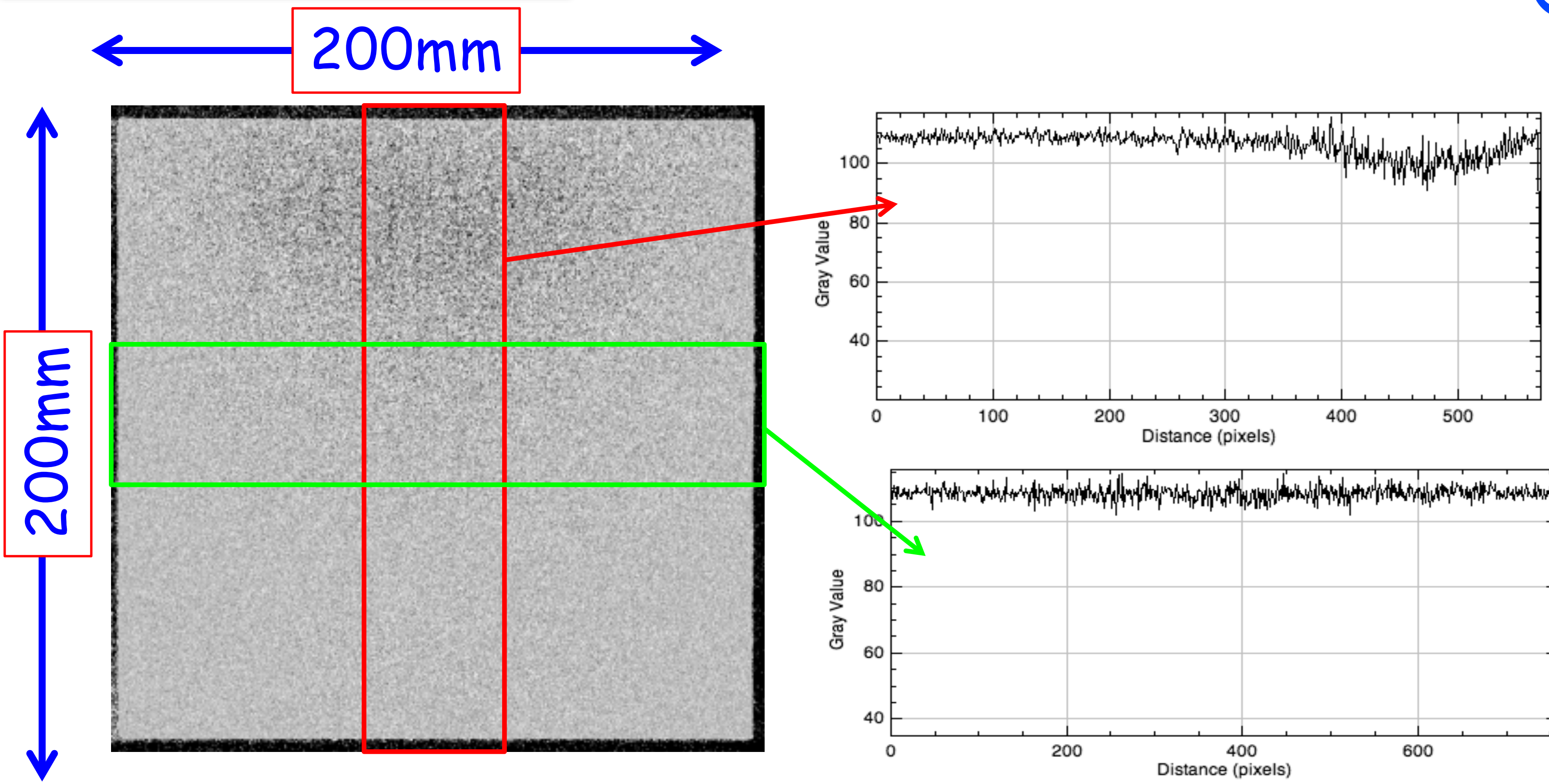


Beneq ALD coater with load-lock

Thermal evaporator

Measurement & test station

ALD performance (Incom)



Gain Uniformity Map

20 micron pores

Dark Noise: 0.1 – 1 cts/sec/cm^2

Uniform Gain within ~15% across the area

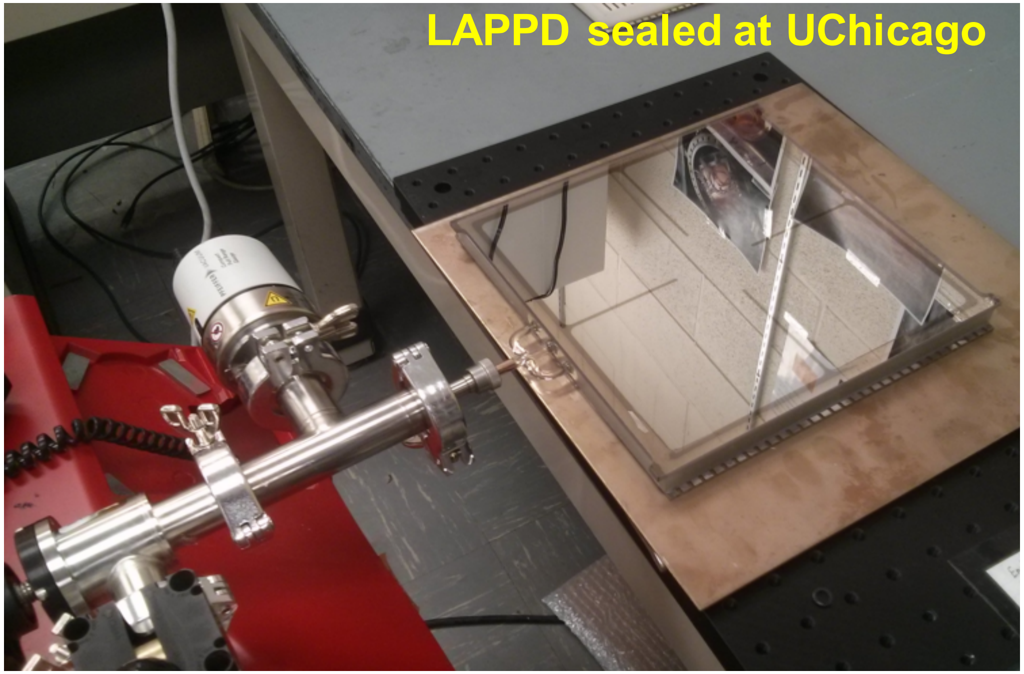
Gen II Development

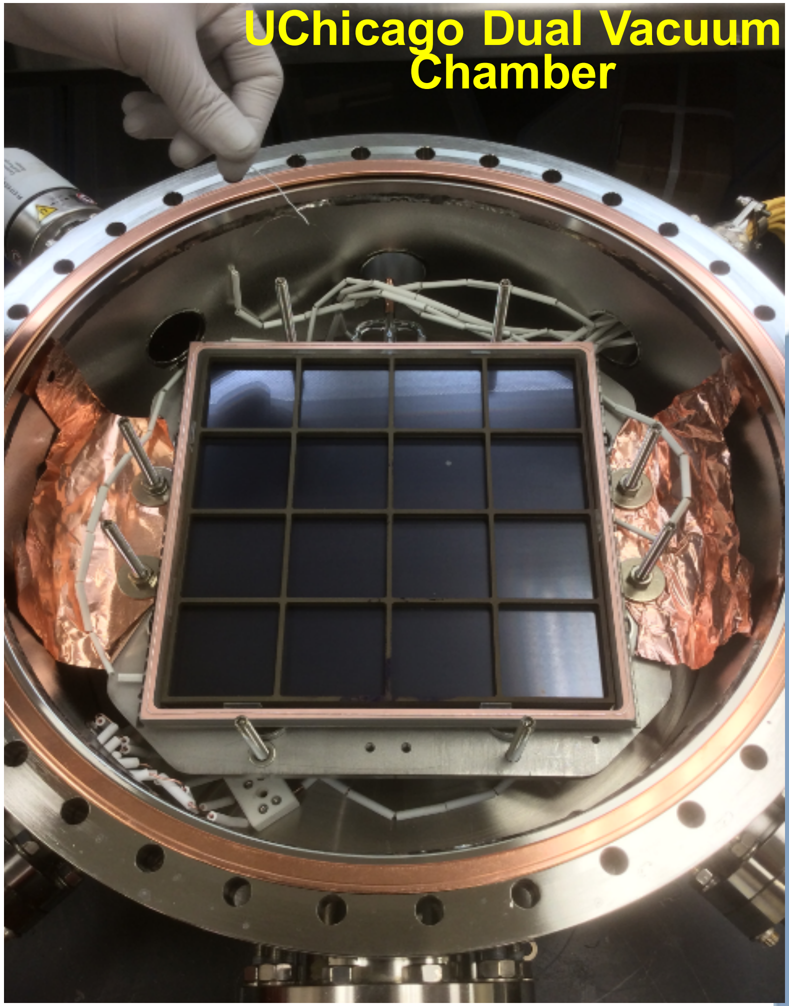
Gen II Development (U Chicago/Incom)

slide credit: Andrey Elagin

To follow closely behind the ramp up of first Incom tiles.

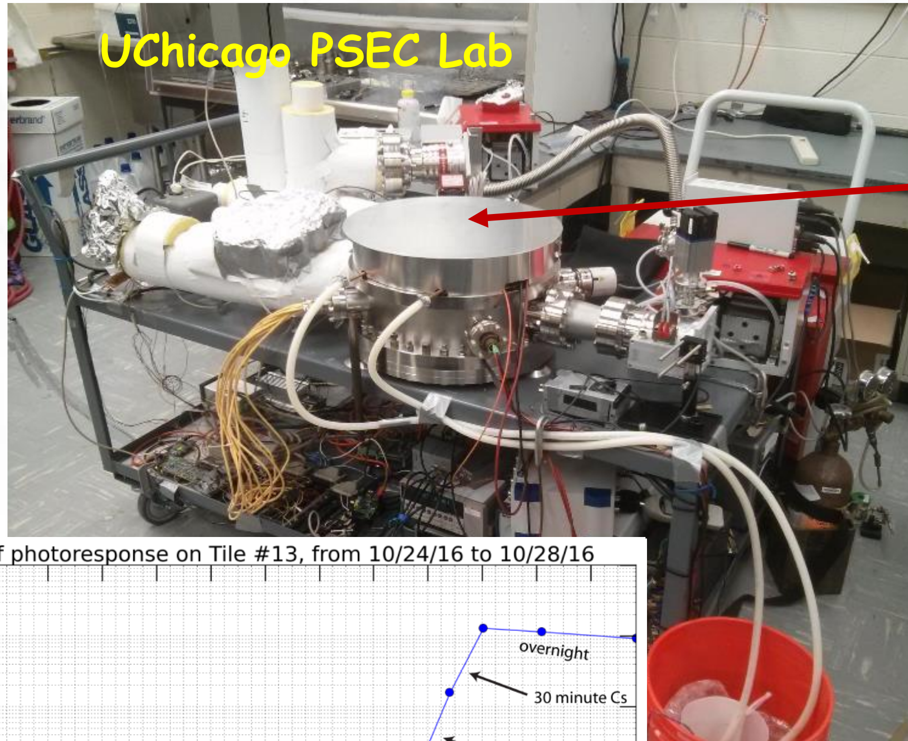
- reduce fabrication costs and increase volume
- improve performance
- Address the vacuum transfer process.
- New approaches to photocathode production
- cheaper and more robust components

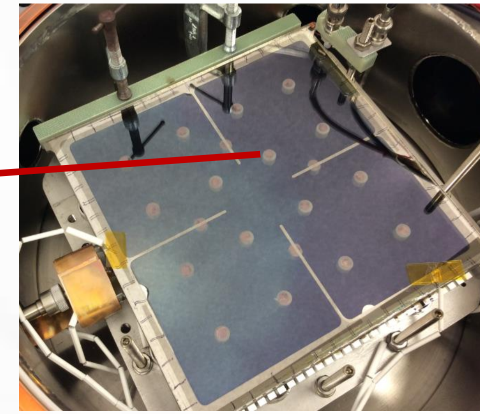


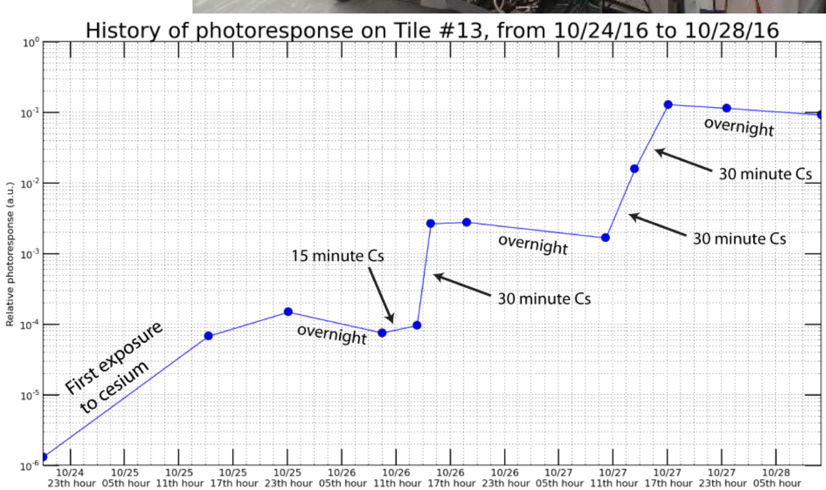


slide credit: Andrey Elagin (UC)

Simplify the assembly process by avoiding vacuum transfer:
make photo-cathode after the top seal
(PMT-like batch production)







Heat only the tile
not the vacuum vessel

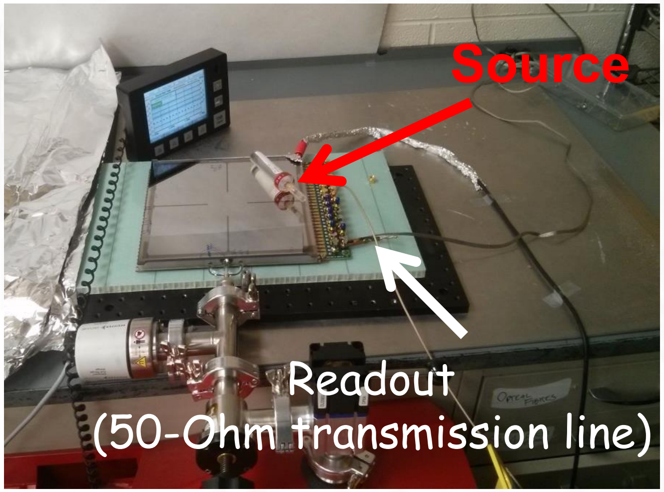
Intended for
parallelization

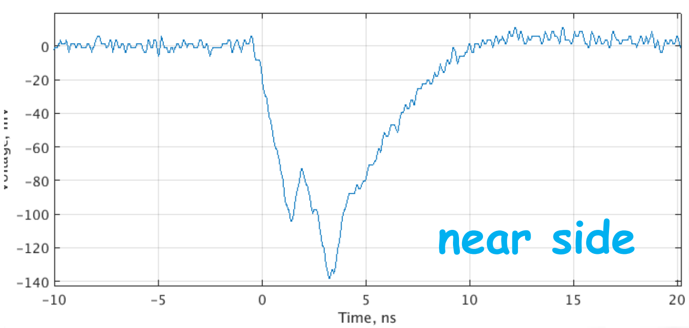
slide credit: Andrey Elagin (UC)

First signals from an In-situ LAPPD

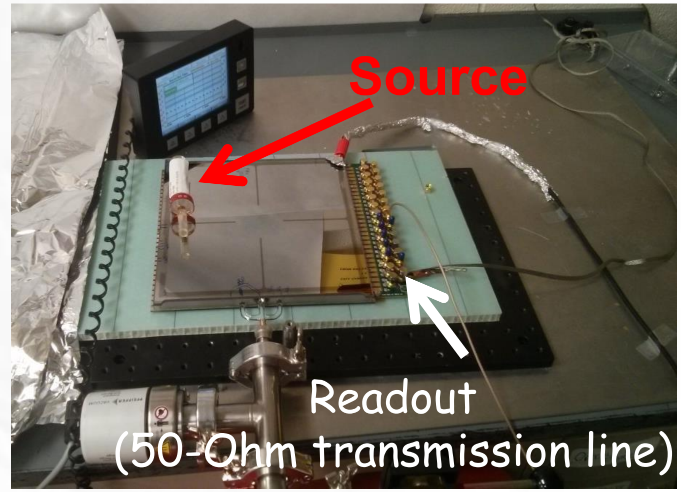
April 2016

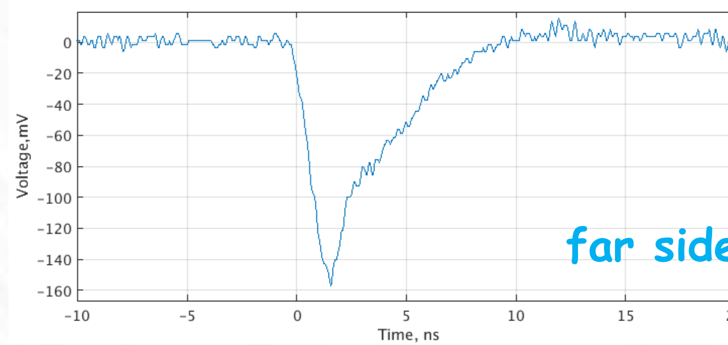
Near side: reflection from unterminated far end





Far side: reflection is superimposed on prompt





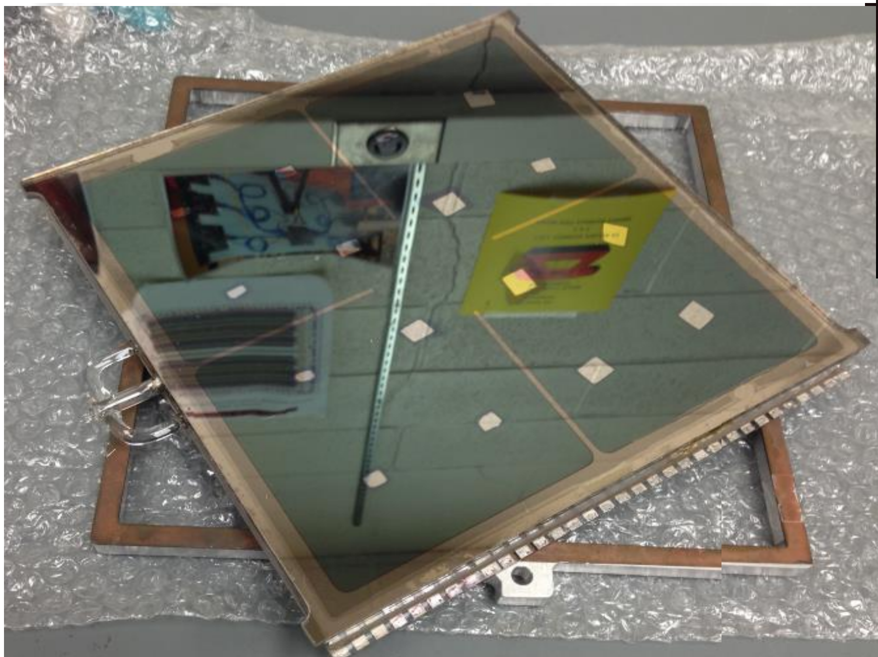
The tile is available for QC before the photocathode is shot

slide credit: Andrey Elagin (UC)

First Sealed, In-situ LAPPD

August 18th 2016

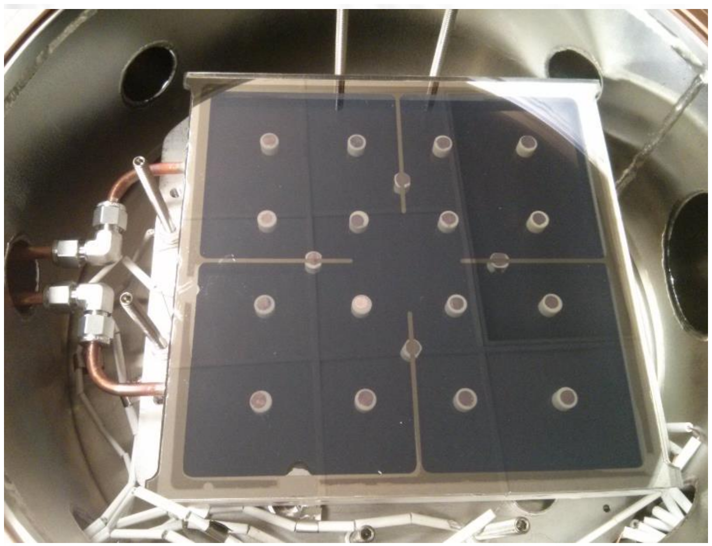
Cs_3Sb photocathode

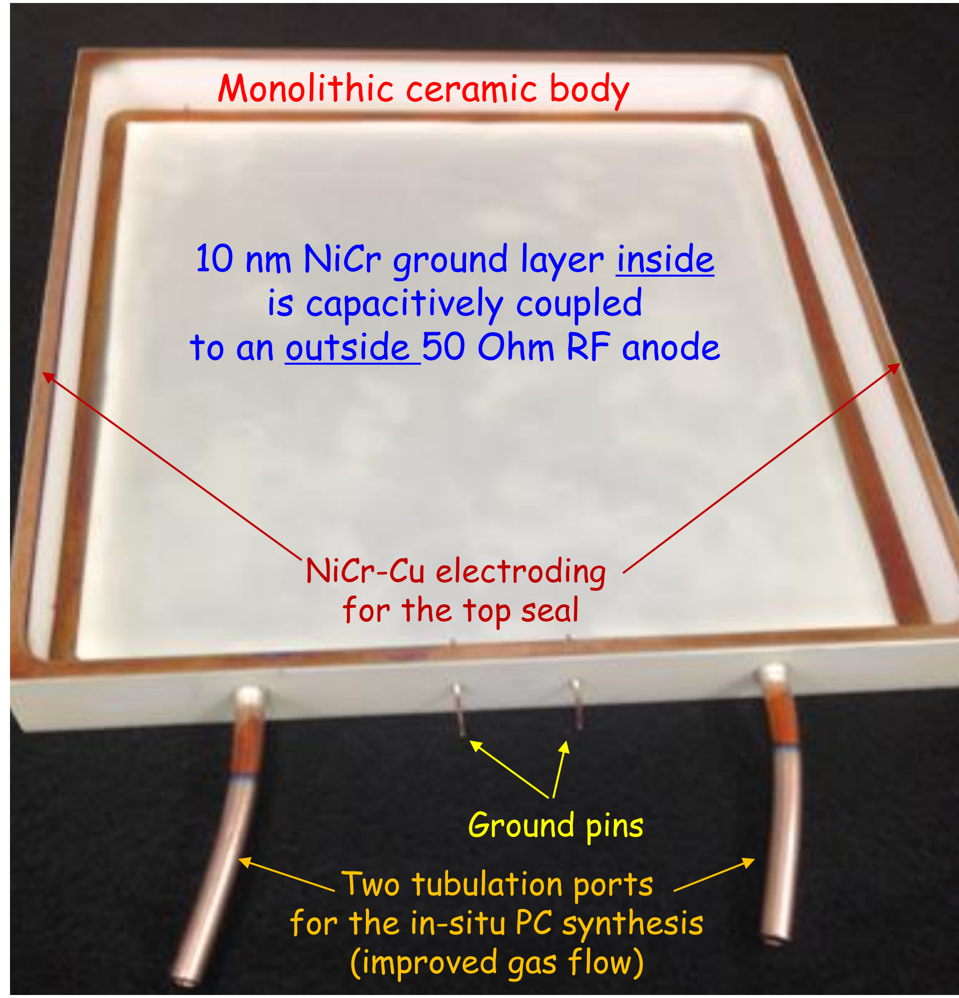


slide credit: Andrey Elagin

Mechanical Advancements

- Robust ceramic body
- Anode is not part of the vacuum package
- Compatible with current Incom fab
- Also compatible (ideal) for gen II, in situ fab

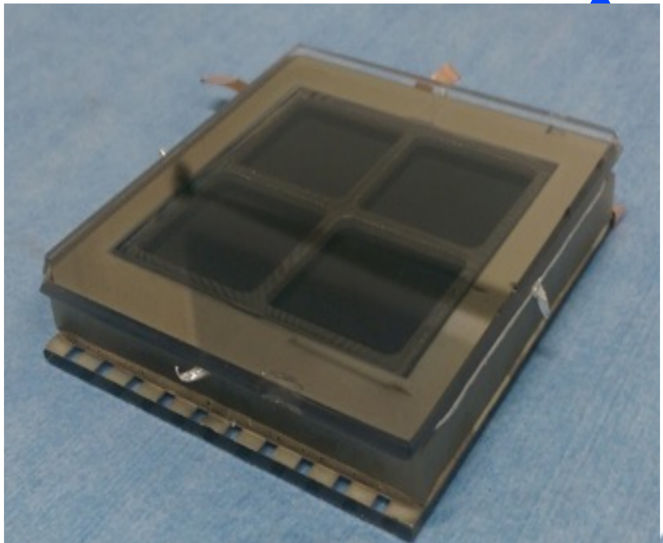




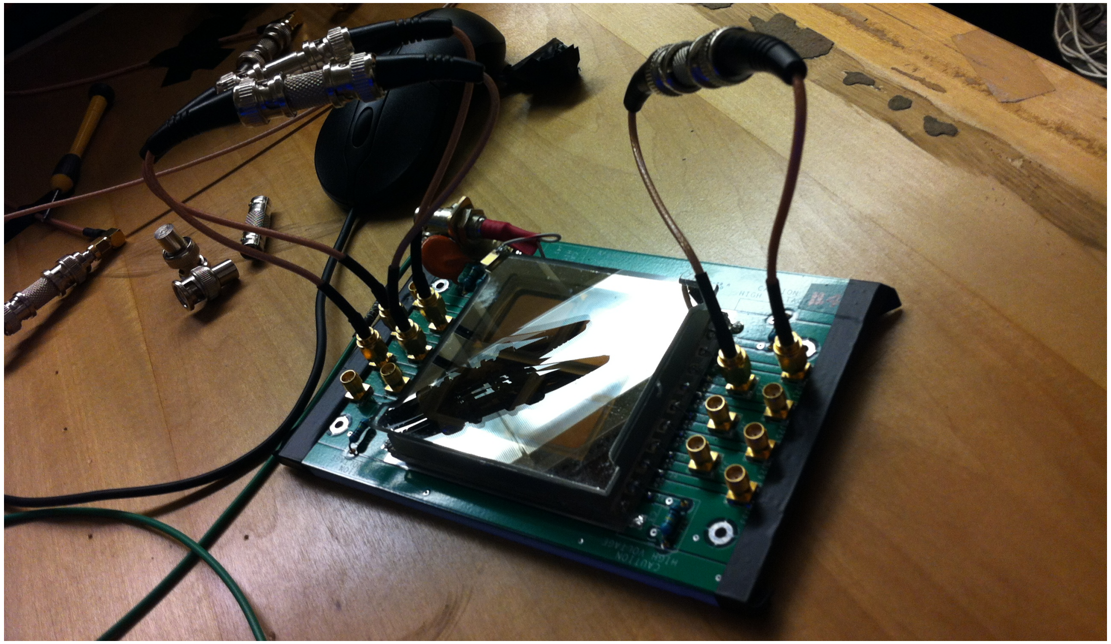
slide credit: Andrey Elagin

ANL 6 cm Tiles

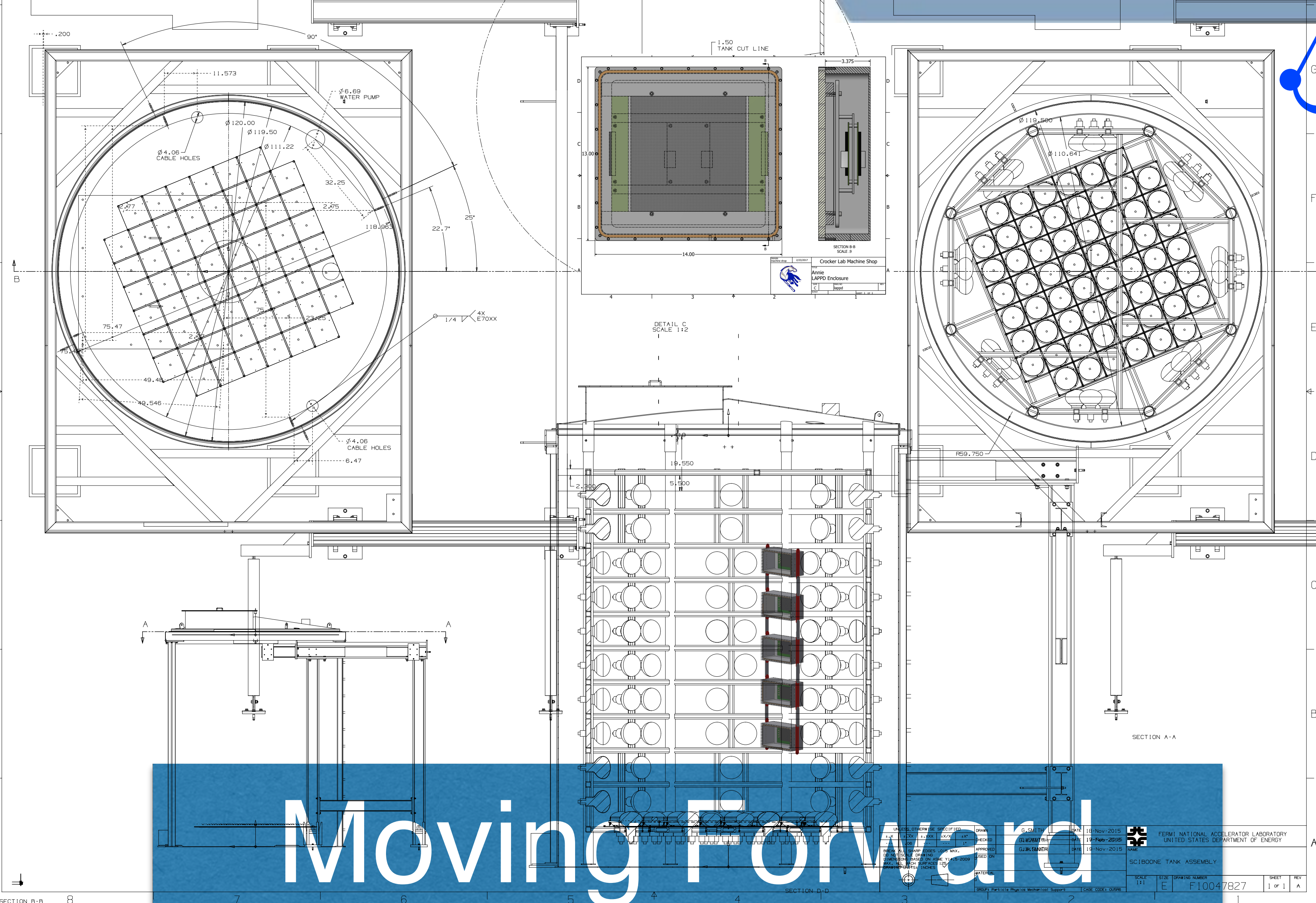
- small format, glass MCP detectors based on the LAPPD concept.
- ANL development facility now producing new tubes regularly and with a high success rate
- slightly low QE (~10%) but high gain and good timing
- a number of long lived prototypes exist, more are on the way and available for testing.



Completed Tube with Photocathode



1



Moving Forward

Early Adopters

First LAPPDs will not be "cheap" (by HEP standards)

- small volumes
- high operational costs
- small market

Even with no further developments, costs are likely to go down with yield, volume, and market size

LAPPD technology is viable outside of particle physics (medical imaging, security, neutron and x-ray imaging, etc)

HEP will benefit from economy of scale.

Gen II could significantly reduce costs.

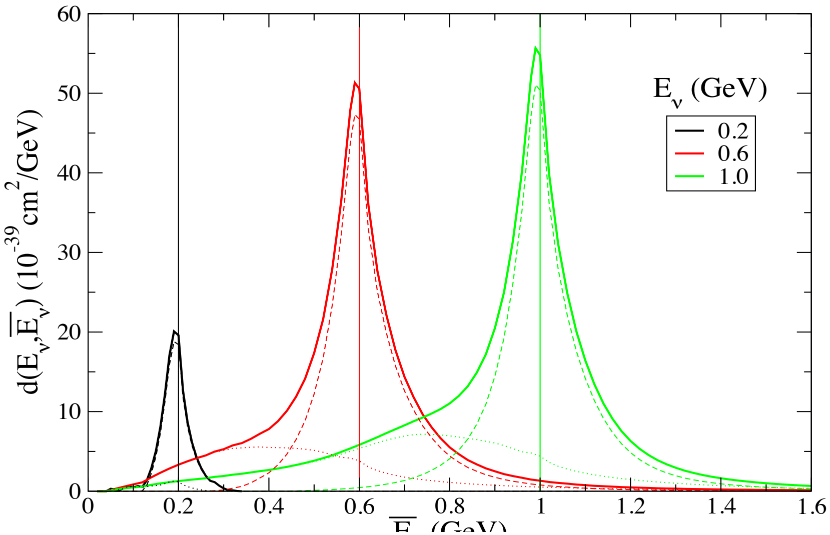
In the mean time, Incom is very interested in HEP early adopters and is willing to help with costs and availability, *especially* for those who can provide detailed testing/feedback

Successful early demonstrations are critical!

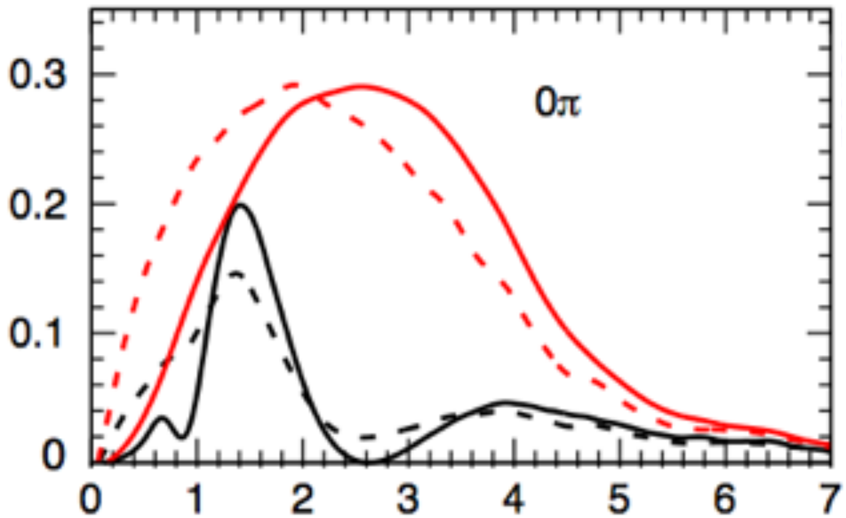
Physics

Neutrino-Nucleus Interactions Are Complicated

- Inelastic processes that look experimentally CCQE-like can bias neutrino energy reconstruction
- This can distort neutrino oscillation patterns in ways that can affect δCP measurements
- These effects can be better understood with a more complete picture of the hadronic system
- Neutrons, in particular, are a good indicator of inelasticity



Martini et al



Mosel et al

ANNIE Physics

Run I: Background Measurement/Proof of Concept

add some LAPPDs

Run IIa: Reconstruction of
    0pi + xN + ?p
versus final states versus muon kinematics

add more LAPPDs

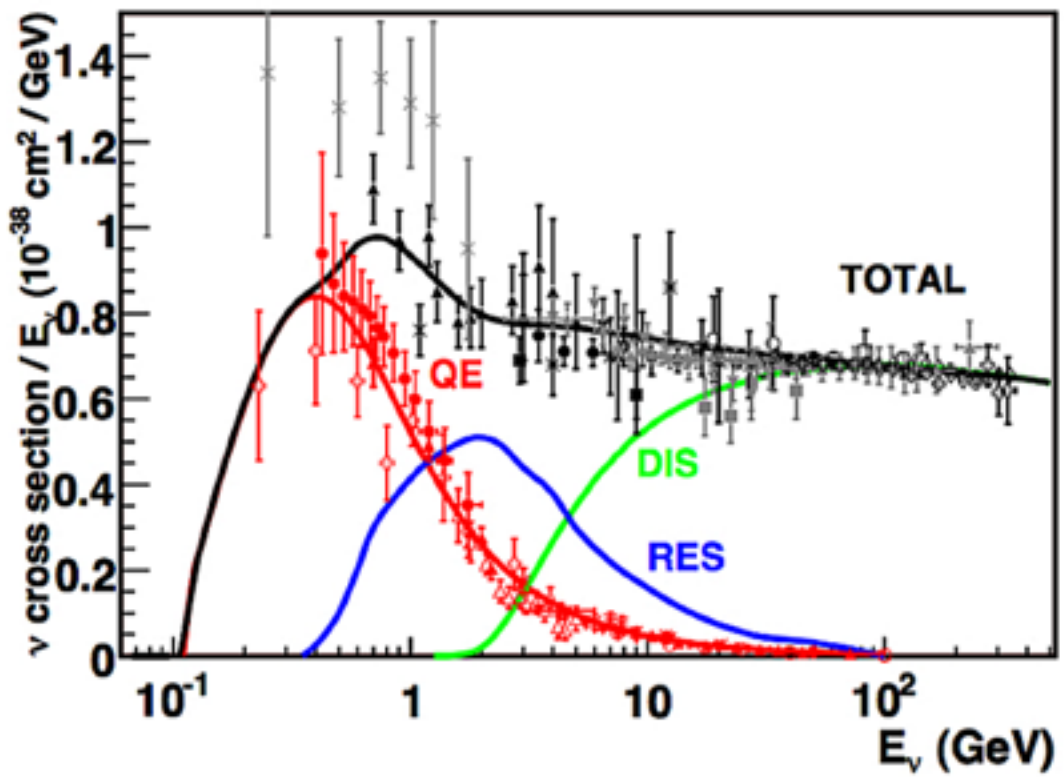
Run IIb: Reconstruction of
    CC 0pi + nN + ?p and
    CC 1pi + nN + ?p and
    NC 1pi 1pi + nN + ?
versus final states versus muon kinematics

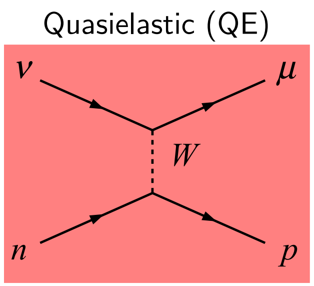
Run IIc: water-based liquid scintillator to see protons?

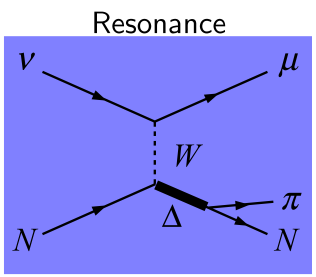
ANNIE Physics

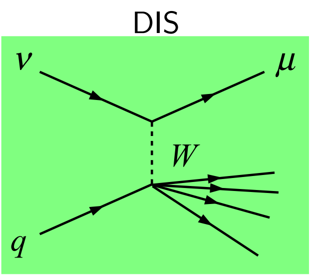
- Ability to detect final state neutrons from neutrino interaction
- Detailed kinematic reconstruction of muon energy and angle
- Number of neutrons is particularly interesting in a neutrino beam one does not expect neutrons, to first order.
- Yet,at 1 GeV production of neutrons is relatively common:
    - 2p-2h effects
    - stuck pions
    - final state interactions/nuclear knockouts
- There is no lower energy limit on detecting free neutrons (unlike multi-proton searches)
- However, there is no (or at least weak) kinematic reconstruction of neutrons

Neutrino Interactions: General Categories of CC Interactions

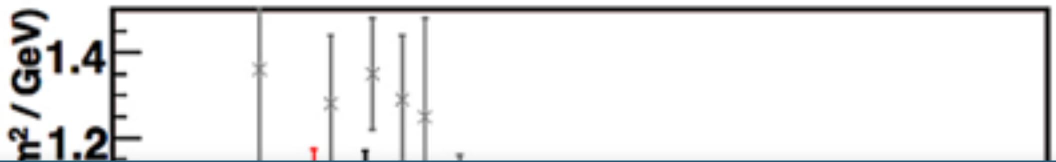








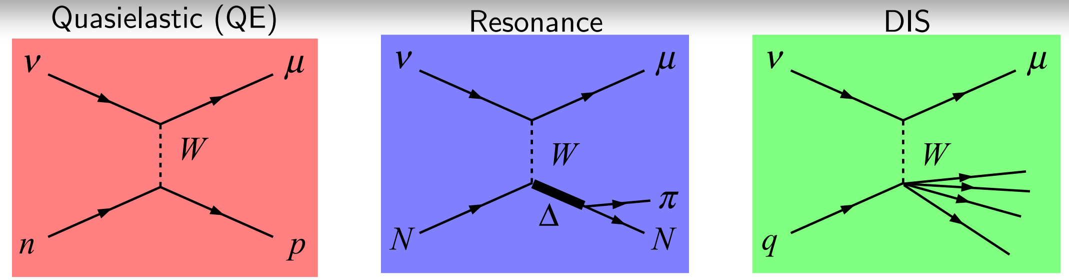
Neutrino Interactions: General Categories of CC Interactions

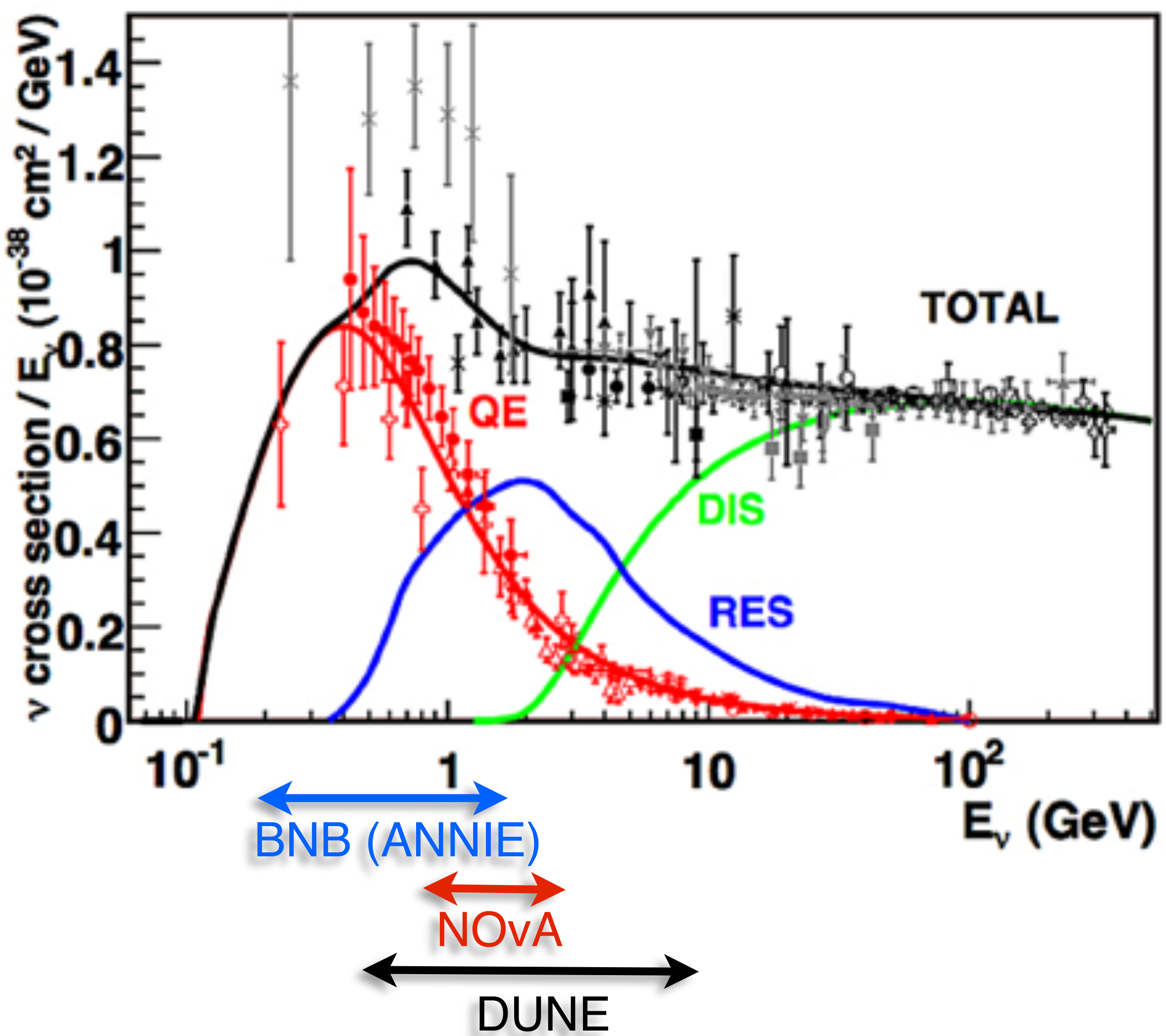


The real world does not factorize as neatly as this

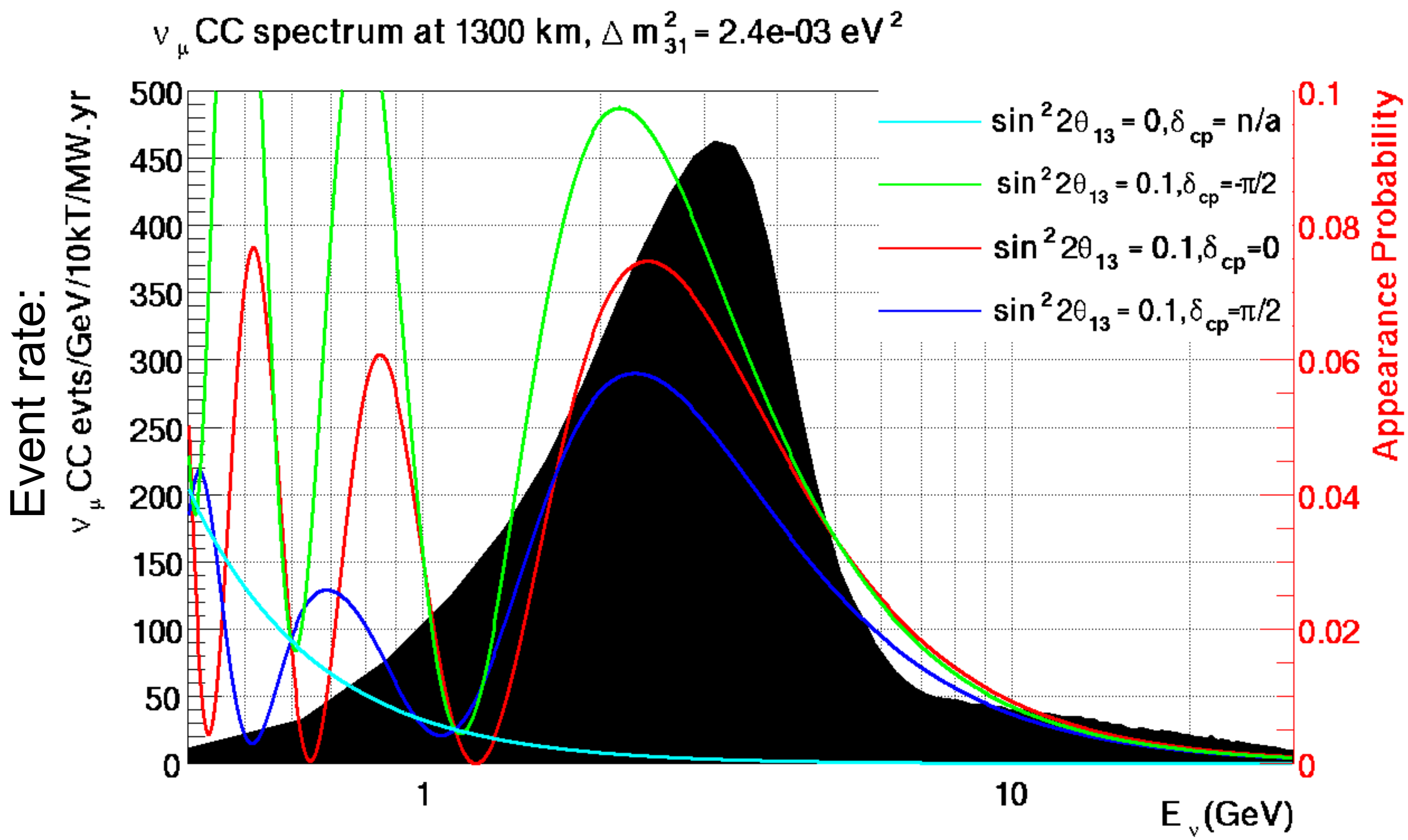
The experimental community is starting to move away from generator-based definitions towards topological definitions:

ie, 1mu + 1pi + nN + mP



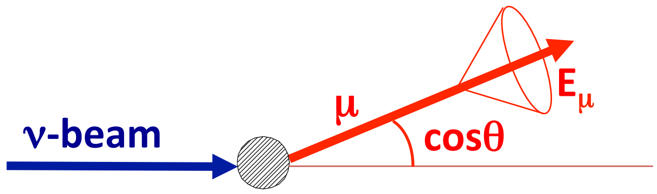

ν cross section / E_ν (10^-38 cm² / GeV)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^-1
1
10
10^2
E_ν (GeV)
TOTAL
QE
DIS
RES
BNB (ANNIE)
NOvA
DUNE

To make precision measurements we need to know the neutrino energy



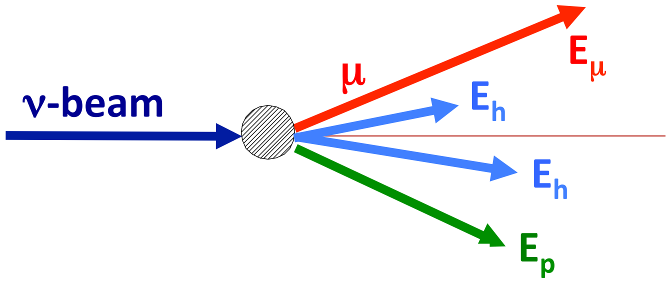
Need better than 100 MeV resolution to really start resolving these curves.

Kinematic Energy Reconstruction



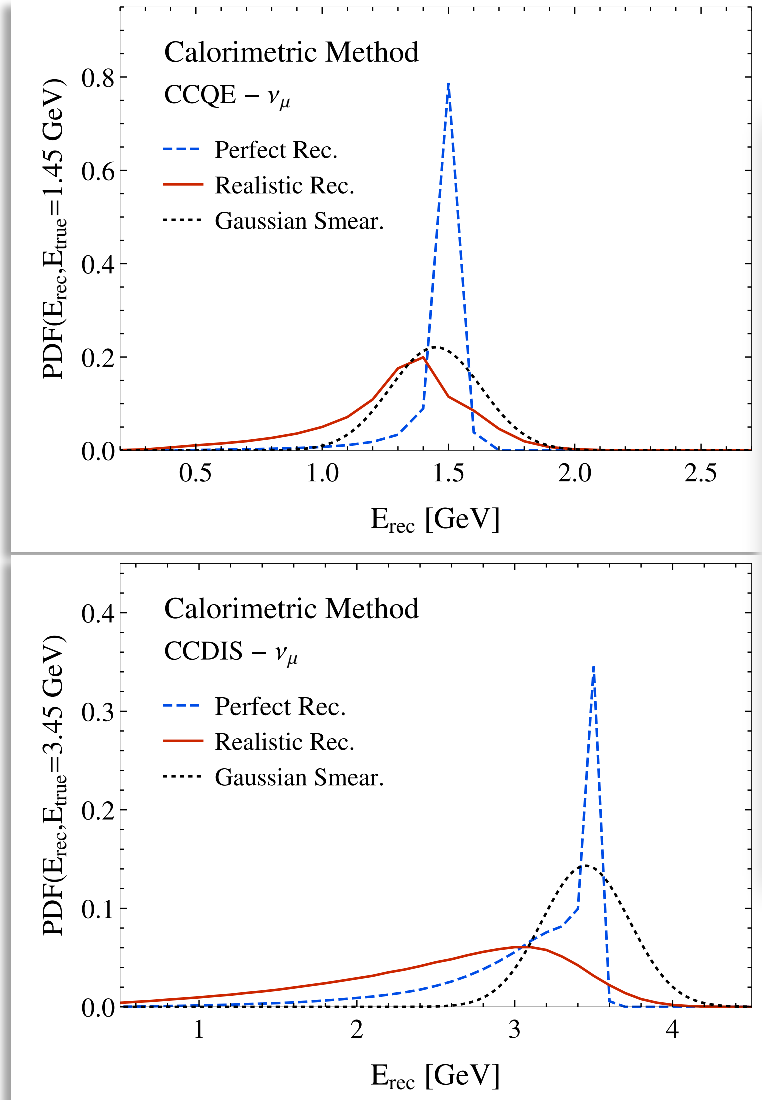
$$E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu \cos\theta_\mu}$$

Calorimetric Energy Reconstruction



$$E_\nu^{Cal} = \varepsilon_n + E_\mu + E_p - M + \sum_i E_{h_i}$$

Calorimetric Reconstruction



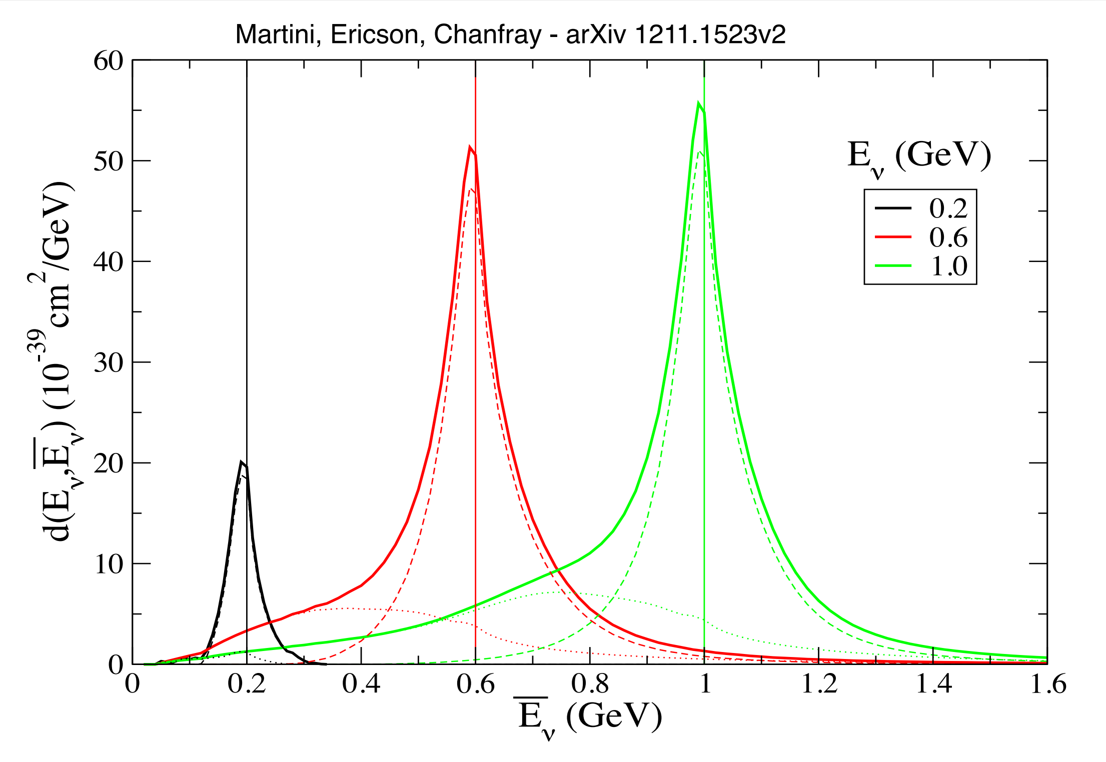
In some detectors, one can see both the leptonic and hadronic final states. Energy determined by summing all visible components.

But, q0<qTOT, not all particles are detected or above threshold!

“Comparison of the calorimetric and kinematic methods of neutrino energy reconstruction in disappearance experiments”

Ankowski et al

Kinematic Reconstruction



Kinematic reconstruction gives much better energy resolution, but depends on the assumption of quasi-elasticity!

Impact On Oscillation Physics

review Article by U. Mosel (Ann. Rev. Nuc. Part. Sci. 2016. 66:1–26)

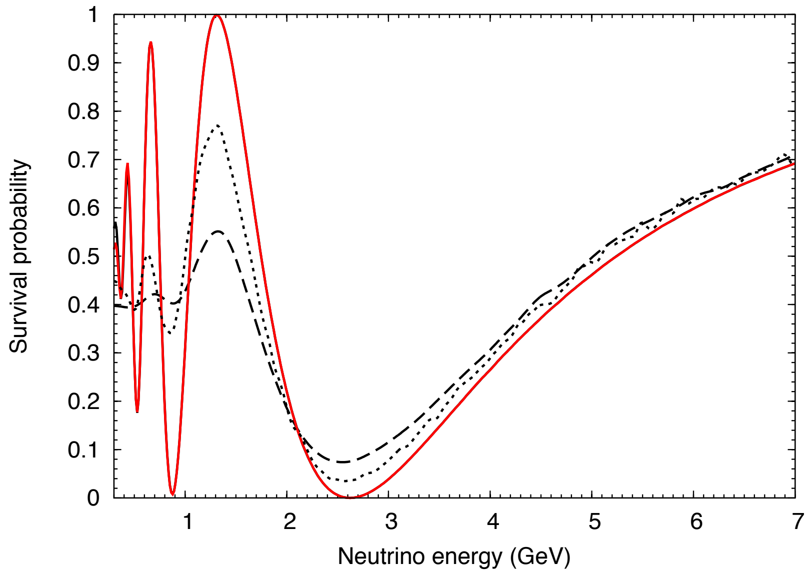


FIG. 3. Survival probability for μ-neutrinos both for true (solid) and reconstructed (dashed) energies for 0-pion events. The dotted curve gives the probability for events with 0 pions, 1 proton and X neutrons.

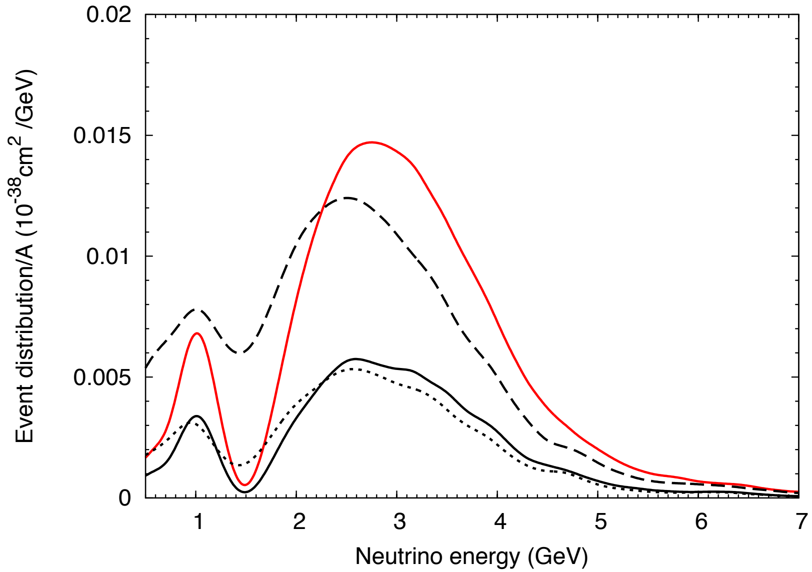
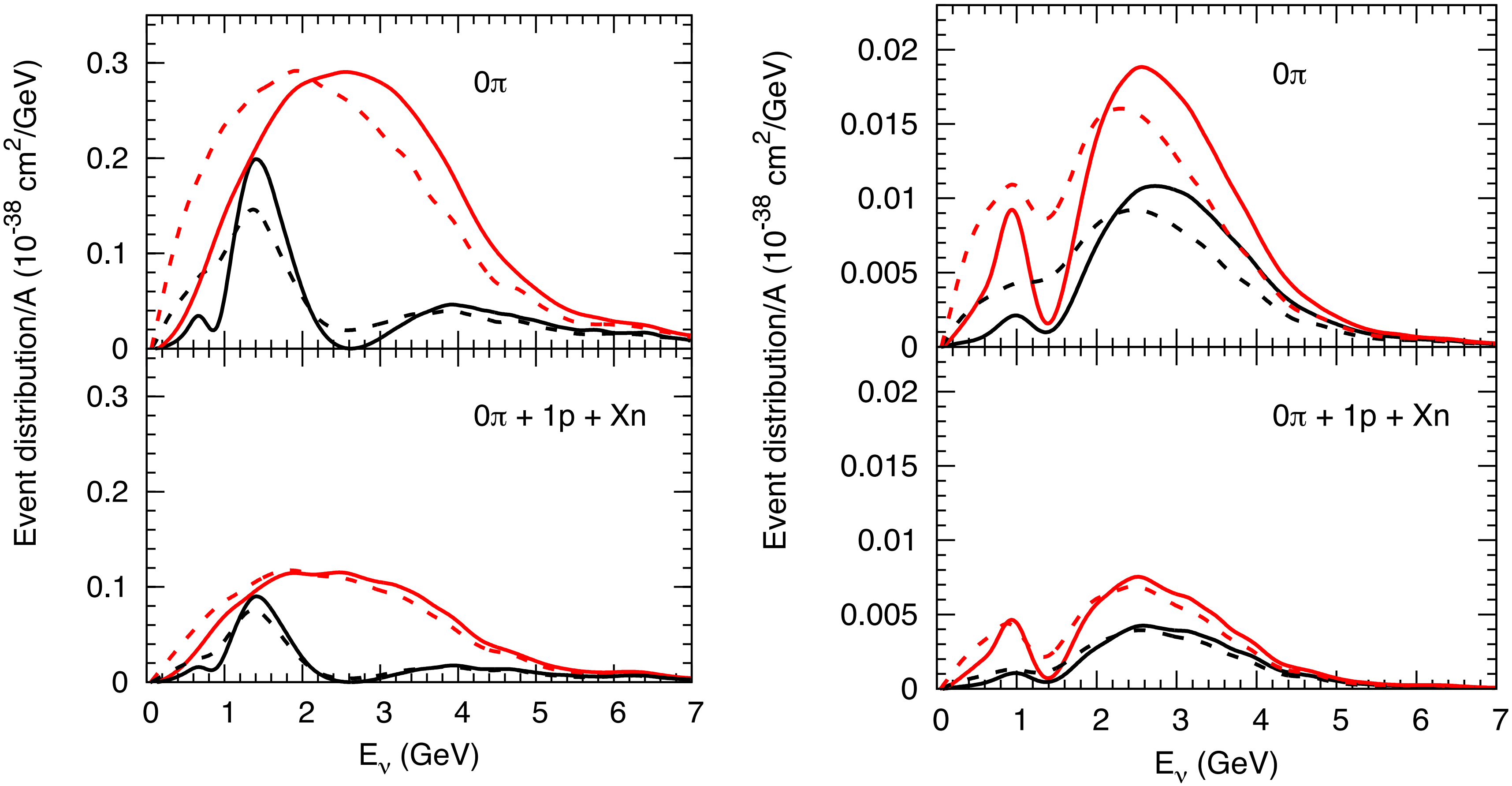


FIG. 4. Event distribution per nucleon for electron appearance both for true (solid) and reconstructed (dashed) energies. The CP-violating phase has been set to 0. The upper two curves are based on 0-pion events, the lower two curves on events with 0 pions, 1 proton and X neutrons.

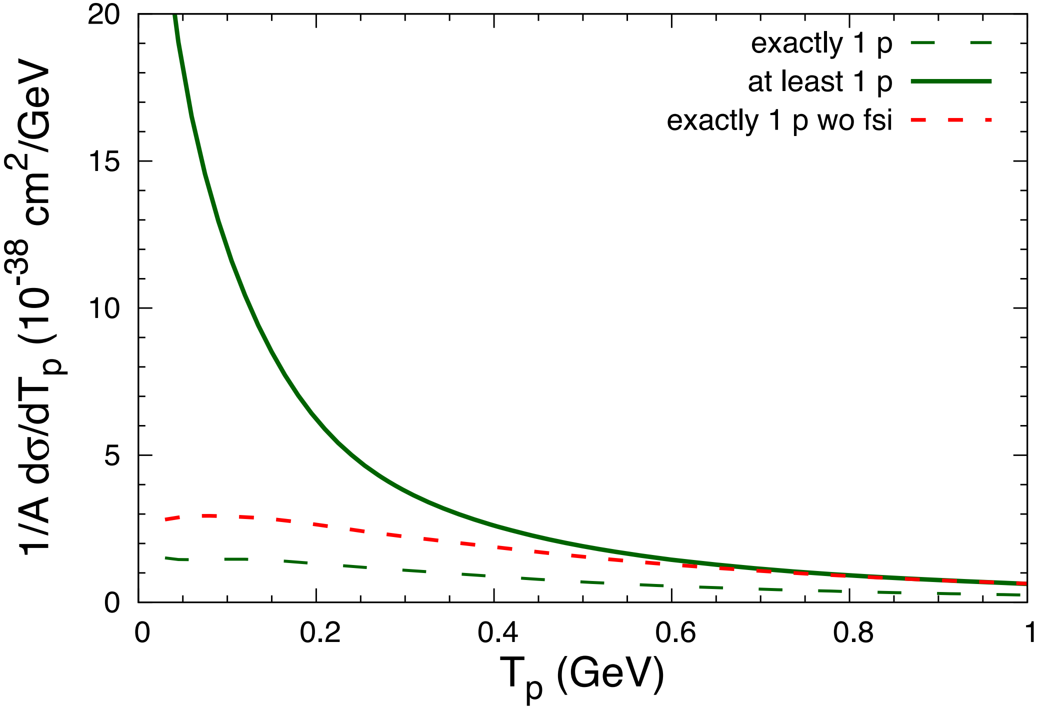
Impact On Oscillation Physics

review Article by U. Mosel (Ann. Rev. Nuc. Part. Sci. 2016. 66:1–26)



Knock-off nucleons

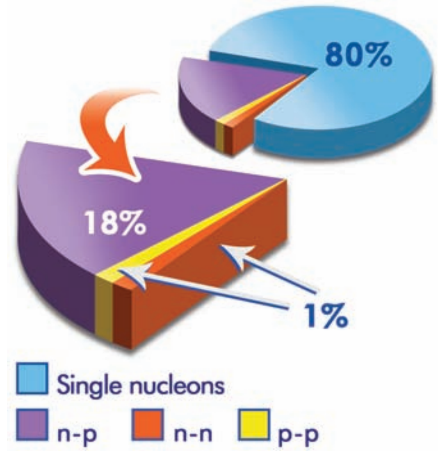
"Comparison of the calorimetric and kinematic methods of neutrino energy reconstruction in disappearance experiments" Ankowski et al



As more knock-off nucleons are produced, the energy per nucleon drops, making calorimetric reconstruction more difficult.

2p-2h Interactions

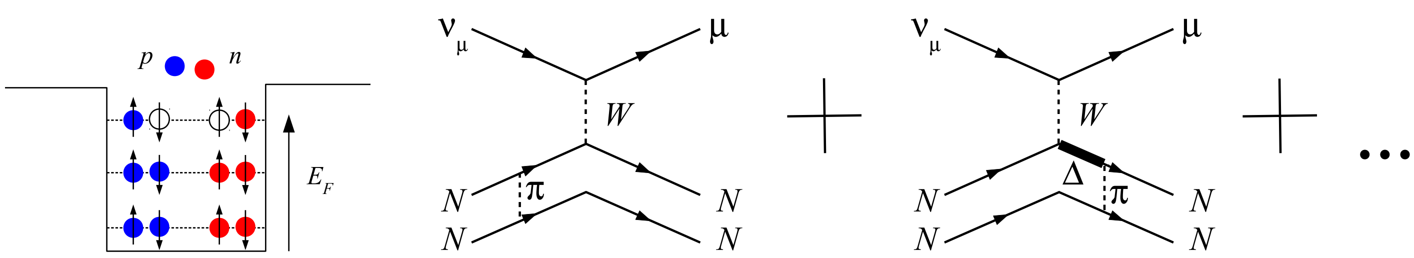
Neutrinos do not just scatter off of single nucleons. In so-called 2p-2h interactions, a neutrino can scatter off of a pair of nucleons or the meson exchanged between them (Meson Exchange Currents)



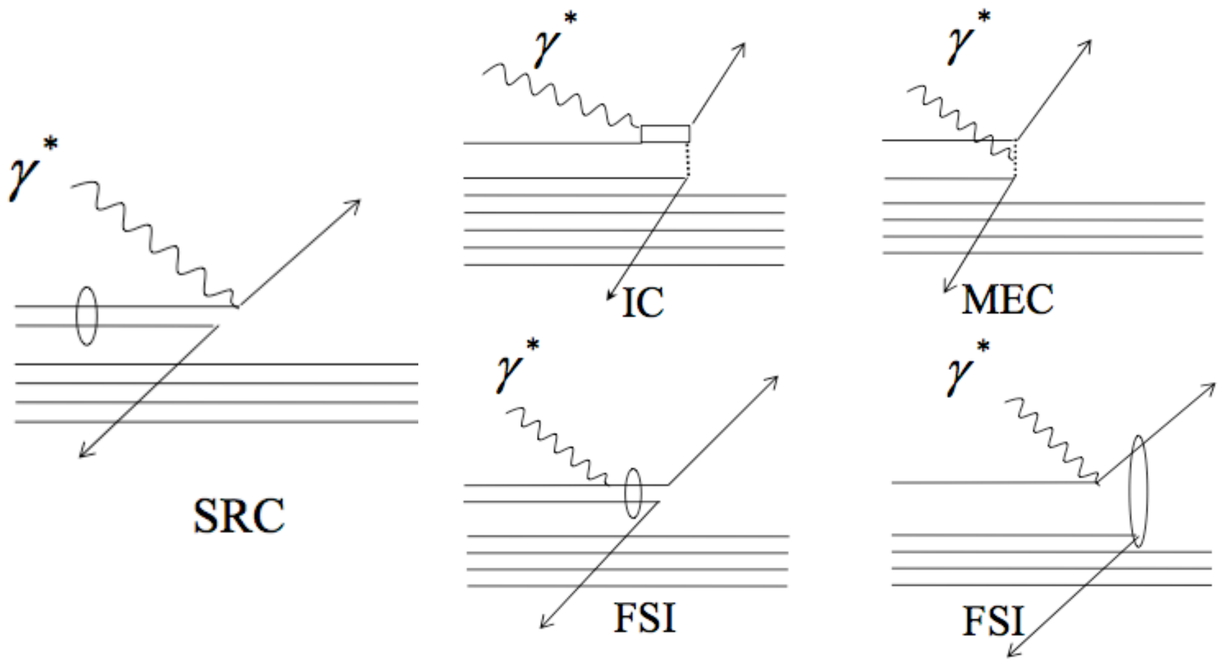
R. Subedi et al, Science 320, 1476 (June 2008)

These events produce different kinematics and final state-nucleon numbers but can fake CCQE events

A big new area in the field



2p-2h Interactions Come in Different Shapes and Sizes



From L. Weinstein - talk at NuINT2014

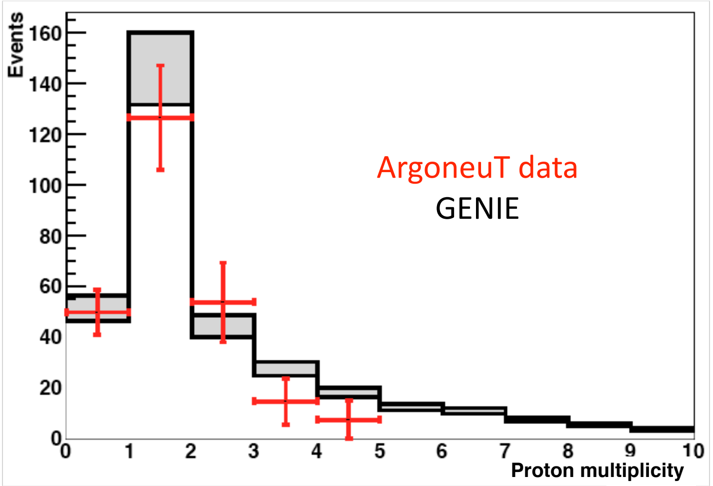
Short Range Correlation (SRC) is an extreme example

- 2 high momenta nucleons, mostly balancing each other
- momentum of each nucleon >> the boost of the 2 nucleon-pair

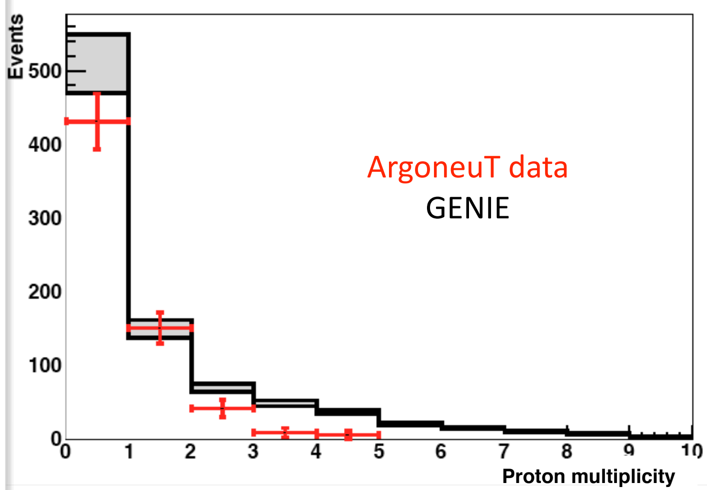
Measurements of Nucleon Multiplicity: a New Development

Proton Multiplicity (μ+Np events)

ν_μ - anti-neutrino mode run



$\bar{\nu}_\mu$ - anti-neutrino mode run



The systematic error band on the MC represent the NuMI flux uncertainty

proton threshold:
T_p>21 MeV

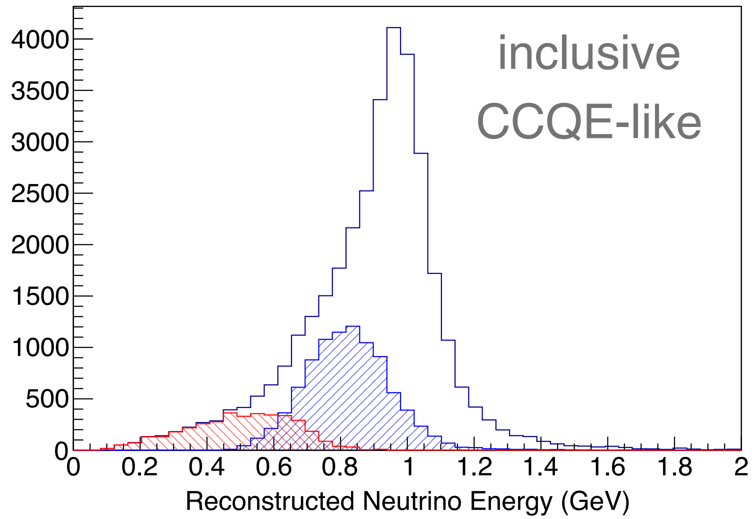
ν_μ events: 50% N≠1
$\bar{\nu}_\mu$ events: 32% N≠0

GENIE MC models more higher multiplicity events

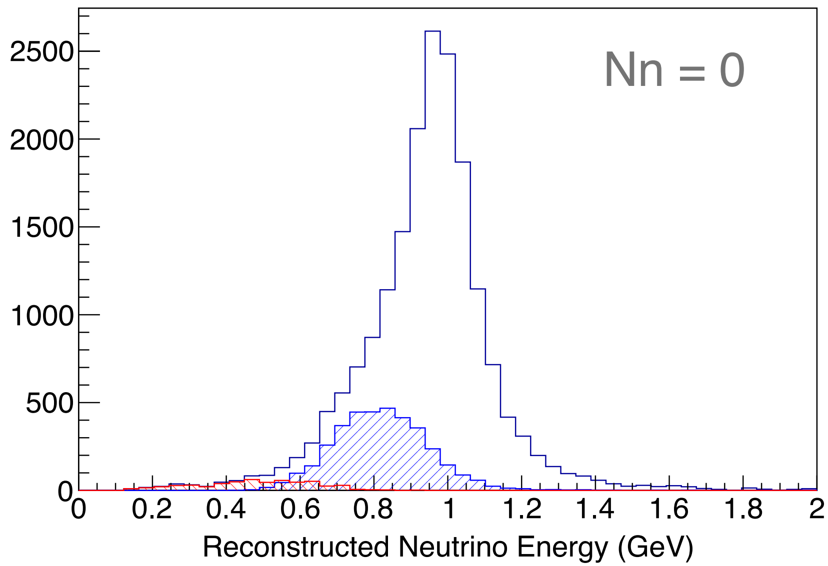
From O. Palmara (Argoneut Wine and Cheese at FNAL)

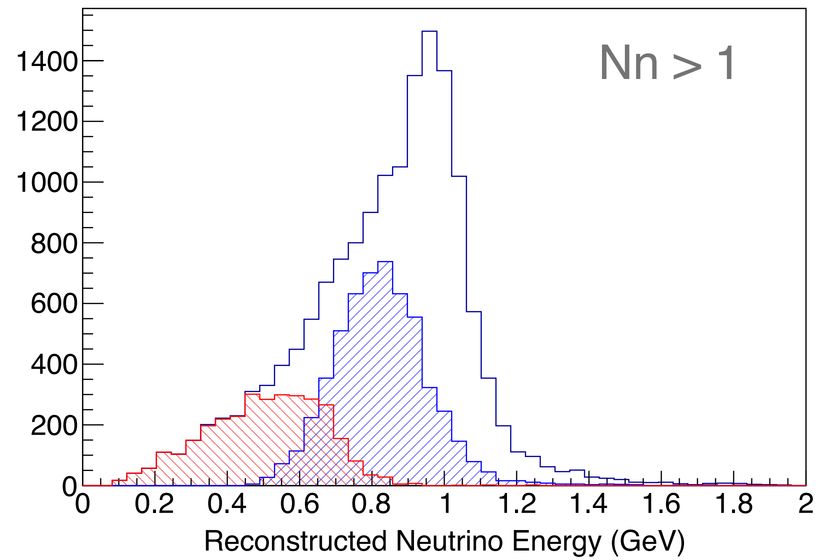
Neutron Tagging and Energy Reconstruction

A mono energetic 1 GeV neutrino simulation

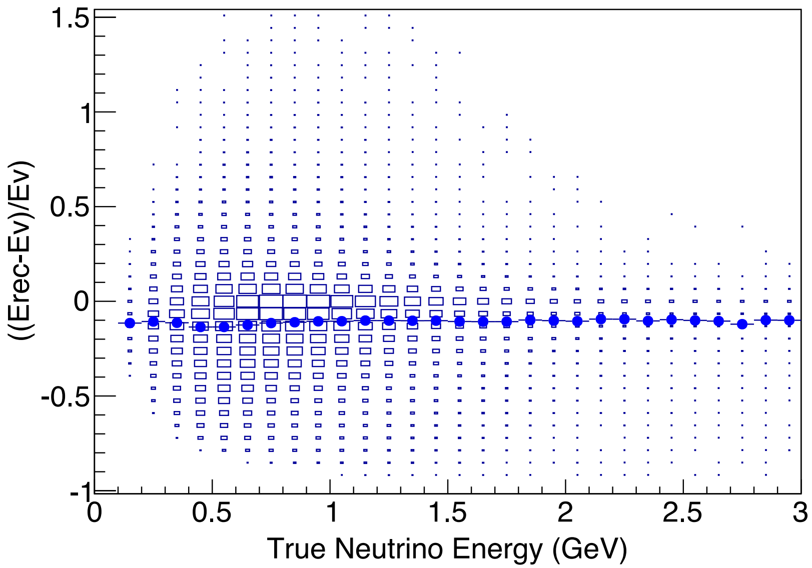


C. Blanco, R. Hill, M. Wetstein



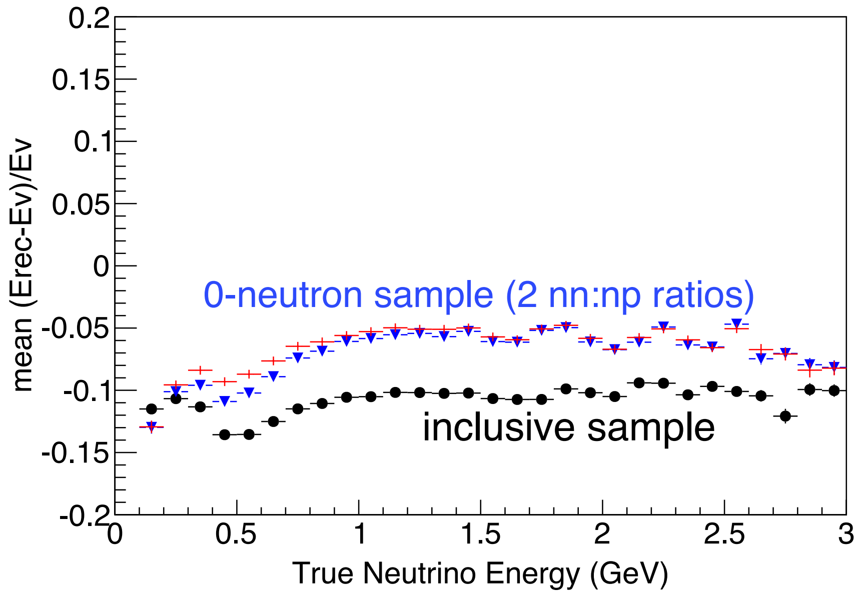


Neutron Tagging and Energy Reconstruction



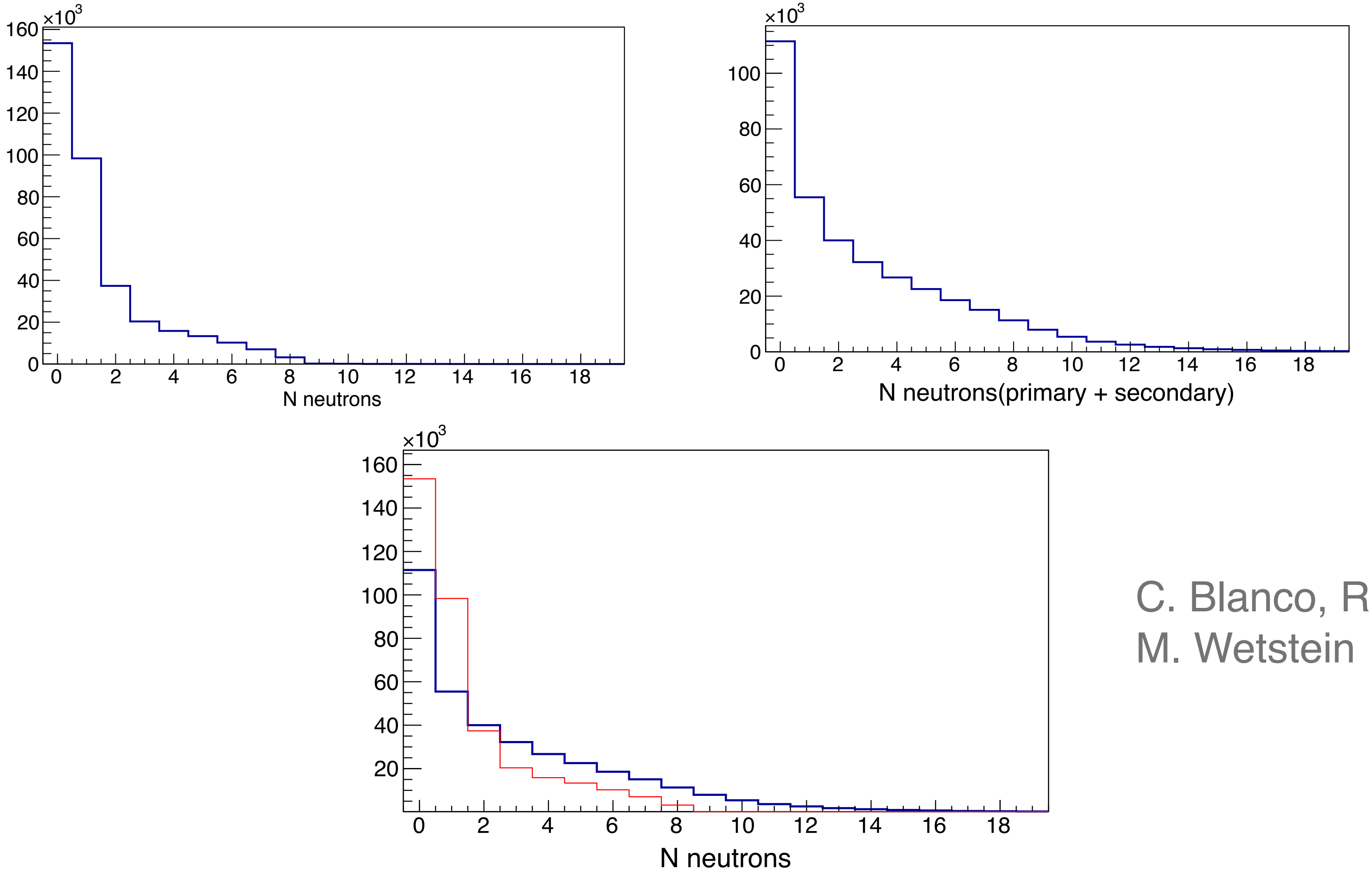
For a realistic BNB neutrino Flux, there will likely be a statistically significant difference in the mean reconstructed energy of a 0 neutron and >1 neutron CCQE sample.

C. Blanco, R. Hill, M. Wetstein



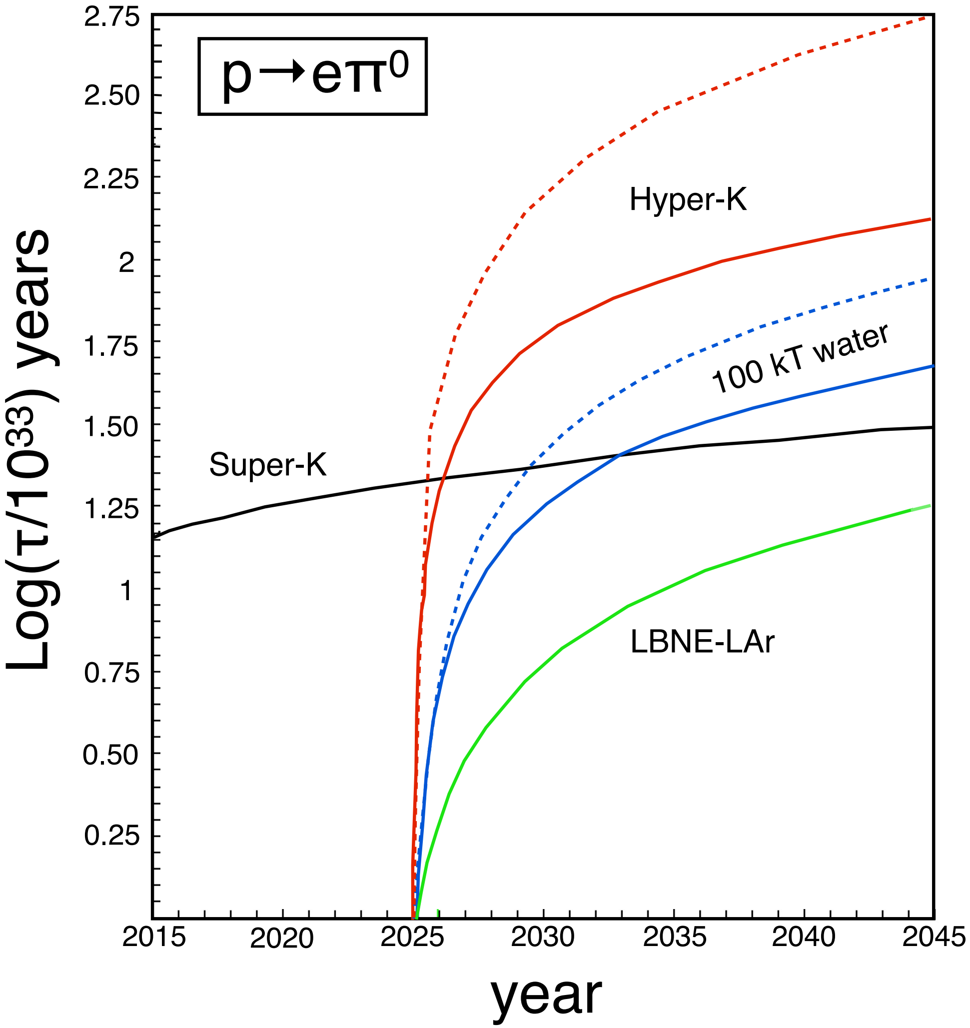
Neutron Tagging and Energy Reconstruction

Geant predicts secondary neutrons appearing ~20% in true 0-neutron events



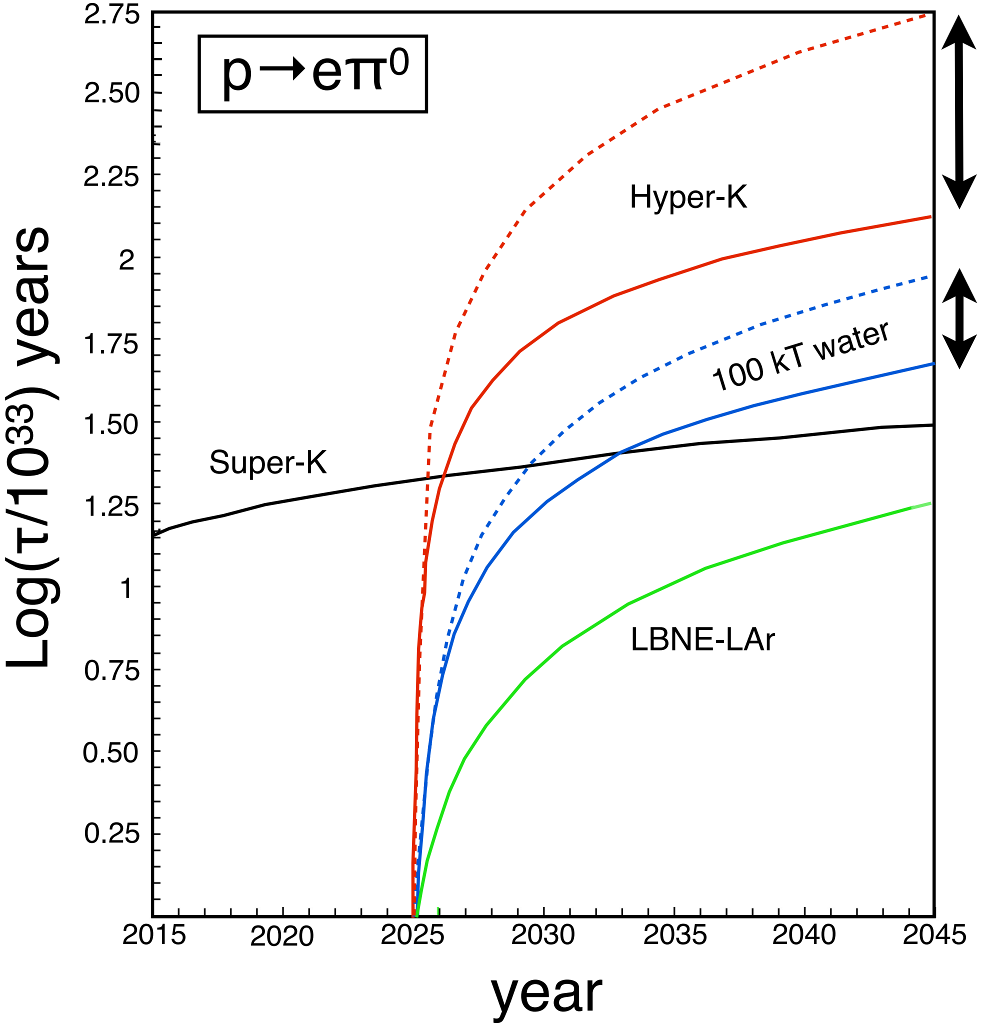
C. Blanco, R. Hill, M. Wetstein

Proton Decay Backgrounds



- Next-gen proton decay (PDK) experiments will be background limited (from atmos. neutrinos)
- These backgrounds very often produce final-state neutrons, whereas PDKs rarely do
- The presence of neutrons detected with Gd-loaded water can be used to reject these. (Beacom and Vagins)
- We need data from a controlled beam experiment
- Fermilab can have a large impact on this P5 physics driver ("The Unknown")

Proton Decay Backgrounds



How much background does neutron tagging remove?

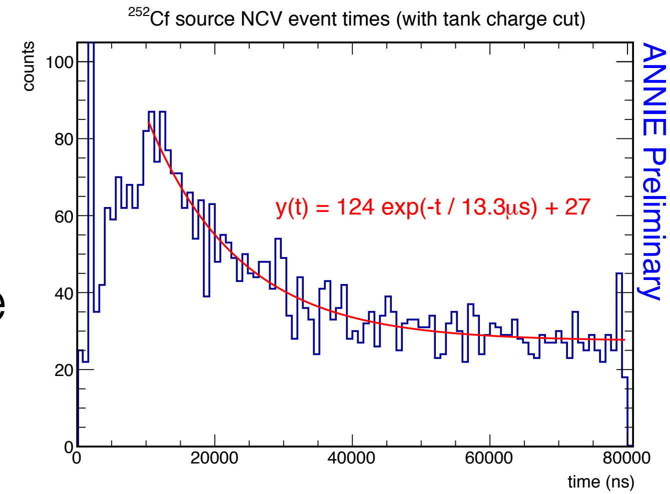
How much background does neutron tagging remove?

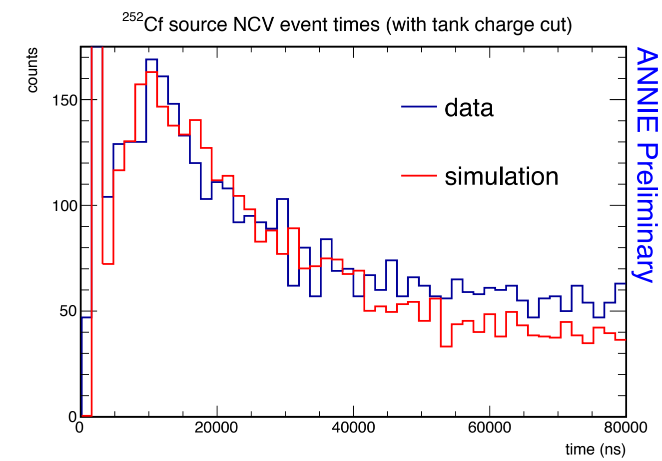
Background uncertainties are an even bigger problem if you have candidate events and want to attribute confidence.

Phase I
Technical Details

Phase I: source calibration

- calibration data was collected using a californium (^{252}Cf) source, triggering on the decay gammas
- we observed the expected capture time constant for the NCV scintillator
- we see fairly good data-MC agreement
- absolute rate calibration limited by uncertainties in the composition of the (very old) source
- plans are under way to repeat these efficiency measurements with a better source



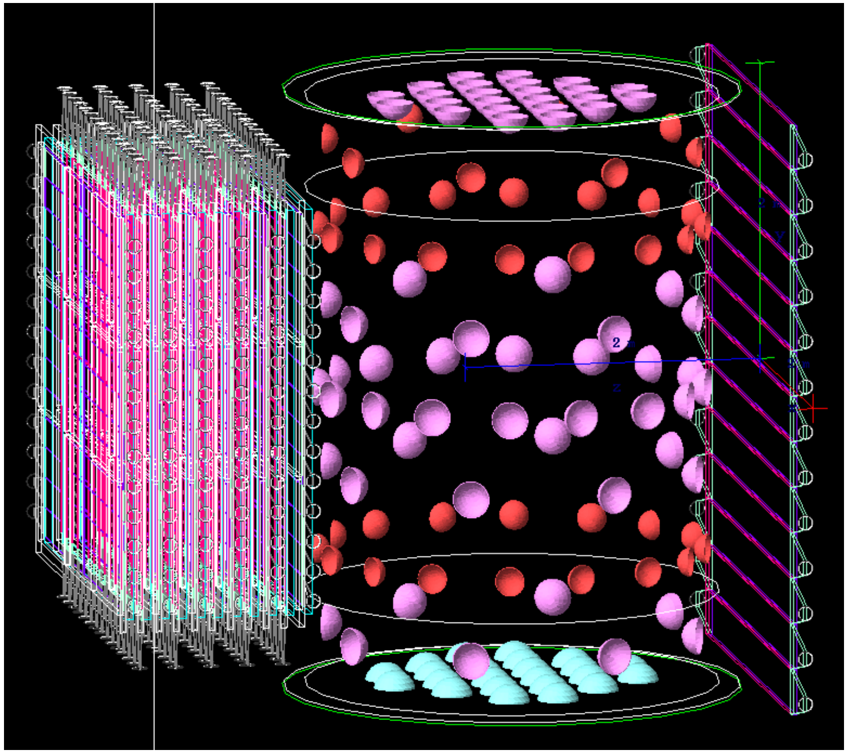


Other calibration sets include min-bias triggers, cosmic muons, LED flashers

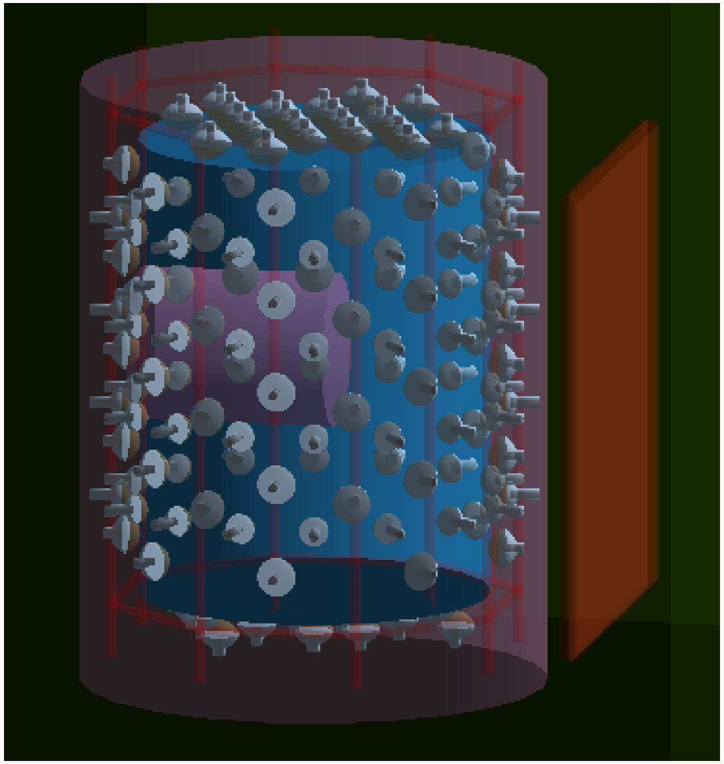
Phase II
Technical Details

Phase II Simulations and Design Specs

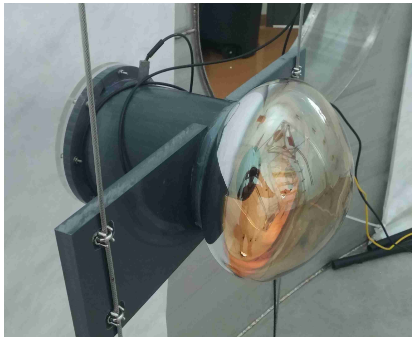
WCSim model



RAT PAC



Acquired PMTs for ANNIE phase II



19 LUX PMTs

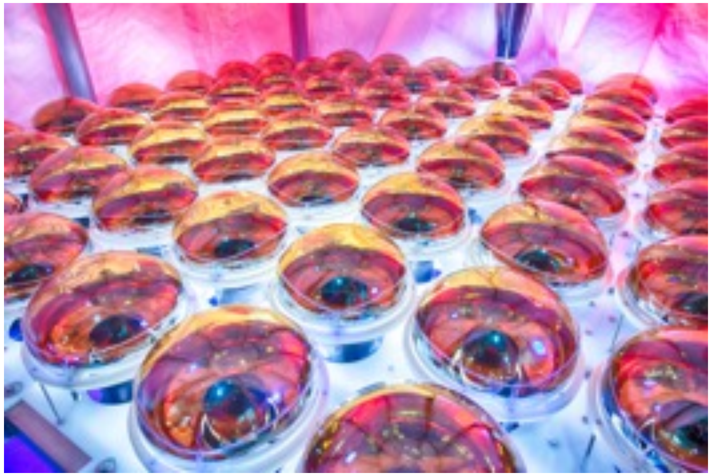
22 ETL (LBNE) PMTs

45 WATCHMAN PMTs

(see ANNIE letters of support)

- Sufficient PMTs have been identified to be able to limit acquisition of new PMTs

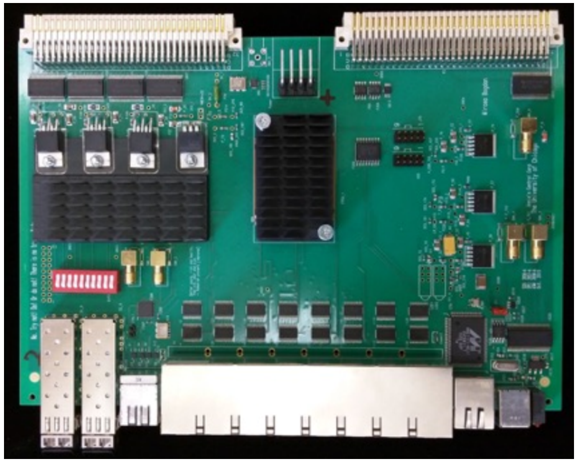
60 existing PMTs to be returned



Phase II DAQ and electronics

- PMT and MRD readout systems are already working and expandable. We only need to purchase more channels
- The LAPPD, PSEC-4 readout system is largely complete and pre-built functionality meets most of our needs. Work to finish PSEC development is ongoing at UC and IA State over this summer, into early fall
- The modular DAQ system is working and stable, with most of the needed functionality. LAPPDs to be added soon.

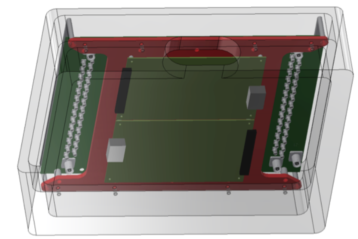
ACDC Card
Eric Oberla, University of Chicago

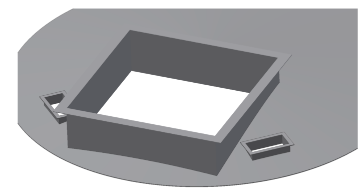


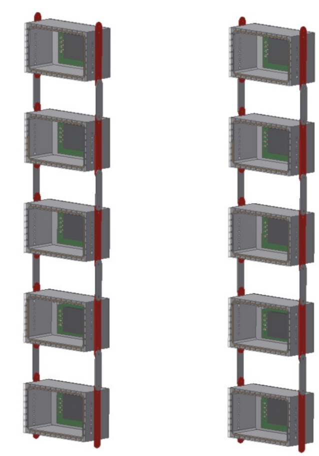
ANNIE Central Card
https://arxiv.org/abs/1607.02395

Installation of the LAPPD System

- New design for the LAPPD housing assemblies allows for LAPPDs to be installed into the already assembled detector
- The LAPPD system is deployed in columns through slots in the top of the already filled detector
- This decouples the LAPPD timeline from the rest of the detector assembly and allows easier access to our most critical system
- First aluminum housing is being machined at UC Davis and will undergo first tests this month







Gd Water Systems

Product Data Sheet

AMBERSEP® 400 SO_4

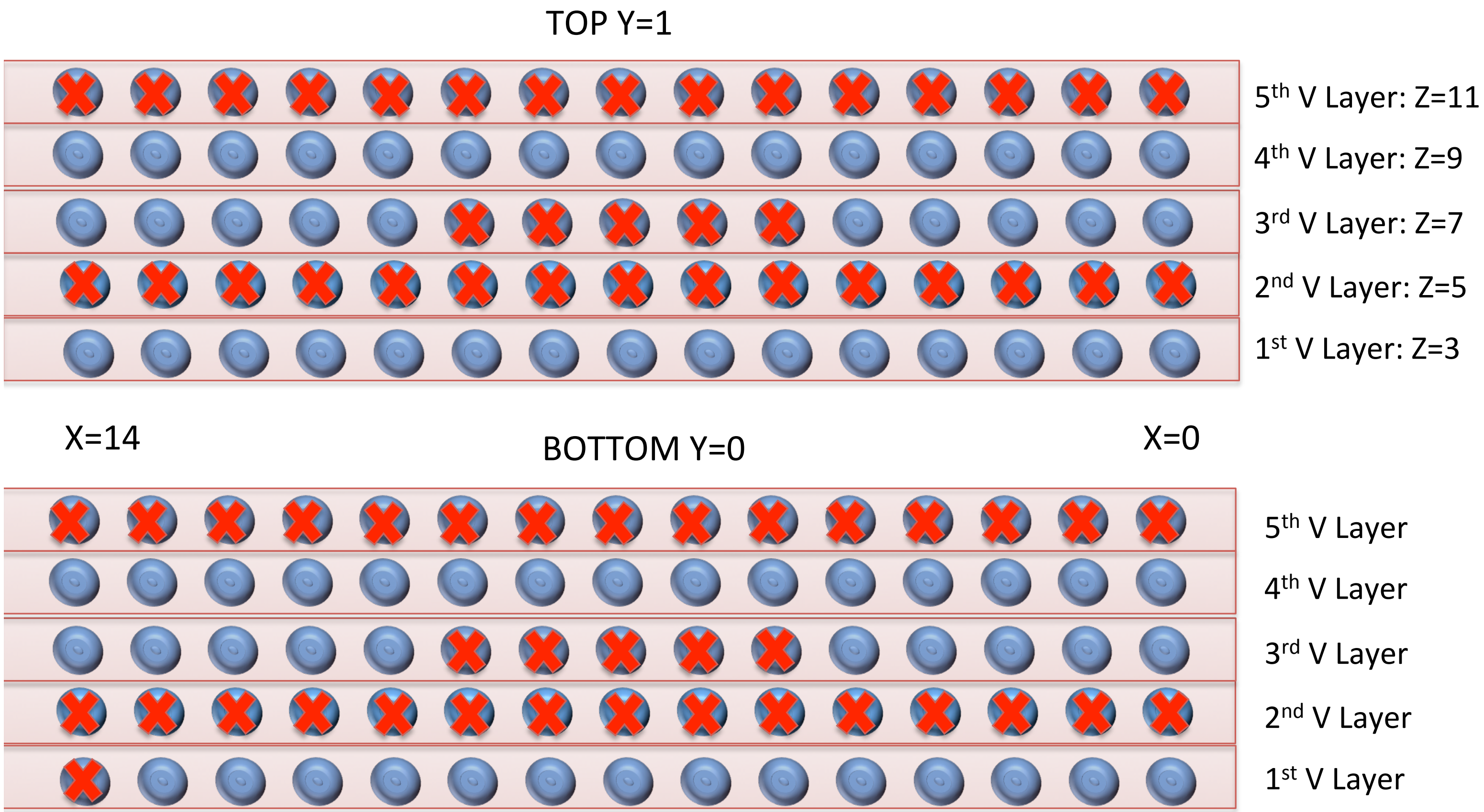
Industrial Grade Strong Base Anion Exchanger

Introduction

AMBERSEP 400 SO_4 is a gel type, strongly basic, type 1 anion exchange resin with superior performance for uranium recovery. Its excellent selectivity for the uranyl sulphate ion over other anions, its high operating capacity, excellent mechanical and physical stability and its resistance to fouling make it the resin of choice. AMBERSEP 400 SO_4 is well suited for recovery of uranium from sulphuric acid leach systems using fixed beds, in situ leaching, fluidized beds or Resin In Pulp (RIP) applications.

- Super-K needs an expensive, *lossless* filtration system
    - given the Super-K scale, Gd losses at the few percent level represents a lot of Gd
- ANNIE is small enough that we can afford small losses of Gd over time
    - it can be measured
    - capture efficiency is logarithmic with concentration
    - the Gd can be replaced in situ
- ANNIE water purification needs can likely be met with our current skid, using a special replacement filter based on a resin used by Super-K in place of the DI filter

MRD Refurbishment (Part of Phase I scope)



71 missing paddles in total

ECL #14 by Carrie

Jun/29/17 E. Tiras, Iowa State University 3

MRD Refurbishment (Part of Phase I scope)

What do we have on hand?

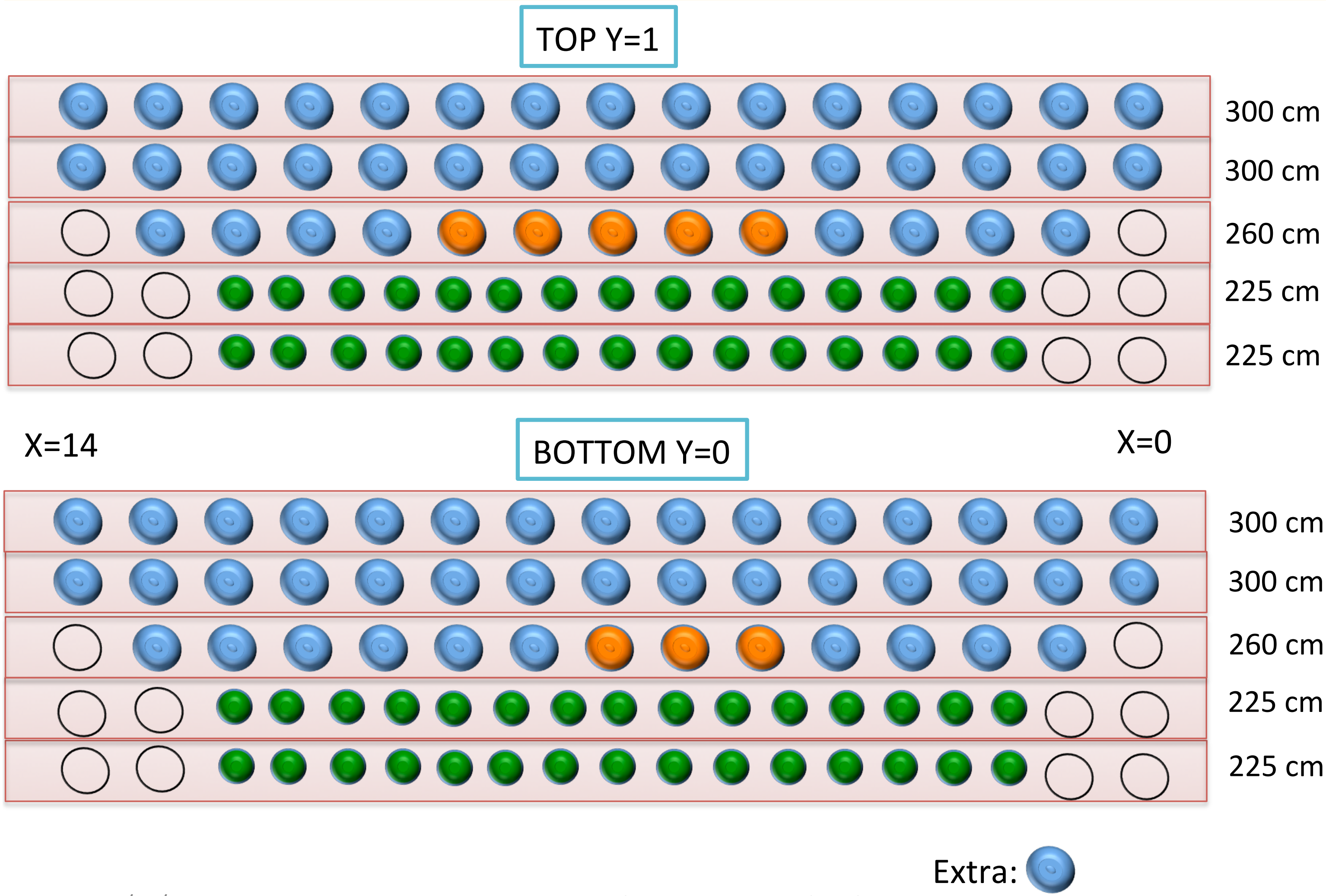
- 8 paddles --- 0.8 cm thick, 20 x 150 cm – will cut them off
- 60 paddles --- 1.4 cm thick, 15 x 150 cm – will cut them off

What do we need?

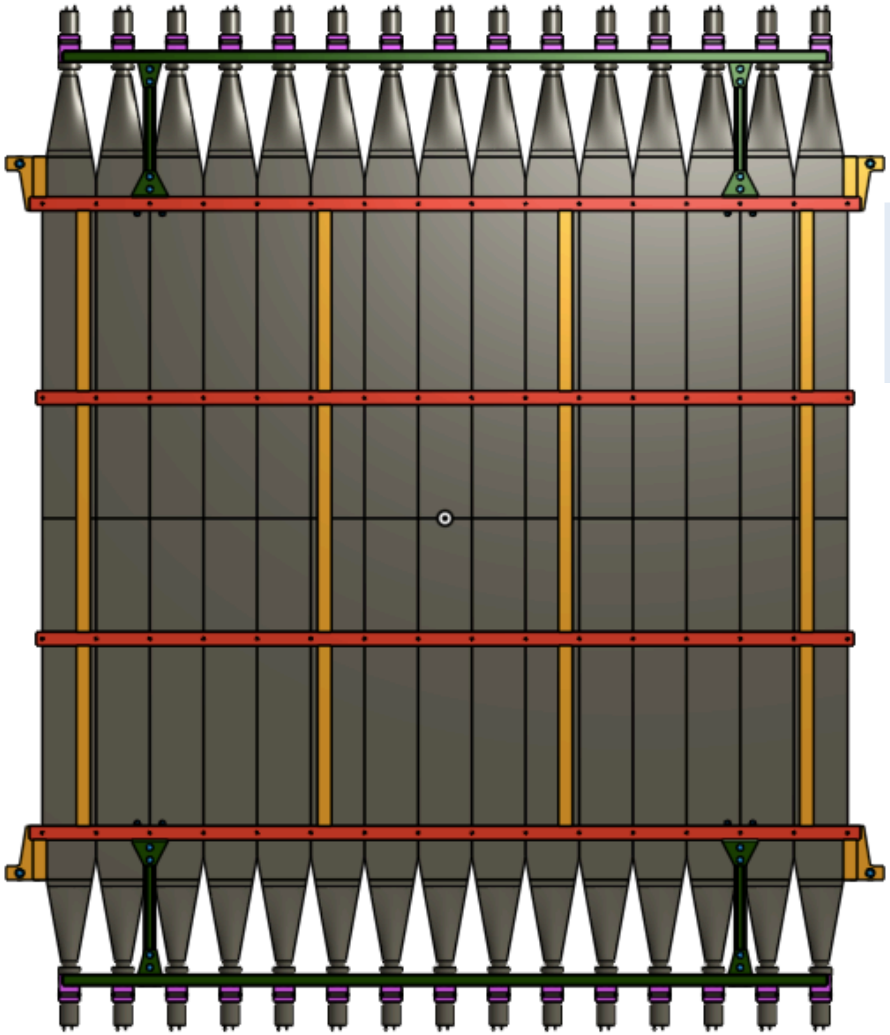
- 71 paddles --- 0.8 cm thick, 20 x 138 cm scintillators

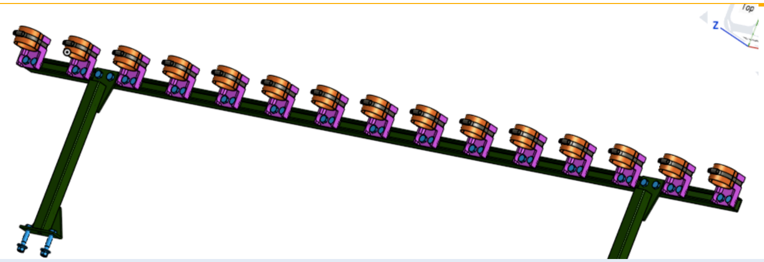
The active area of a vertical layer is 300 x 276 cm^2.

MRD Refurbishment (Part of Phase I scope)

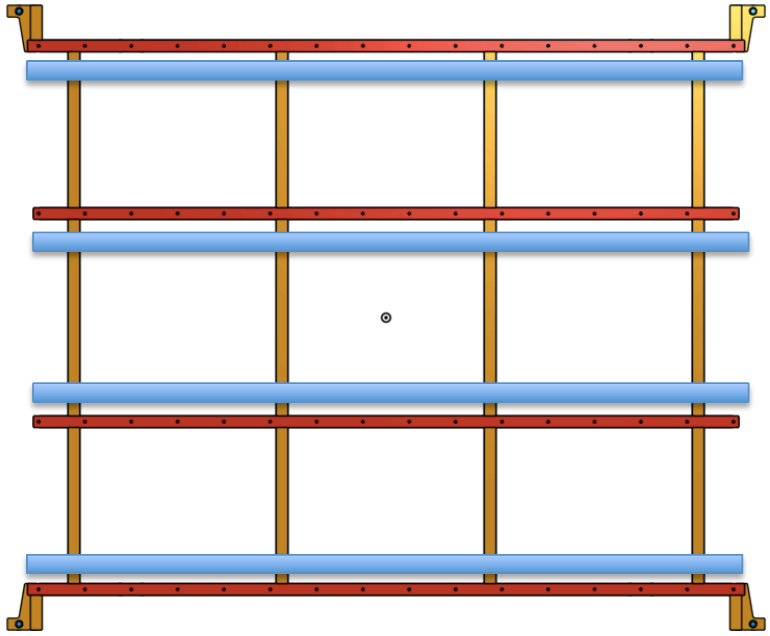


MRD Refurbishment (Part of Phase I scope)





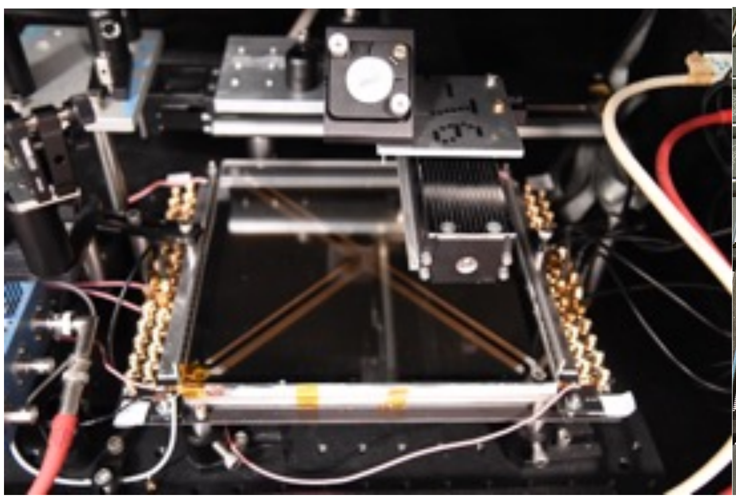
Modification for the aluminum frames for 2nd and 5th vertical layers is necessary – new bars with the holes will be mounted.



Phase II
Planning Details

ANNIE Phase IB Goals

- Obtain and Test an LAPPD
- Vertical integration of PSEC electronics system
- Water Proof Housing for LAPPDs
- Water Purity/Gd-Compatibility
- Complete system testing with LAPPD or 6cm tile




ANNIE Effort

Iowa State

- 1.5 FTE among 4 PIs
- 1.7 FTEs among 4 post docs

UC Davis

- 0.4 FTE PI synergistic with THEIA
- 1.25 FTEs among 2 post docs
- 1 FTE graduate student
- 1 FTE post-bac
- Mechanical Engineering support

LLNL

- 0.2 FTE PI (estimated/pending)
- 0.2 FTE postdoc (estimated/pending)
- Watchboy PMTs

UC Irvine

- Synergistic work with 2 PIs
- Engineering and tech support
- PMTs and Gd and related expertise

U Chicago

- Synergistic work with PI
- Electrical Engineering and technical support
- Significant electronics contributions

Sheffield

- 0.2 FTE PI
- 1 FTE graduate student
- HV system
- Simulations/Reconstruction

Queen Mary

- 0.1 FTE PI
- 0.3 FTE post doc
- Electronic Engineering support
- DAQ

Edinburgh

- 0.2 FTE PI
- 0.5 FTE post doc
- Simulations/Reconstruction

Fermilab Effort

Table 5: Labor estimate for remaining work on the inner structure of the ANNIE tank (source: J. Kilmer).

activity	# of tech-days	# of welder-days
modifications to the side of the inner structure	10	4
modifications to the top of the inner structure	1	1
adding 6 mailbox slots and 2 J-tubes to tank lid	11	3
rust proofing of the bottom of the tank lid	3	0
TOTAL:	26	8

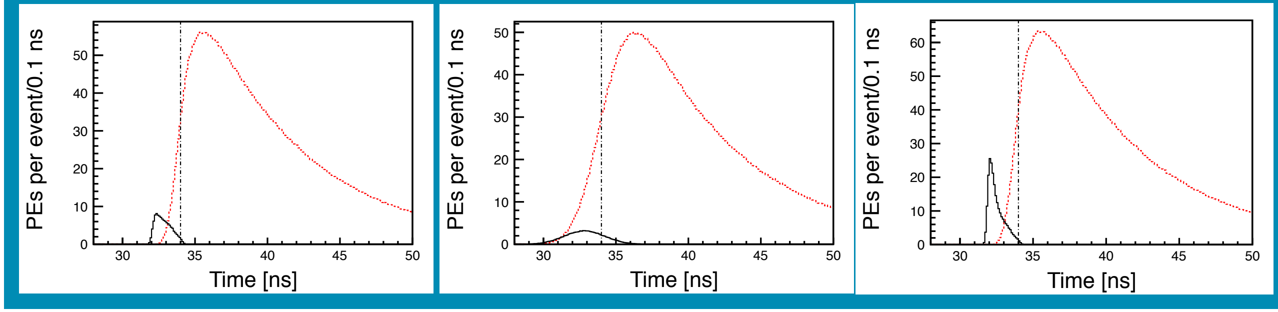
. As a reference during the February 2016 construction and installation of the ANNIE Phase I detector we used a total 43 person days of technician labor. We expect this to be an upper limit on the e↲ort necessary to reinstall the detector as most elements of experiment are already built.

Phase I required roughly 22 person-days of electrical work, most of which was spent significantly modifying the 3 crates we need to execute Phase II. Some time was also spent helping the collaboration with rack protection needs. Since all of the VME work and most of the rack protection work is already complete, we estimate that we will need roughly 1 person-week focused specifically on the minor modifications to the rack monitoring and power distribution particular to Phase II.

Next Gen Water-based Neutrino Detectors

Cherenkov Scintillation Separation

Timing to separate between Cherenkov and scintillation light

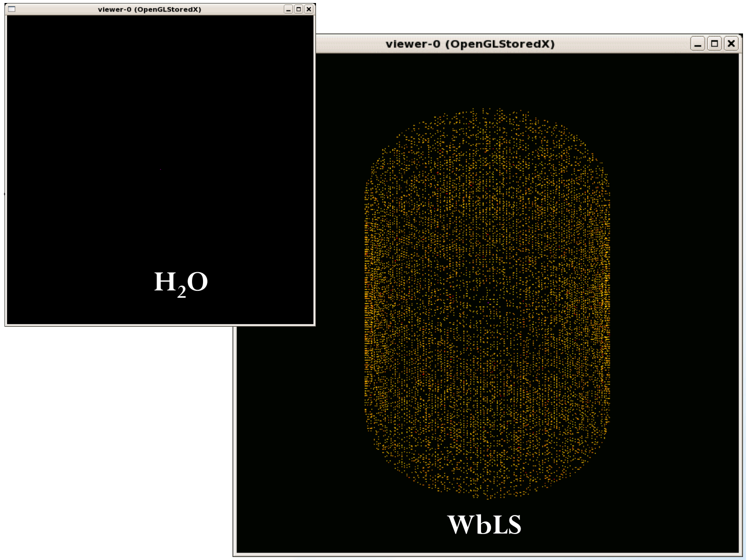


(a) Default simulation. (b) Increased TTS (1.28 ns). (c) Red-sensitive photocathode.

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

K+ in water and liquid scintillator

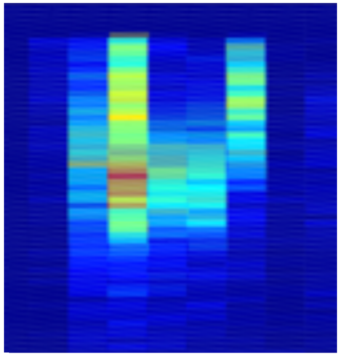


Cherenkov + scintillation -> tracking + calorimetry

Detecting scintillation light as a means of seeing particles below Cherenkov threshold

Spatial Granularity + Timing

$$\mathcal{L}(\mathbf{x}) = \prod_{\text{unhit}} (1 - P(i\ \text{hit}; \mathbf{x})) \times \prod_{\text{hit}} P(i\ \text{hit}; \mathbf{x})\ f_q(q_i; \mathbf{x})\ f_t(t_i; \mathbf{x})$$



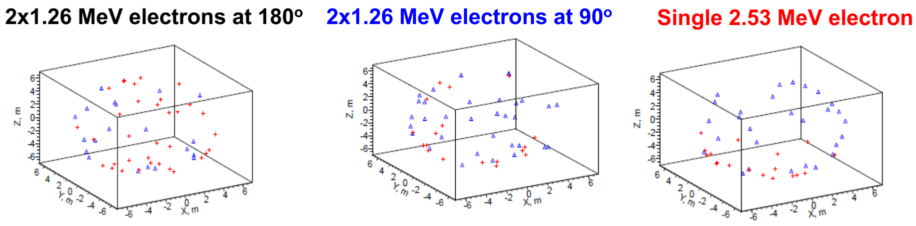
with conventional PMTs

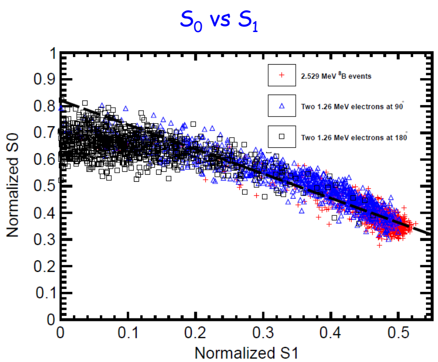
- Measure a single time-of-first-light and a multi-PE blob of charge
- Likelihood is factorized into separate time and charge fits
- History of the individual photons is washed out

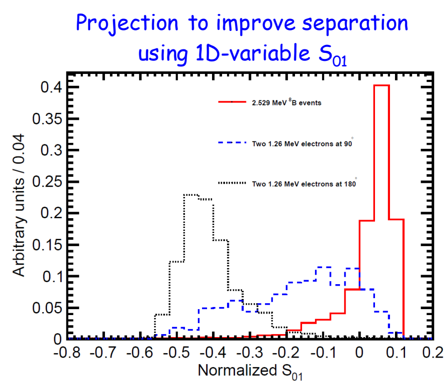
with hires imaging tubes

- 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)

Precision Timing and Spatial Granularity

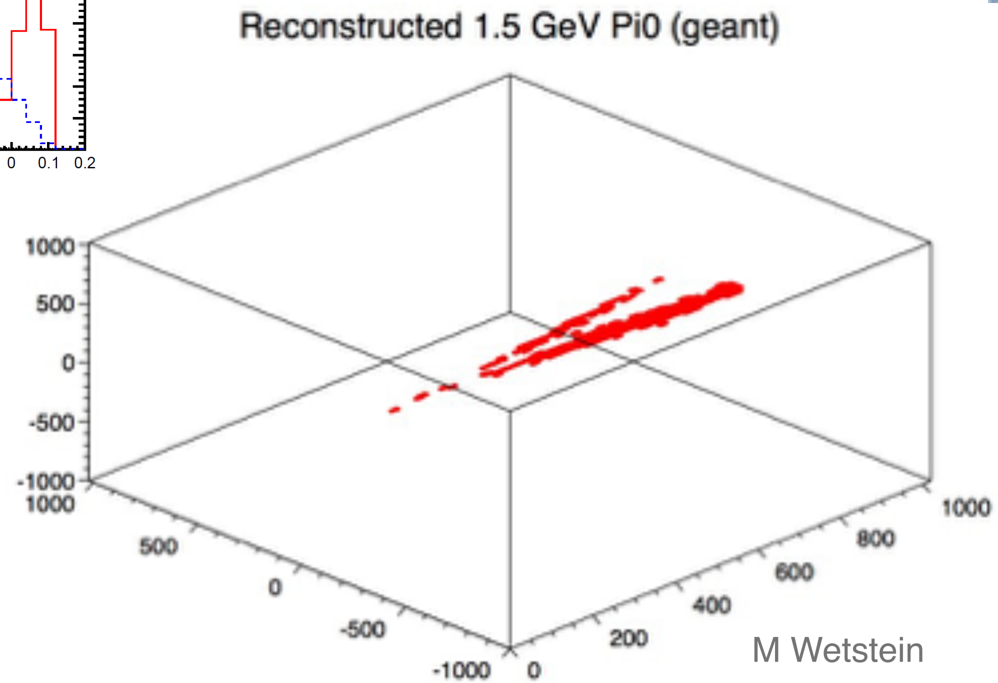






Spherical harmonics of double beta topology - a new way to reject backgrounds but requires good timing. (Elagin, et al) https://arxiv.org/abs/1609.09865

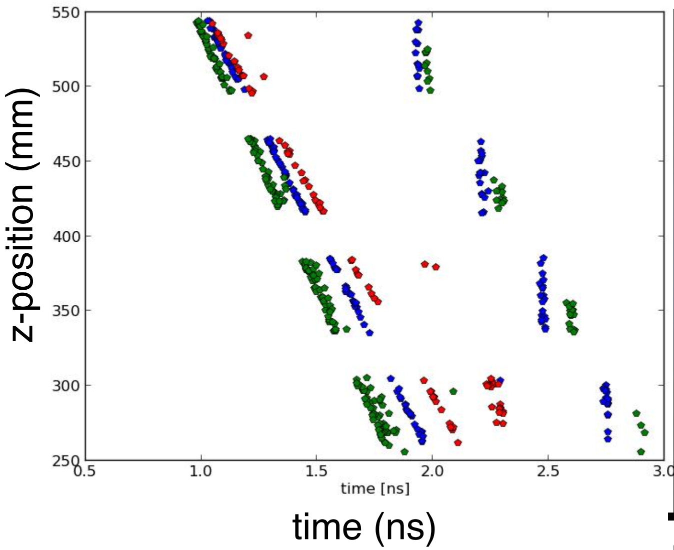
Time reversal algorithms ("working backwards") provide narrow down the details of the event.

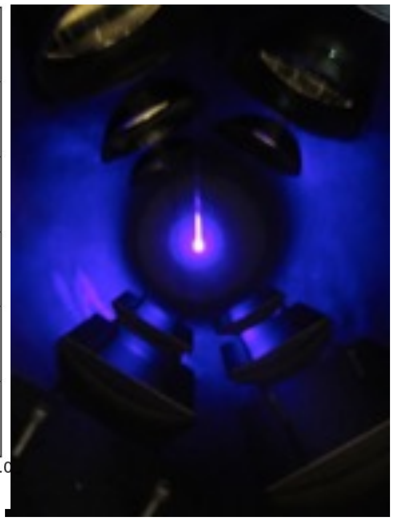


M Wetstein

Imaging Optics

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

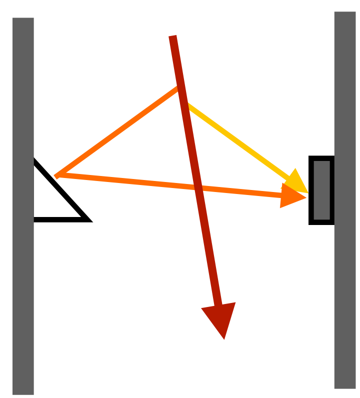




"Optical TPC"

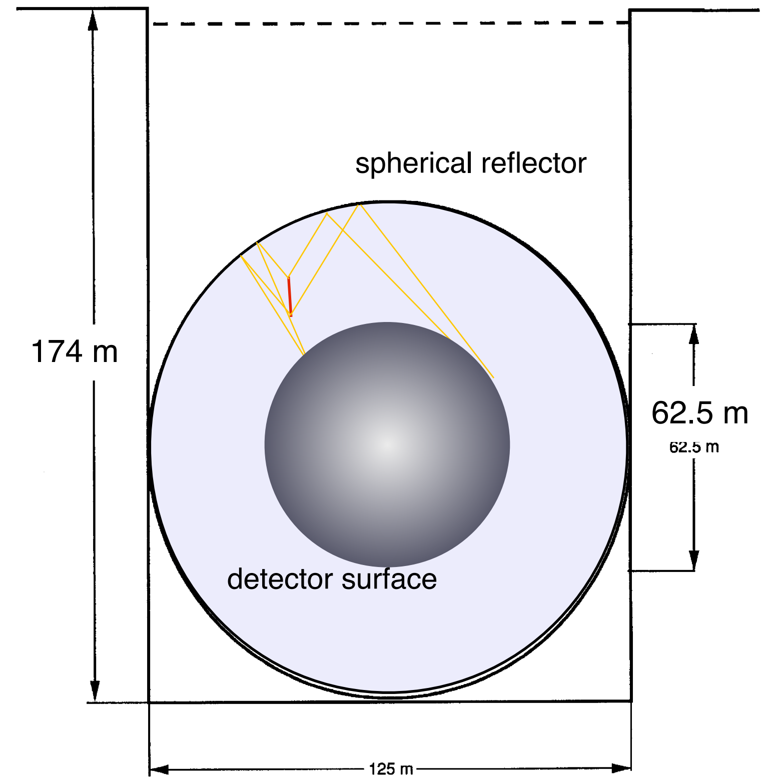
E. Oberla, H. Frisch, R. Northrop

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



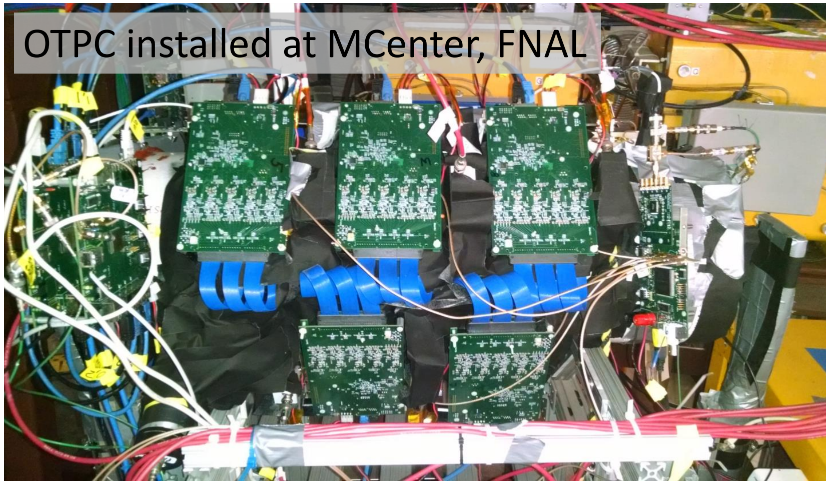
Aqua-RICH

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



Optical TPC

Eric Oberla (UC grad student) finished implementing self-triggering in the PSEC electronics firmware. Operated a 180 channel system on a test beam experiment, using the feature.



A picture of the optical TPC installed at MCenter at Fermilab. Along the tube axis, 5 PSEC ACDC cards instrument 5 Planacons in a stereo configuration. One additional Planacon and ACDC card instrument the front of the tube. This 180 channle system is controlled by two Central Cards.

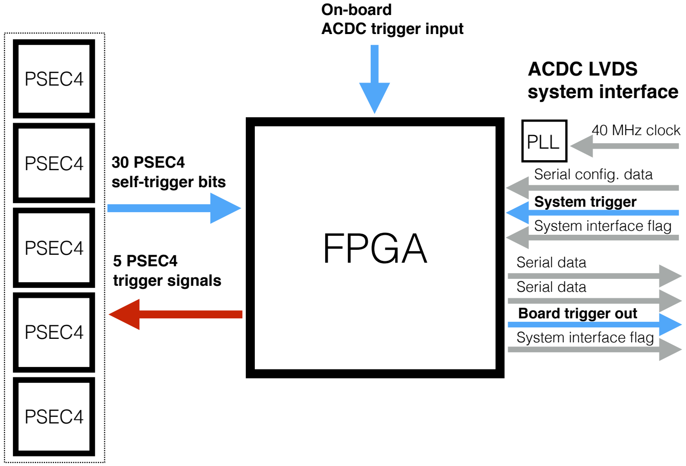
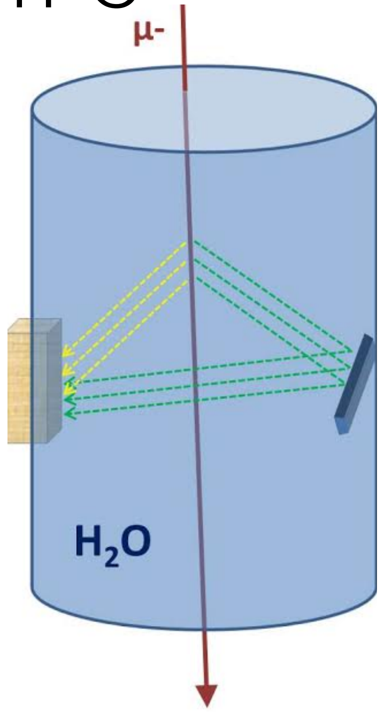
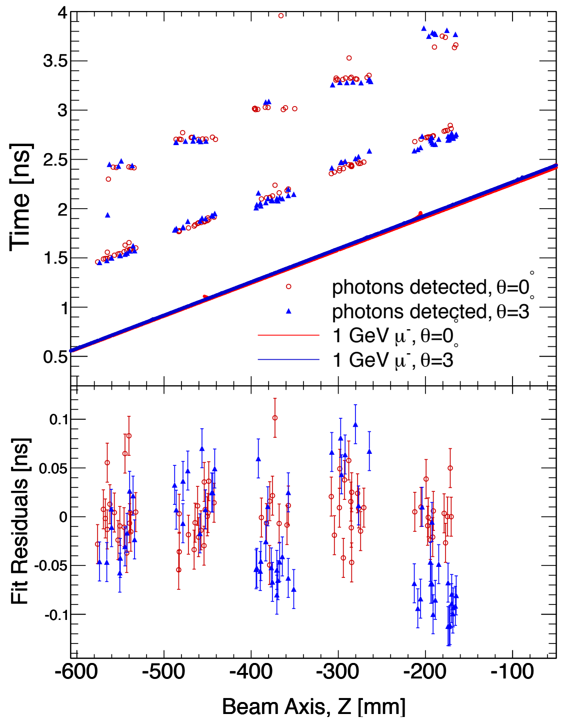


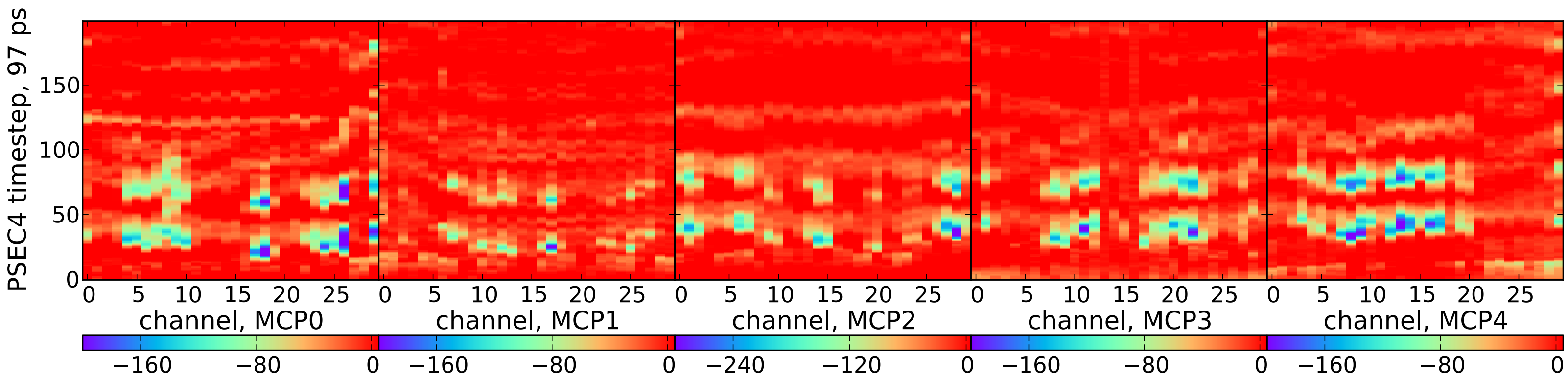
Diagram illustrating the level-0 system trigger for the OPTC, which relied heavily on coincidence with self-trigger bits from PSEC4 chips.

https://arxiv.org/abs/1510.00947

Optical TPC



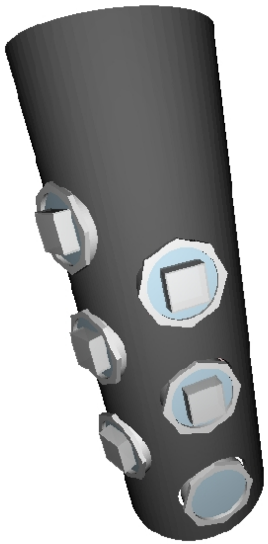


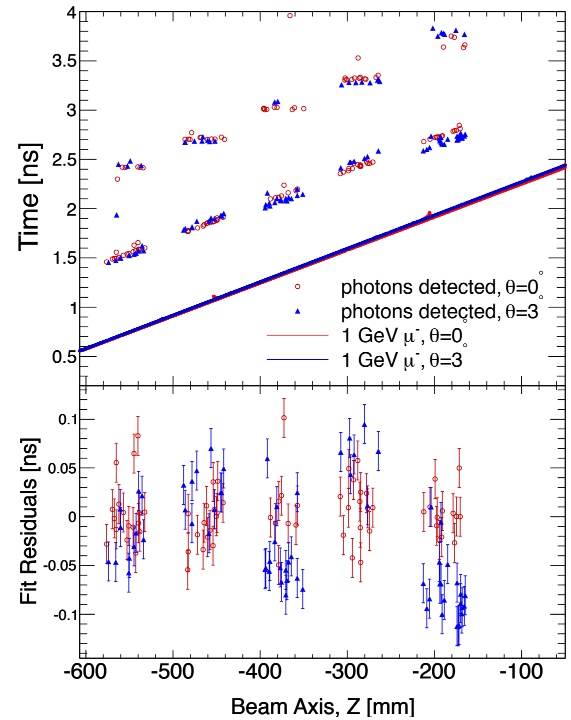


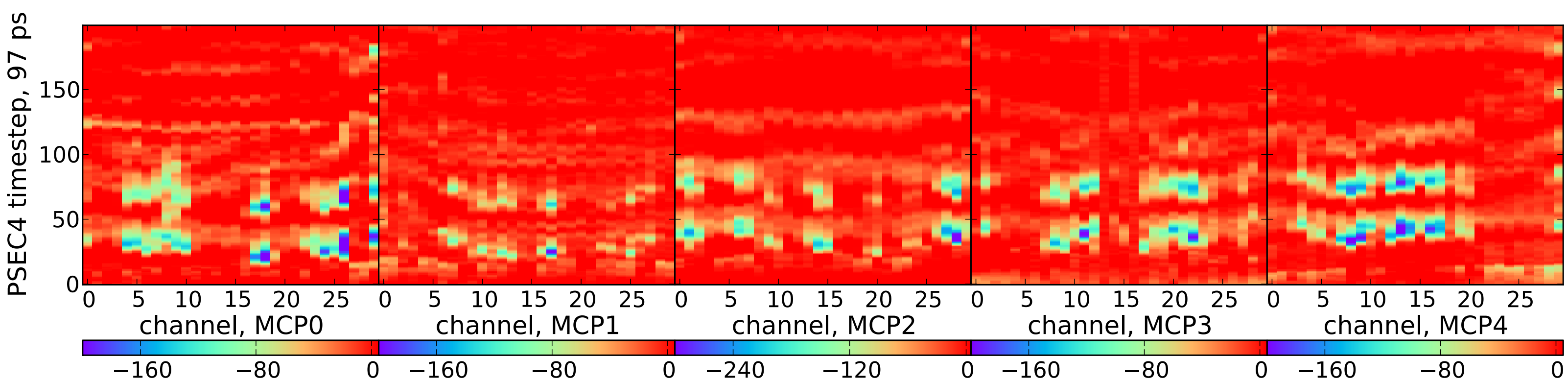
(a)

https://arxiv.org/abs/1510.00947

Optical TPC







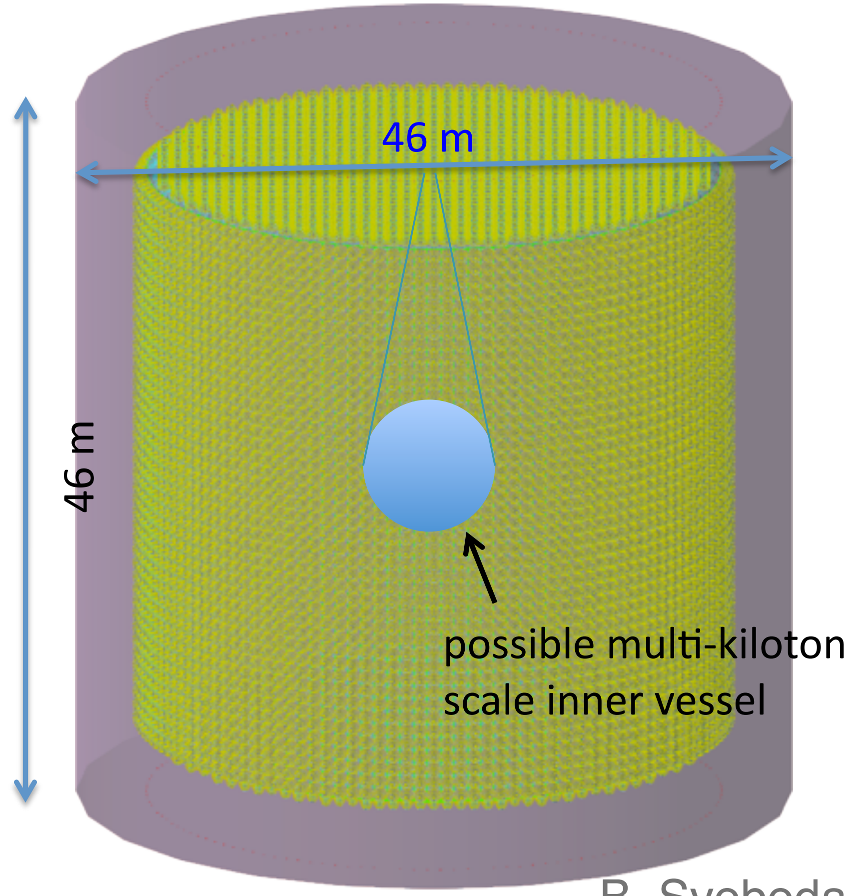
(a)

https://arxiv.org/abs/1510.00947

THEIA Concept

arXiv:1409.5864

- **50 kilotons** fiducial
- **Deep depth** (>4000 mwe)
- **Fast timing**, high efficiency photosensors, high coverage
- **Isotopic loading**, possibly with a balloon to avoid "wasting" isotope and to achieve long attenuation lengths
- **Reconfigurable**, capable of economically for long periods to have a broad program



B. Svoboda

Theia

- Advances in LS technology and photosensors make possible a hybrid WC/LS detector that could be located deep underground at the LBNF, now being built
- Very broad and flexible physics program at deep (4200 mwe) and remote (from reactors) site that will also have a powerful neutrino beam.
- Very active and ambitious R&D program
- Internatoonal collaboration forming now, new members welcome

B. Svoboda

Big Picture

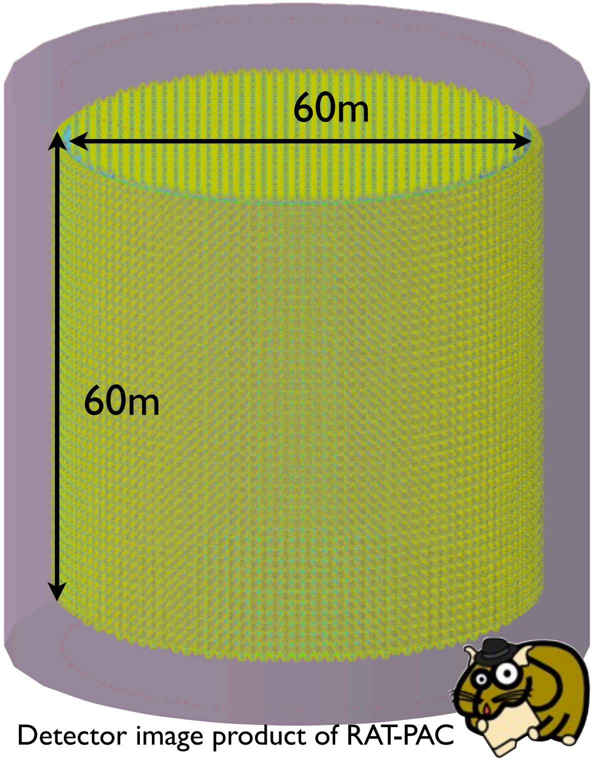
Over the next 5-10 years, it may be possible to develop new and advanced water and scintillator neutrino detectors concepts

These detectors can bring a much needed scale and physics diversity to neutrino experiments in the US and abroad.

A key ingredient in advancing this technology is the development of advanced photosensors.

Modest investments in R&D and in small and medium scale experiments can go a long way in making this new technology happen.

THEIA



Detector image product of RAT-PAC