Accelerator
Neutrino
Neutron
Interaction
Experiment

Status and Future Plans

Frank Krennrich, Iowa State University
for the ANNIE Collaboration

Collaboration

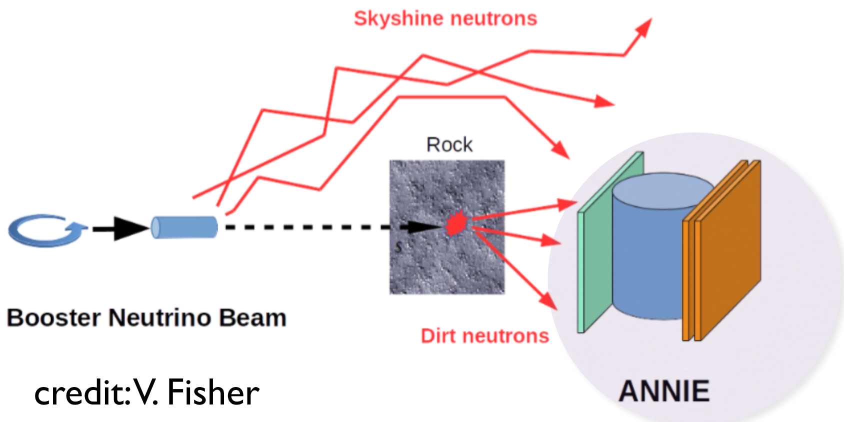
- Argonne National Laboratory
- Brookhaven National Laboratory
- Fermi National Accelerator Laboratory
- Imperial College of London
- Iowa State University
- Johns Hopkins University
- MIT
- Ohio State University
- Ultralytics, LLC
- University of California at Davis
- University of California at Irvine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

Outline

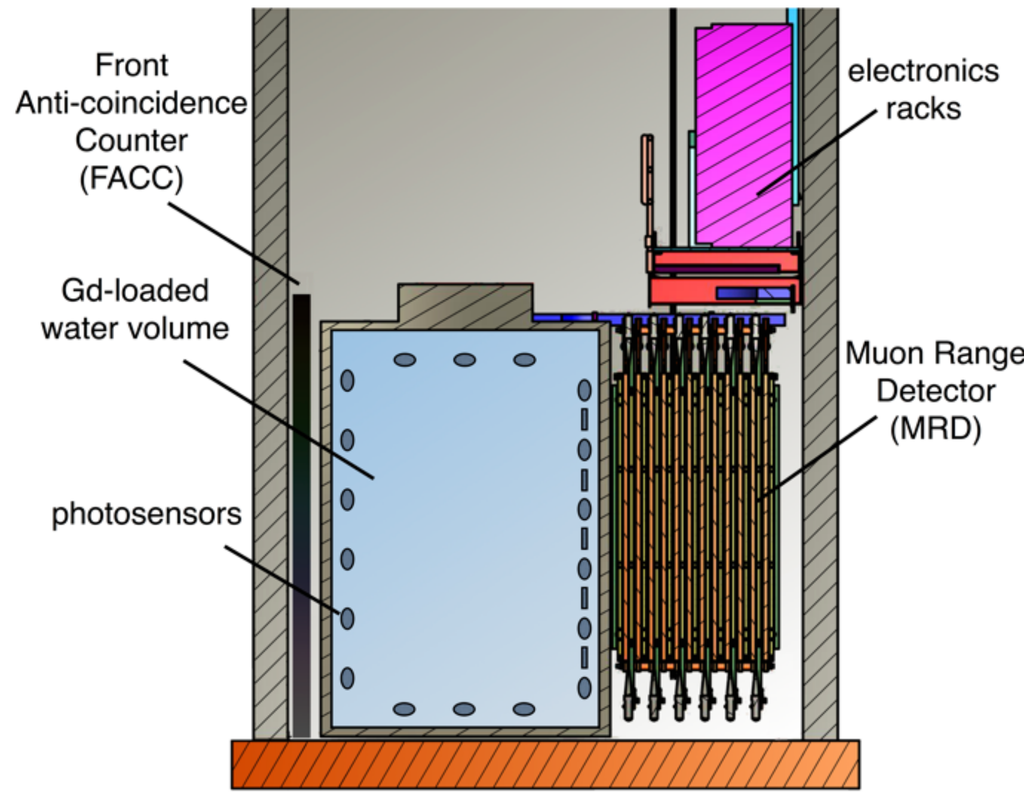
- What is ANNIE?
- Physics Motivations
- ANNIE Design Considerations
- Status

What is ANNIE?

- Study final state neutron abundance of neutrino interactions at 0.5 - 3 GeV using neutrino beam (BNB at Fermilab).
- Gd-doped water: **large cross section for neutron captures** from neutrino interactions.
- 8-inch PMTs for detection of neutron captures (time scale: **30 - 100** us).
- Large Area Picosecond Photodetectors (LAPPDs): < **100 ps time resolution** for improved track reconstruction of muons.
- MRD for **muon range** measurement.
- FACC to **veto muons** not originating in volume.
- Phase I: neutron background measurement.
- Phase II: physics measurement.

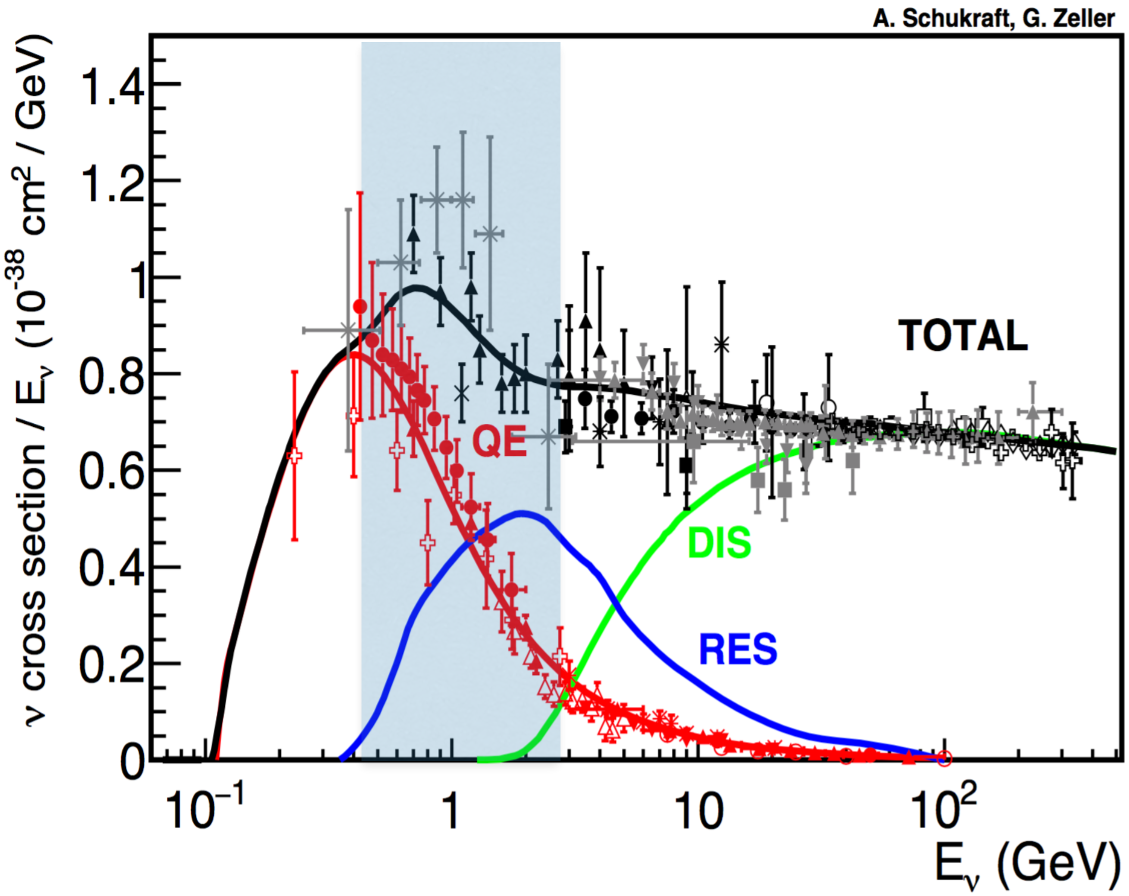


credit: V. Fisher



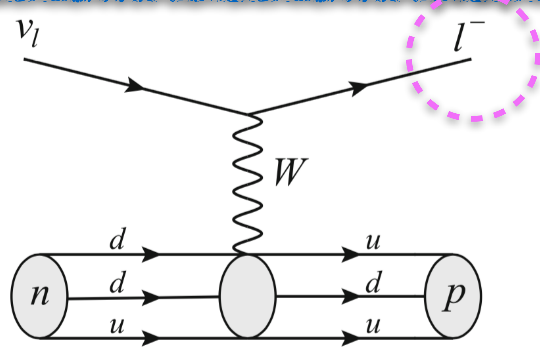
Physics Motivations: Nuclear Physics Effects

- **Measure the abundance of final state neutrons** from neutrino interactions in water at 0.5 - 3 GeV.
- A key physics measurement, e.g., to model the **nature of "CCQE-like" neutrino/nucleus interactions.**
- Cr**oss section in the QE-regime** is **substantially affected by multi-nucleon ejection (np-nh)** and of great interest for models, and relevant for precision oscillation experiments.
- **ANNIE** will measure neutron yields as a **function of energy** and **direction of the final state muons.**
- **ANNIE will provide** a sample of **dominantly-pure neutrino events**.



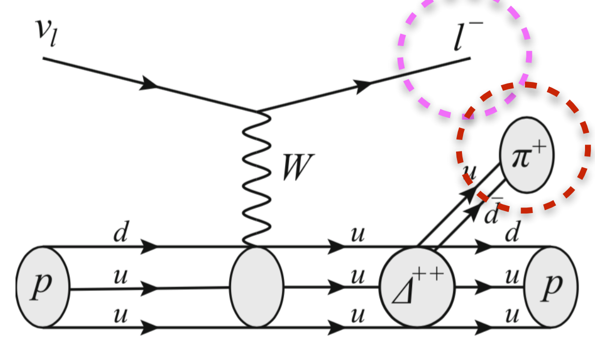
Relevant Neutrino Interactions

QE



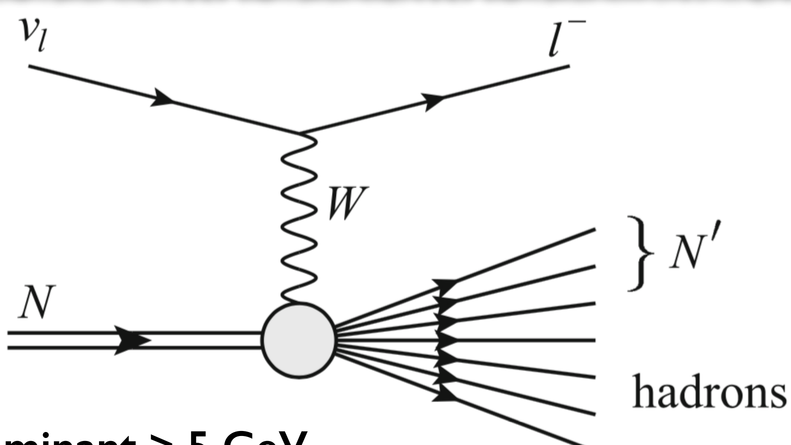
- **dominant < 1 GeV** for CCQE, NCE
- lepton mostly in forward direction

RES



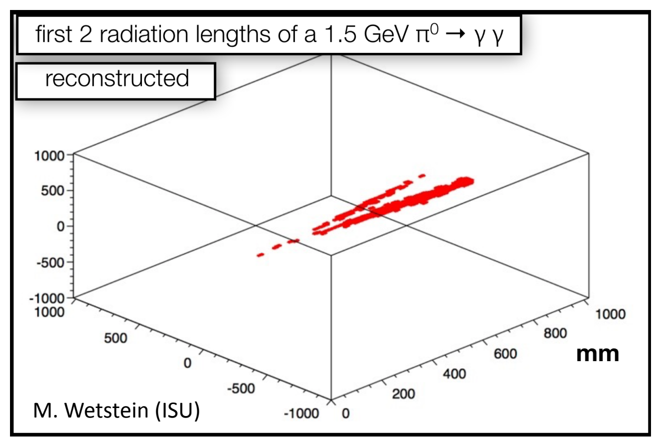
- CC1pion, NC1pion
- can also produce FS **neutrons**, protons, …

DIS

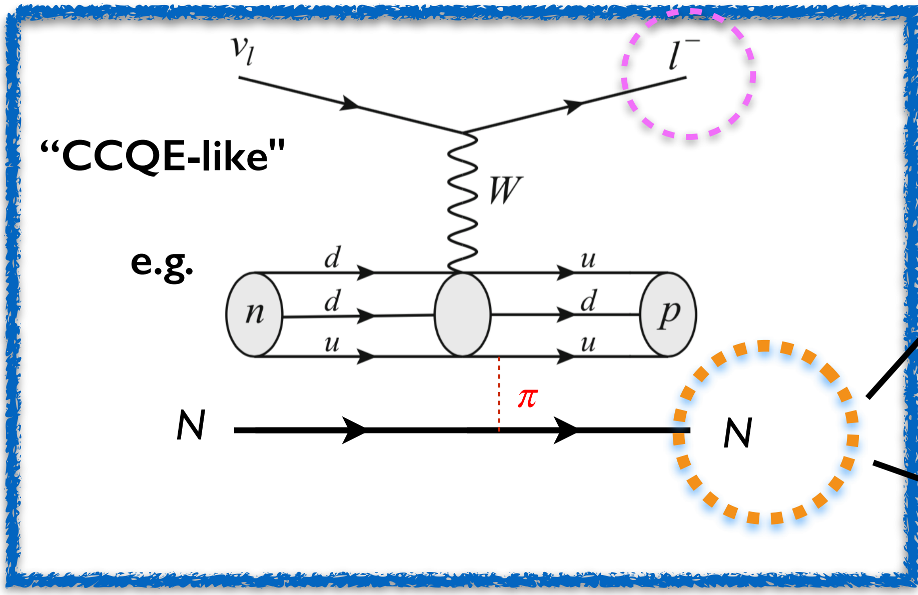


- **dominant > 5 GeV**
- interaction with quarks, high momentum transf.

ANNIE can potentially **separate 2 track events**



… additional processes …



neutron(s):
neutron capture in Gd-doped water produces delayed signal (30 us)

proton multiplicity:
liquid-argon technique

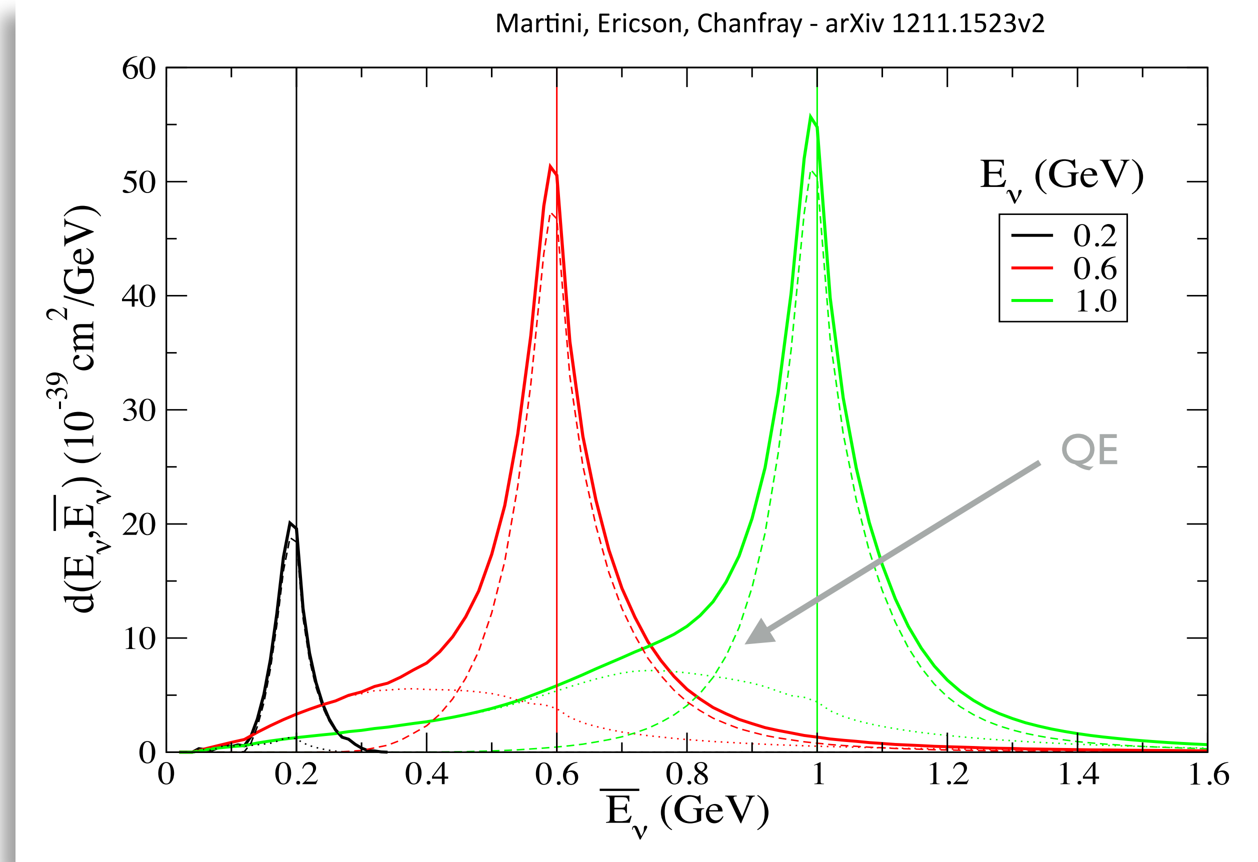
i) **Initial state** nucleon-nucleon correlations: excitation of particles.

ii) **Final state correlations**: scattering between a struck nucleon and spectator particles.

iii) Two-nucleon meson currents: **meson exchange** between two interacting nucleons.

Physics Motivations: Energy resolution (QE)

- The **reconstructed energy** from oscillation experiments differs from the **true neutrino energy.**
- Energy dependent, **asymmetric biases** in the energy reconstruction imply systematic limitations to oscillation analyses.
- **Multi-nucleon contributions** (dotted) may be largely responsible.
- Measurement of the proton (liquid Argon) and **neutron multiplicity (Gd-water doped Cherenkov)** as a **function of energy** is a key input for reducing these nuclear physics related systematic energy biases.



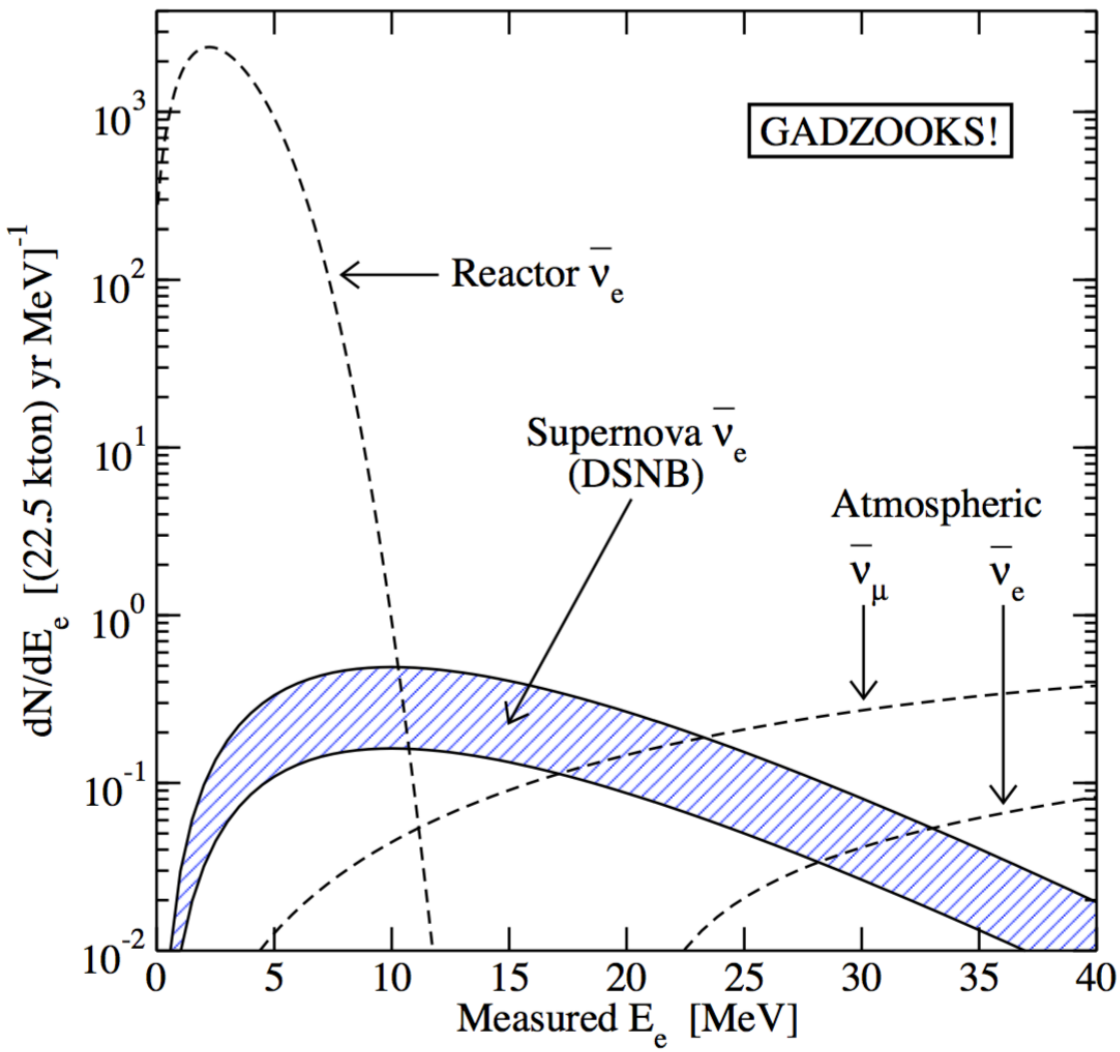
Physics Motivations: Supernova Neutrino Background

- Accumulation of neutrinos from all past supernovae provide **important cosmological constraints** to supernova rate, star formation rate & cosmic infrared background.
- Detection of neutrinos from cosmological distances.
- **Neutron tagging** of neutrino signal:

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

- **dominant background (E > 20 MeV)**: from the **decay of low energy** (sub-Cherenkov) **muons** in water produced by atmospheric neutrinos.
- good understanding of “neutronless” atmospheric neutrino interactions is important to estimate background.

Beacom & Vagins, PRL, 93 (2004) 171101

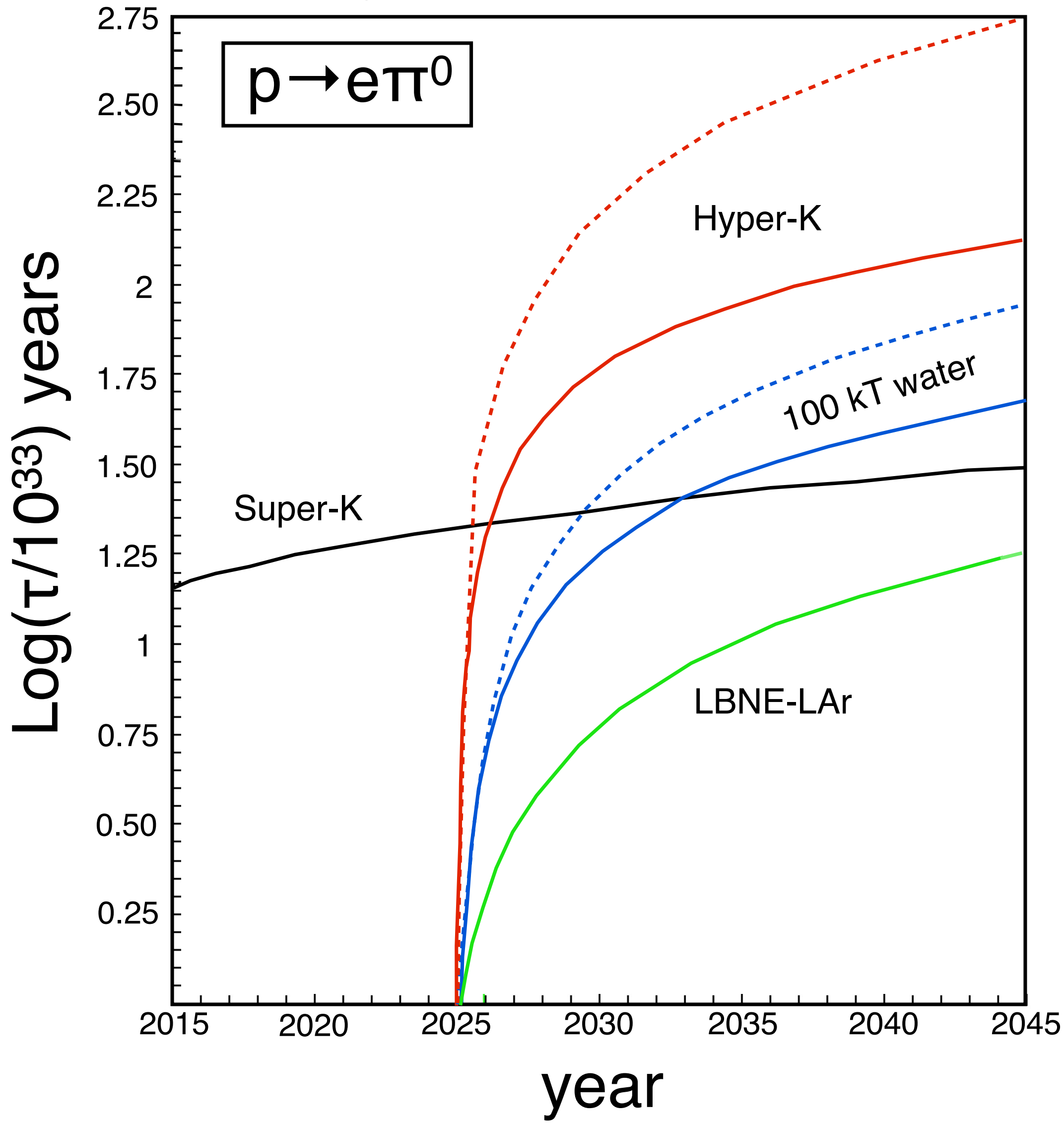


… **very relevant for Super-K-Gd …**

Physics Motivations: Proton Decay

- Proton decays, e.g., $p \rightarrow e^{+} + \pi^{0}$
- > **90% of proton decays** in water are **not expected to yield neutrons**.
- Background: **atmospheric neutrinos**, have **many ways** to produce **secondary neutrons**, however, predictions are not data driven.
- **ANNIE measurements** of neutron abundance in QE interactions **will provide important input for simulations** of atmospheric neutrinos.
- BNB/atmospheric neutrino spectrum similar.
- Better **understanding of background rejection from neutron tagging** (Gd-doped water) is critical for future proton decay experiments.

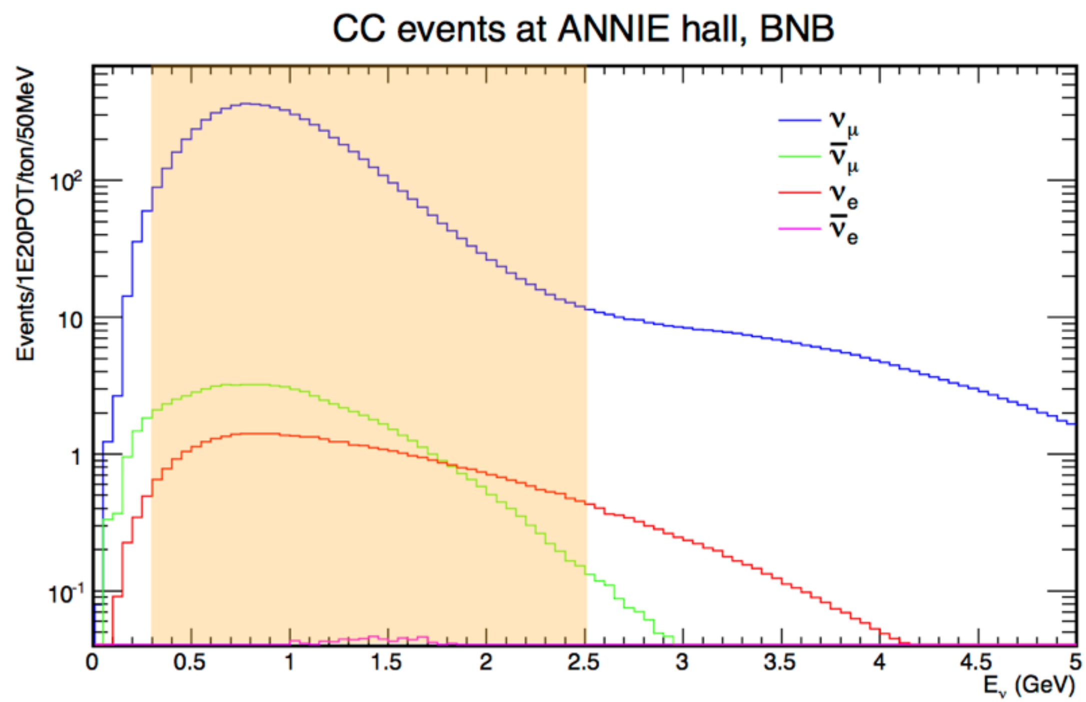
Anghel, I. et al., - arXiv 1504.01480



Beam at ANNIE/SciBooNE Hall

- **Energy range**: spectrum similar to the atmospheric neutrino spectrum, and range comparable to future oscillation experiments.
- 93% purity in neutrino mode.
- **Statistics**: **# of interactions** expected in **1 ton of water** over 6 months.

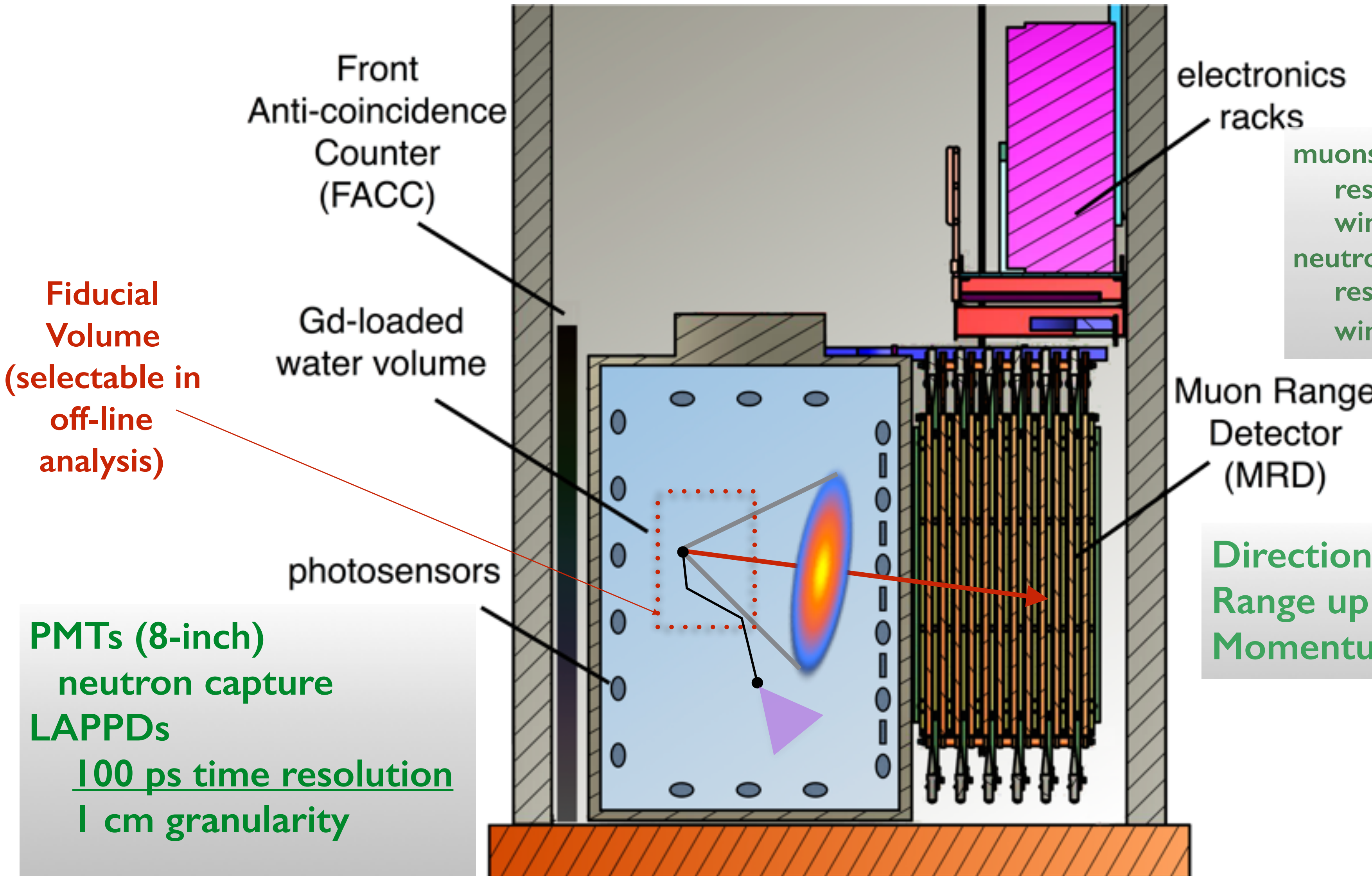
ν-type	Total Interactions	Charged Current	Neutral Current
ν_μ	9892	6991	2900
$\bar{\nu}_\mu$	130	83	47
ν_e	71	51	20
$\bar{\nu}_e$	3.0	2.0	1.0



- **Low pileup rate**. 1 neutrino interaction every 150 spills.

Location	ν_μ events/POT/ton	ν_μ events/spill	Avg. pileup/spill
SciBooNE	$2.80 * 10^{-16}$	0.03	5.0×10^{-5}
NOvA ND	$6.04 * 10^{-16}$	0.65	0.0045
MINOS ND	$1.85 * 10^{-14}$	20	3.76

Basic Design Considerations



muons
resolution ~ 50 ps
window ~ 20 ns
neutron capture
resolution ~ few ns
window ~ 100 us

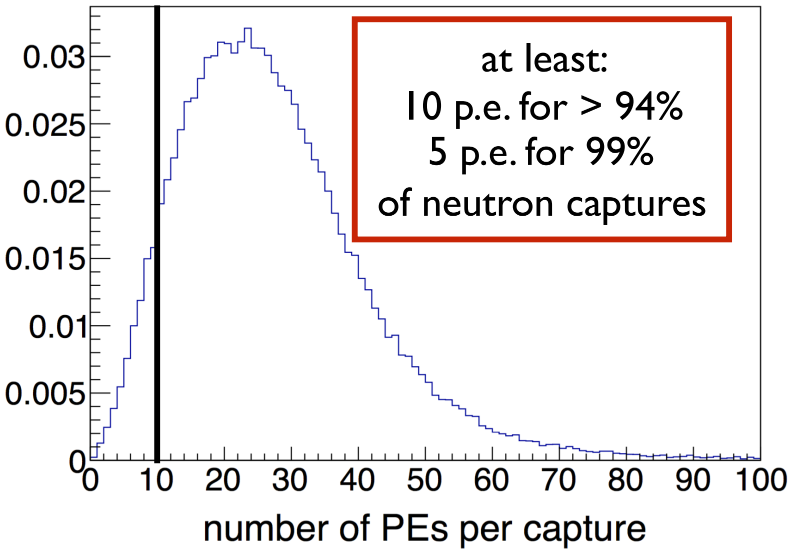
Direction ~ 10 deg.
Range up to 1.2 GeV/c
Momentum res. ~ 20%

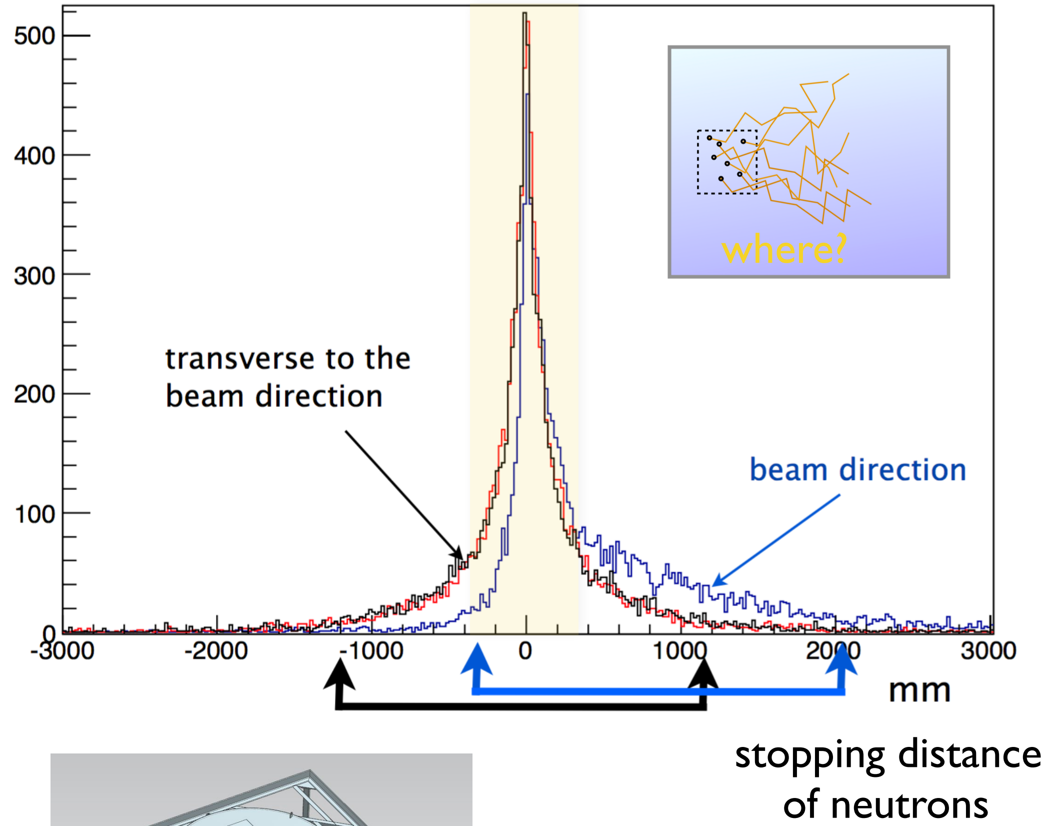
PMTs (8-inch)
neutron capture
LAPPDs
100 ps time resolution
1 cm granularity

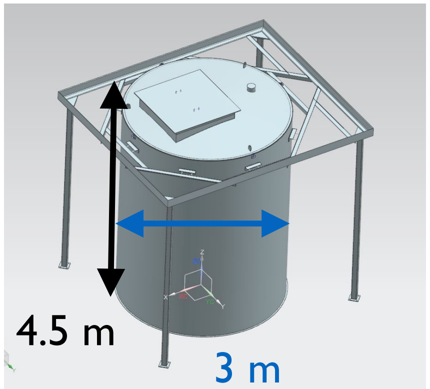
Geometrical Requirements

- Appropriate **size of fiducial volume** (set by analysis) to stop neutrons within the water tank.

- **PMT coverage** to ensure the detection of sufficient light from neutron captures (simple case with 100 PMTs, 20% Q.E.)

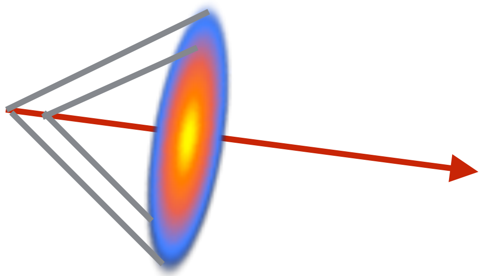




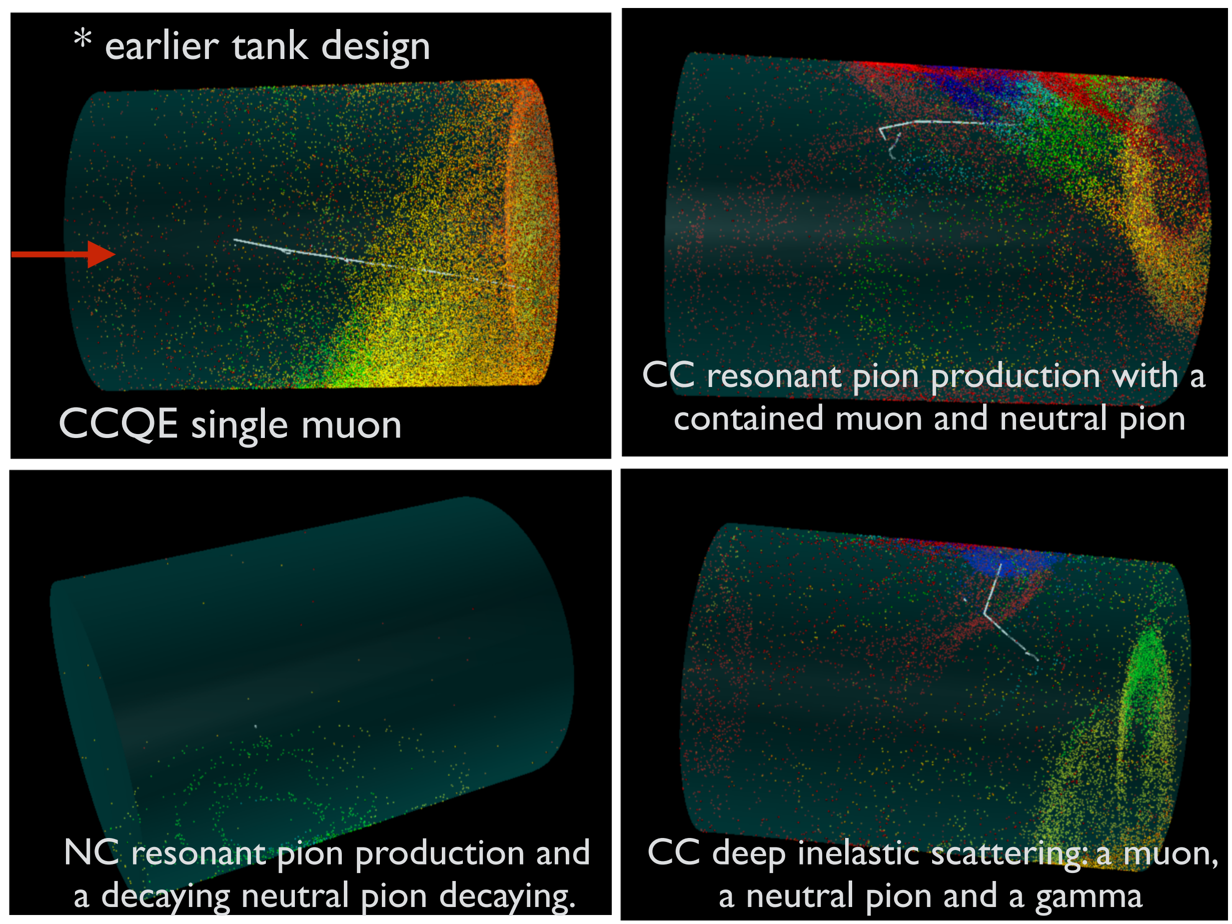


Photodetector Coverage

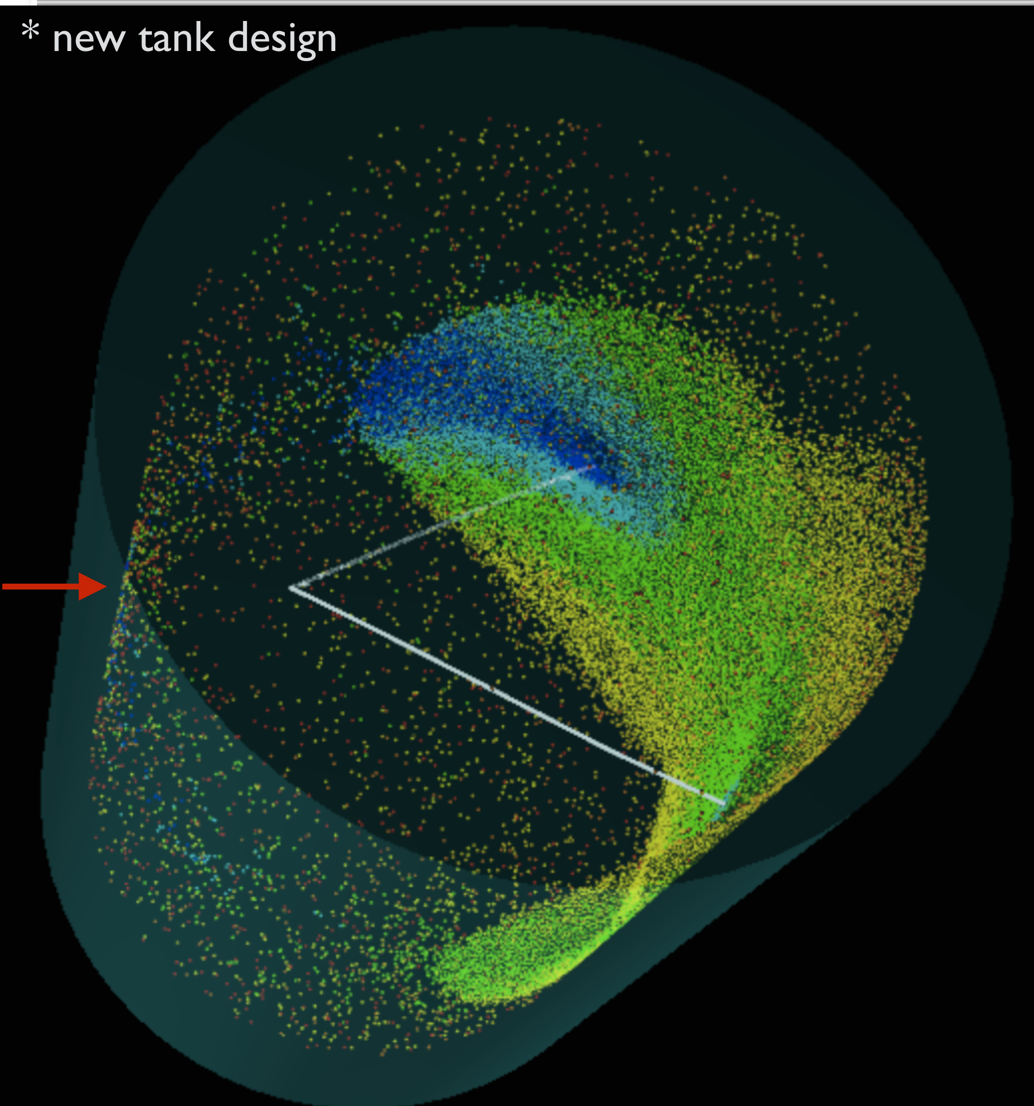
- **LAPPD coverage** to separate single tracks vs. multi-track events (resonant pion production).
- Cherenkov light from CCQE interactions **hit predominantly (70%, 92% MRD) the forward wall** of the detector.
- Place **LAPPDs on forward wall**.
- **Timing insufficient** to get the interaction vertex for single tracks.



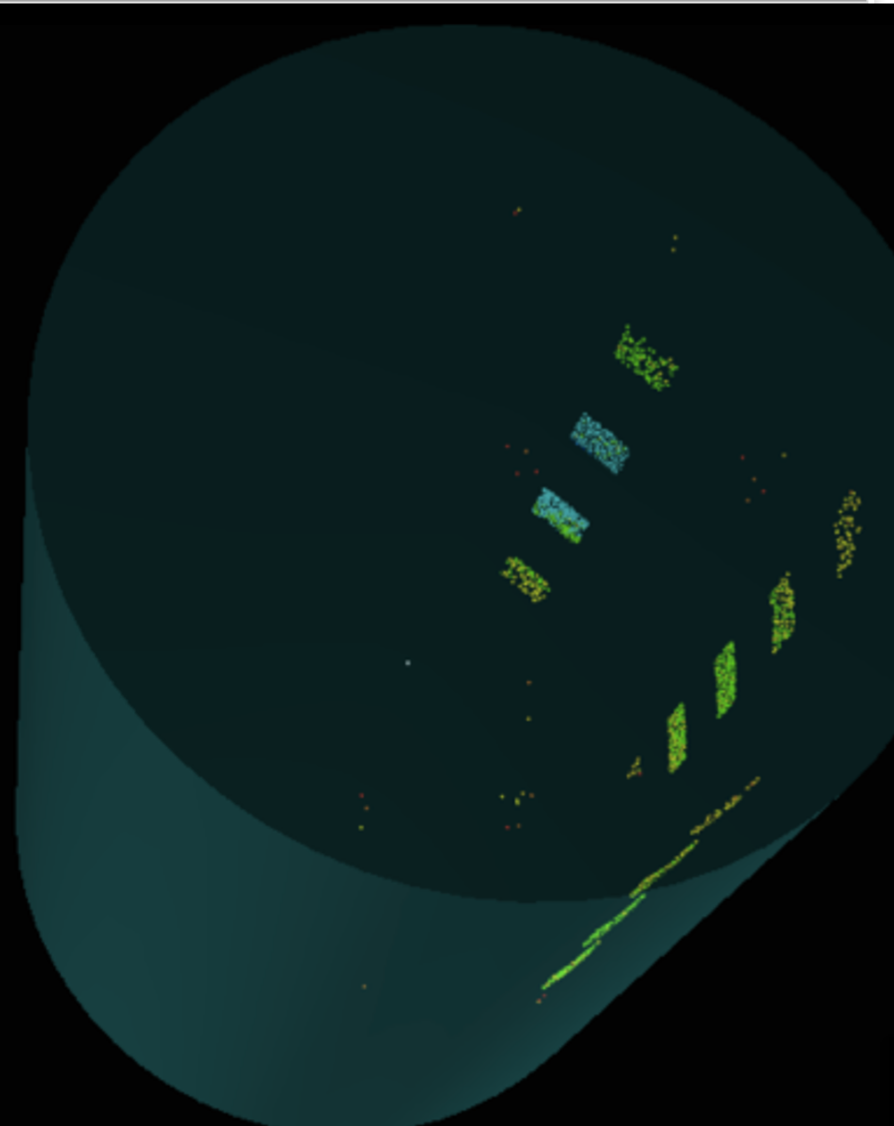
- **Find edge** of Cherenkov cone, LAPPDs (if cone edge crossed sensor), and/or use MRD, PMTs.
- **LAPPDs**: excellent timing and spatial resolution to separate single/multiple tracks.



Photodetector Coverage

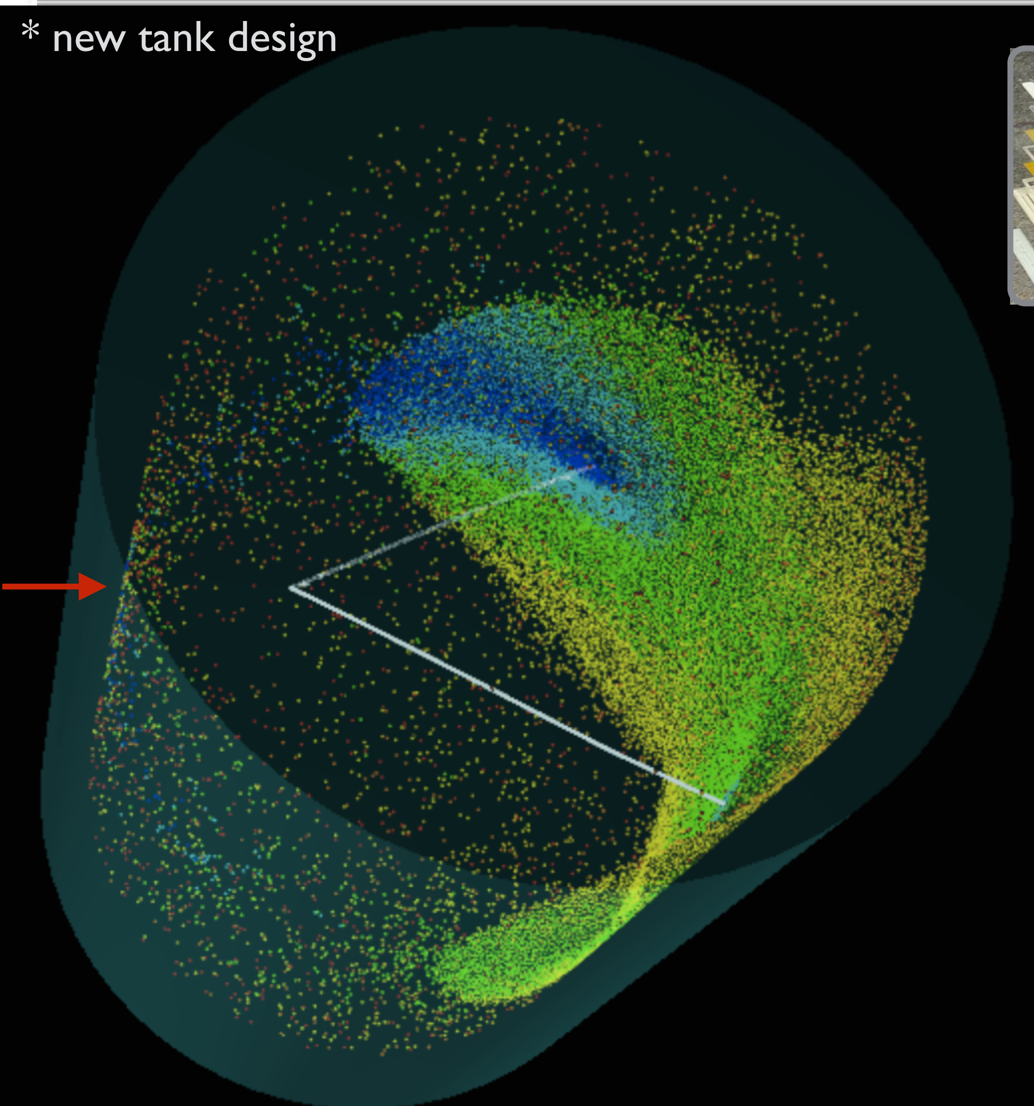


CC resonant pion production, a muon and a pion.

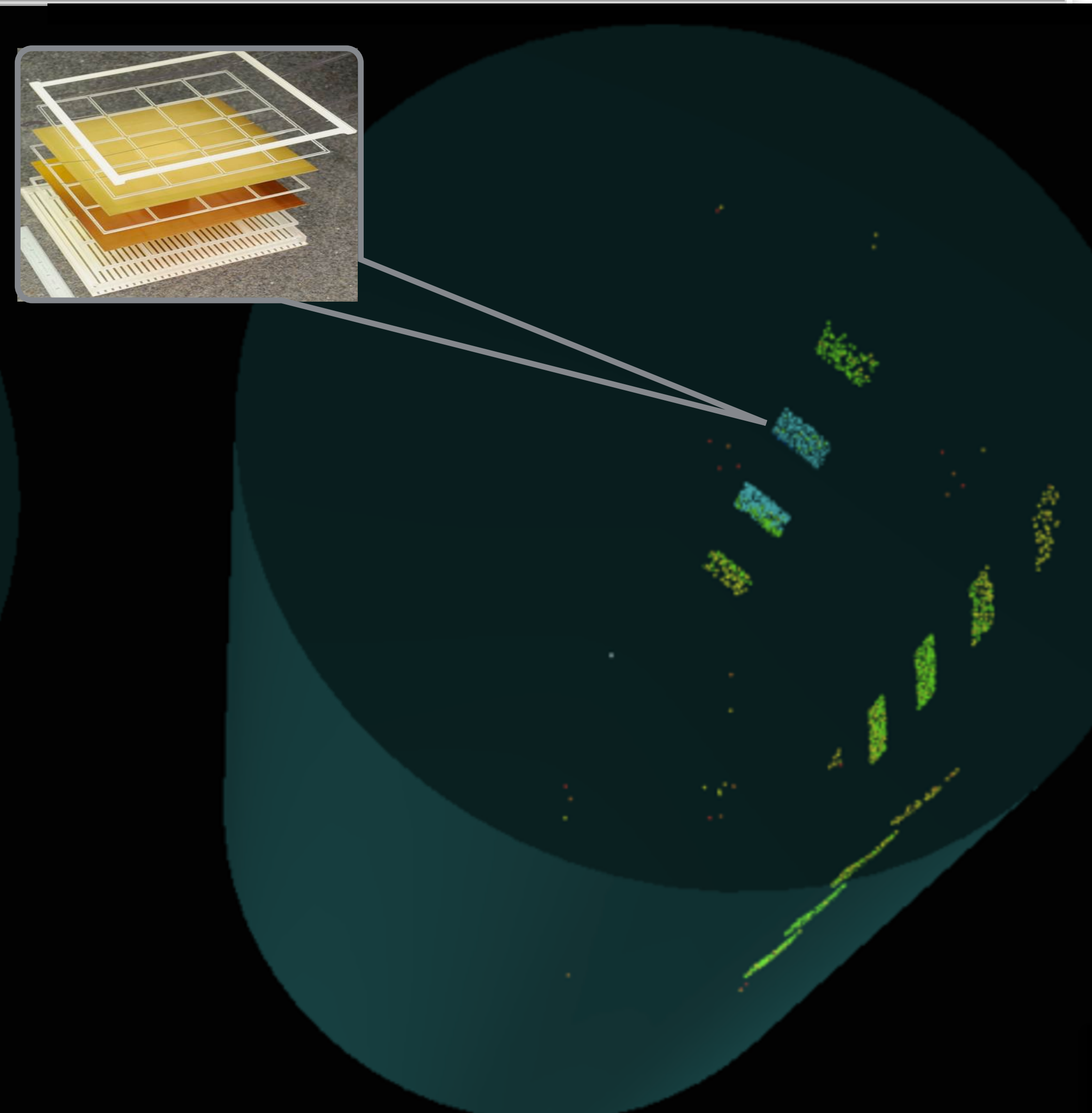


Coverage by 20 LAPPDs.

Photodetector Coverage

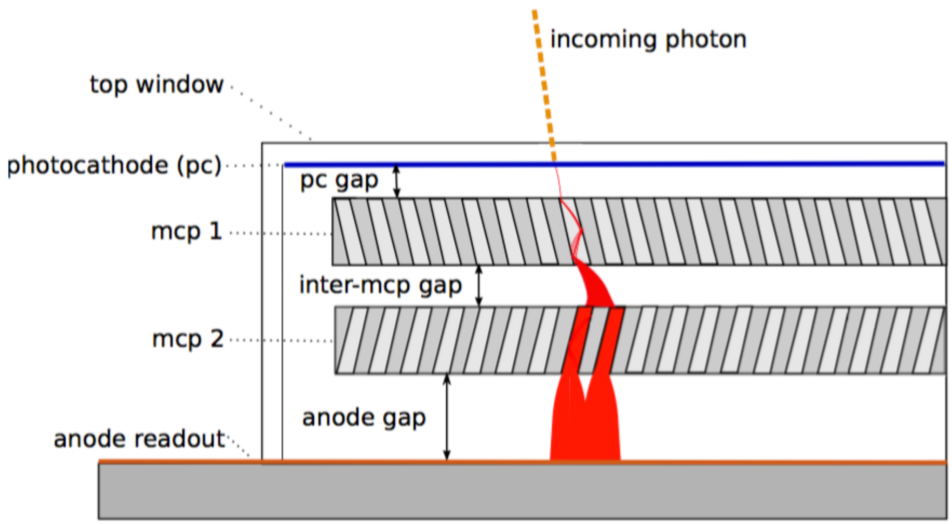


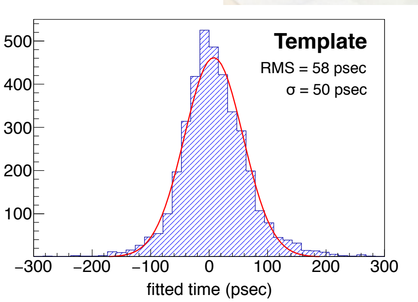
CC resonant pion production, a muon and a pion.



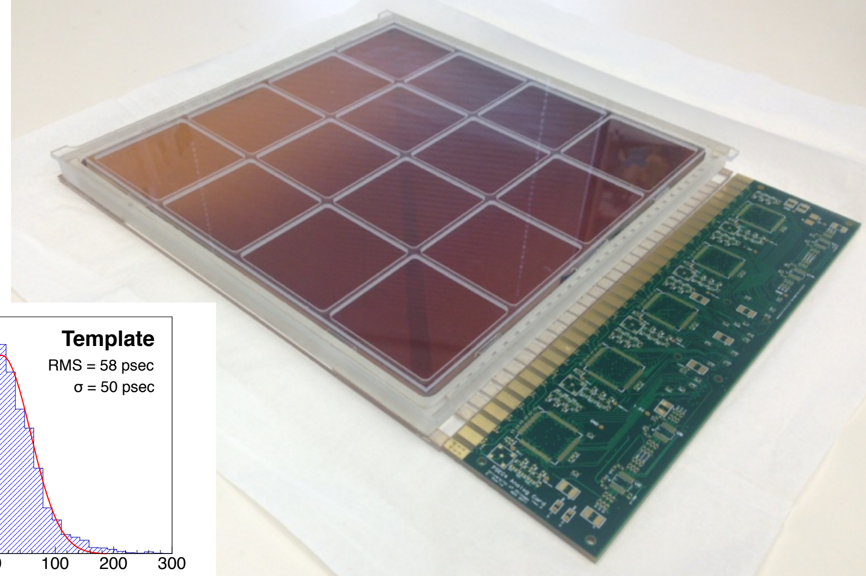
Coverage by 20 LAPPDs.

LAPPDs



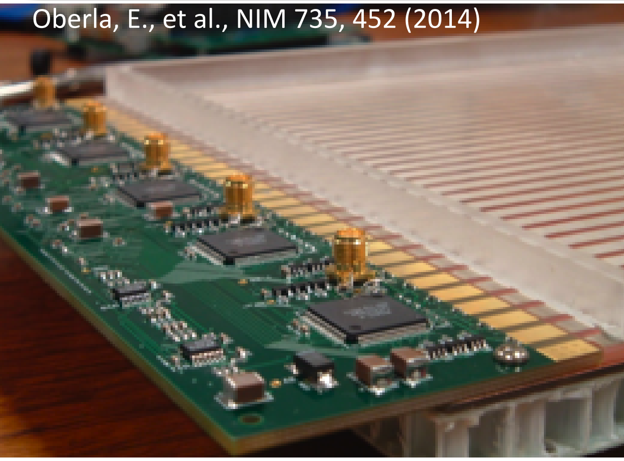


Adams, B.W. et al., NIM A, 795, 1 (2015)

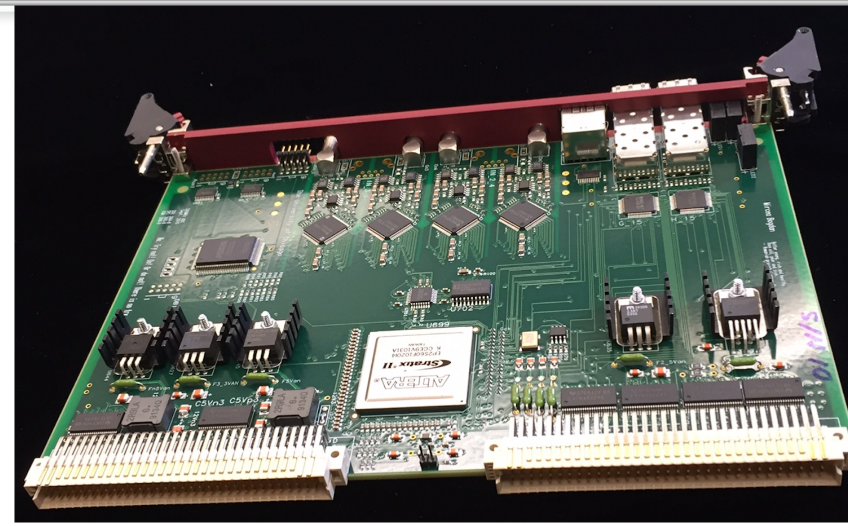


- LAPPD (Large Area Picosecond Photodetector): 20 cm x 20 cm (8'' tile) flat panel photocathode.
- 2 MCPs (ALD): **100 ps time resolution**, multi-anode readout gives < **1 cm spatial resolution**.
- ANNIE: minimal pileup and **single photon resolution** are the basis for cm scale vertex reconstruction, single-/multi-particle separation, …
- Incom Inc. has set up commercial production facility, ANNIE will get up to 20 LAPPDs (3-years).
- ANNIE physics program benefits from **LAPPD capabilities** but is also developing their **first use in an experiment**; experience in a liquid environment and physics data.

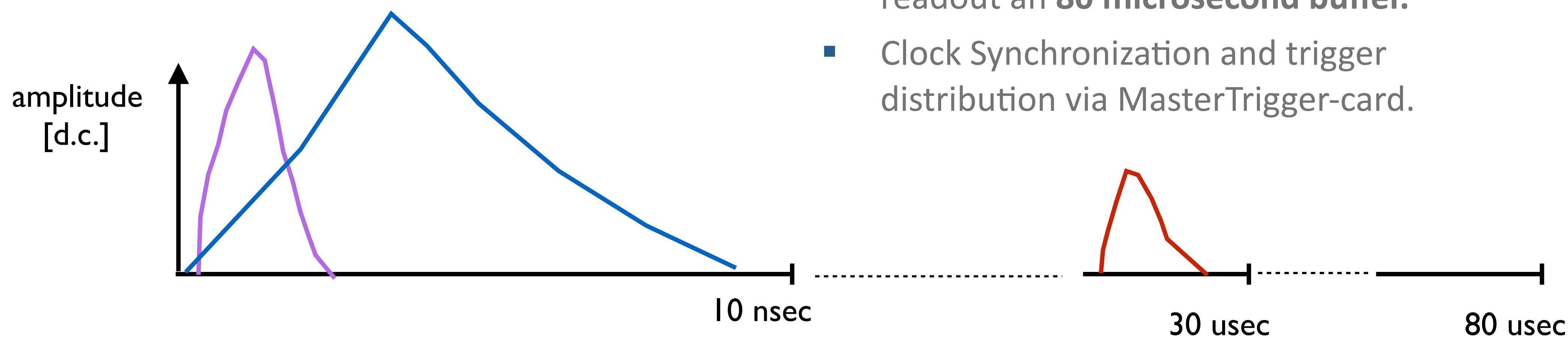
Readout Electronics



- **Fast readout** (**LAPPDs**, track reconstruction):
- **PSEC4 chip** samples at **10 GHz for 30 ns**.
- Central Card provides synchronization, triggering and readout for 240-channels.

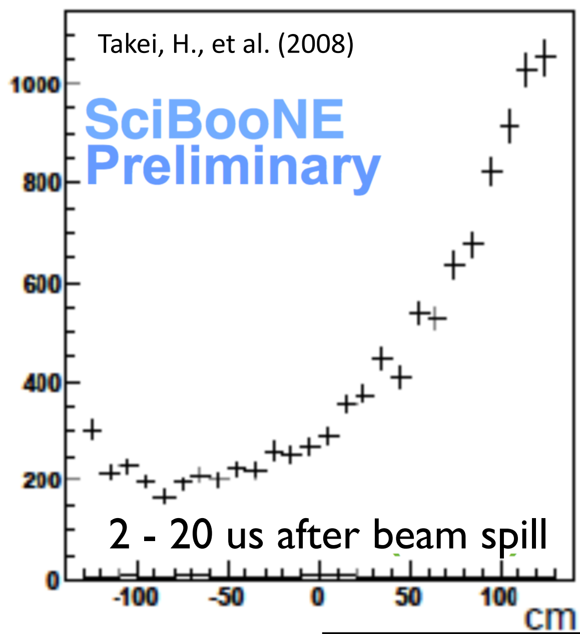


- **Long readout**: (**PMTs**, **neutron capture**)
- **500 MHz** VME-FADC boards (KOTO experiment, U. Chicago) configured to readout an **80 microsecond buffer.**
- Clock Synchronization and trigger distribution via MasterTrigger-card.

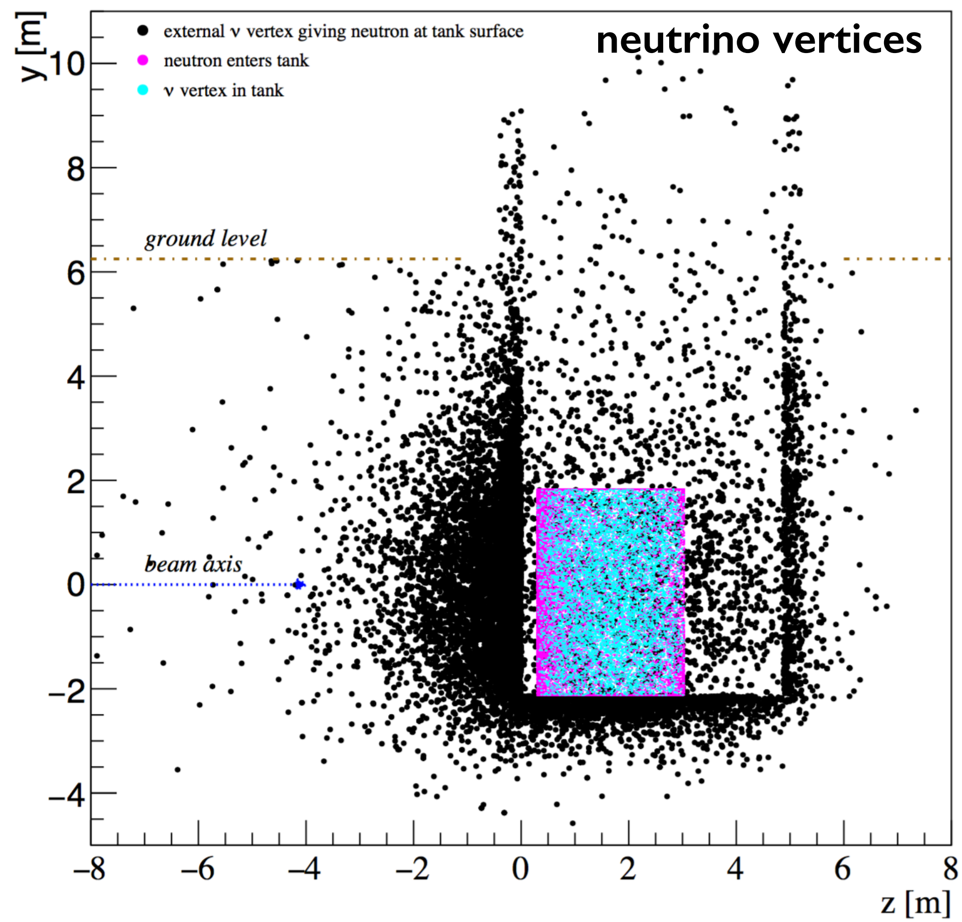


Neutron Background at ANNIE

- **Correlated neutron background**: **Dirt/Rock neutrons**: from neutrino interactions upstream of ANNIE. **Simulations give** one neutron per 87 spills reaching the tank, but **needs to be measured.**
- **Sky shine neutrons**: produced at BNB target, leak into atmosphere and into detector, show strong vertical dependency.



vertical, above beam axis



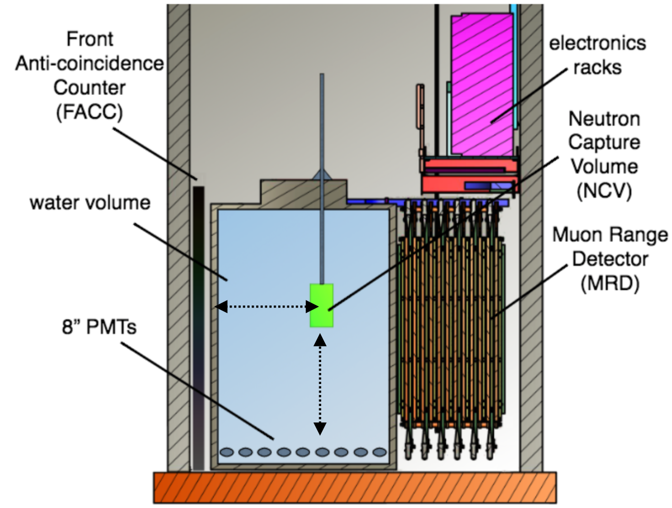
ANNIE: Phased Approach

Phase I: Fall 2015 - 2017

a) **Construction** of the water tank, mechanical support structure, 60 PMTs, HV-system, trigger & readout electronics, DACQ.

b) **Measurement of the neutron background**

c) Readiness for testing LAPPDs.



Funded, approved by Fermilab

first light in May 2016

Phase II: 2017 - 2021

a) Physics Run (1 year) with limited LAPPD coverage, enhanced PMT coverage (130), focus on CCQE-like events.

b) Physics Run (2 years) with full LAPPD coverage (up to 20 LAPPDs), study neutron yields for CC, NC and inelastic scattering.

proposal stage

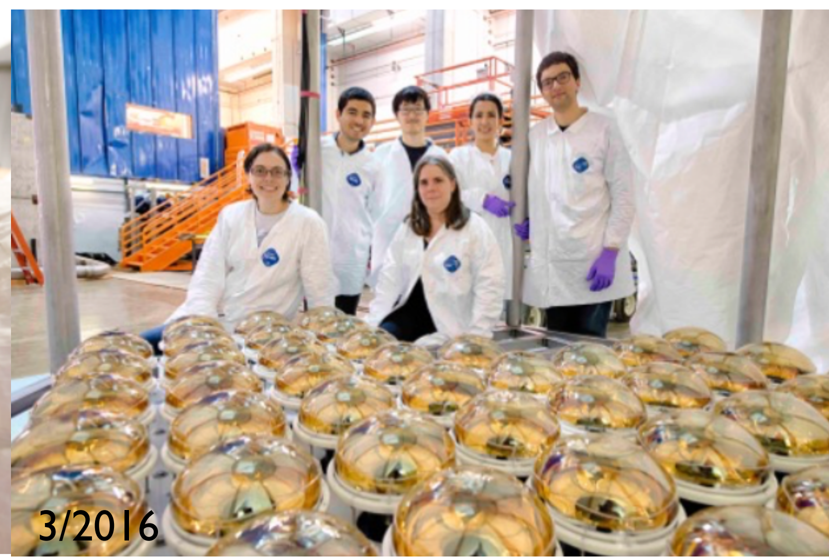
simulations of optimal configuration under way

Tank, Structure, Liner, PMTs

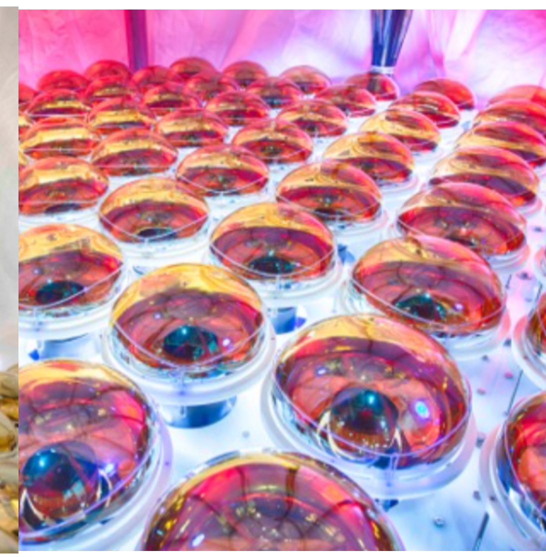

Fermilab engineering, support staff, safety

3/2016

Energetic postdocs and students



3/2016



Veto, MRD, HV

Veto:
2 layers
26 channels

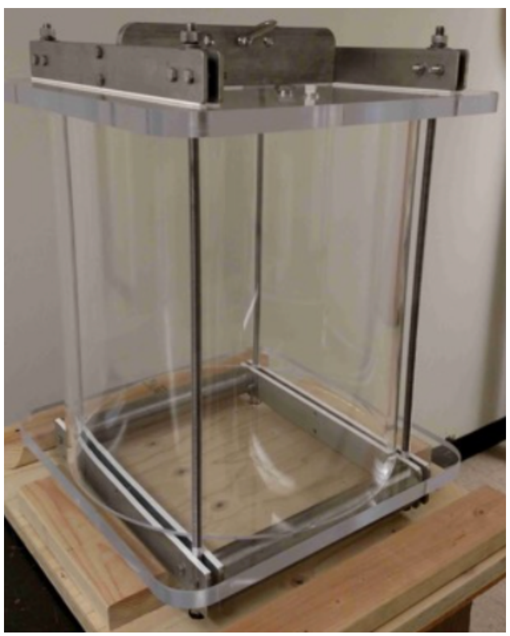
2 layers
of MRD
refurbished
55 channels
(Phase I)

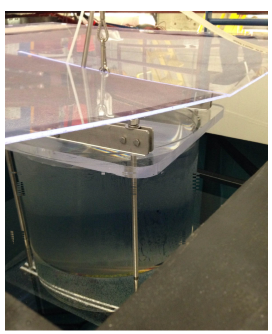
HV system
81 negative
(MRD, Veto)
60 positive HV
(tank PMTs)

ANNIE
Accelerator Neutrino Neutron Interaction Experiment

Water Purification, Neutron Capture Volume

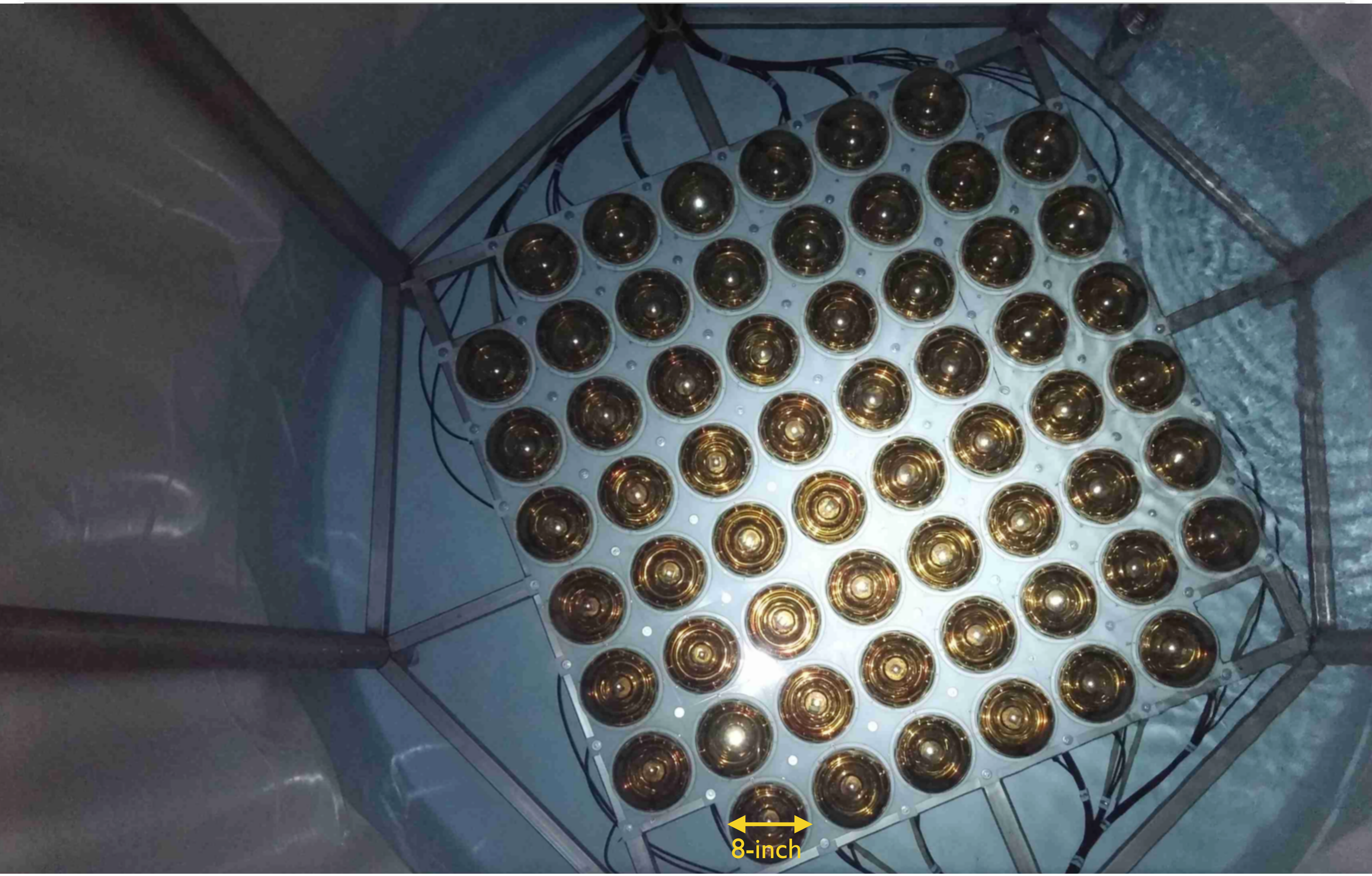
- Ultra pure water (0.5 ppm).
- Resistivity > 10 MOhm/m.
- 7,000 Gallons are continuously flushed with nitrogen and filtered through a deionizing purification system.



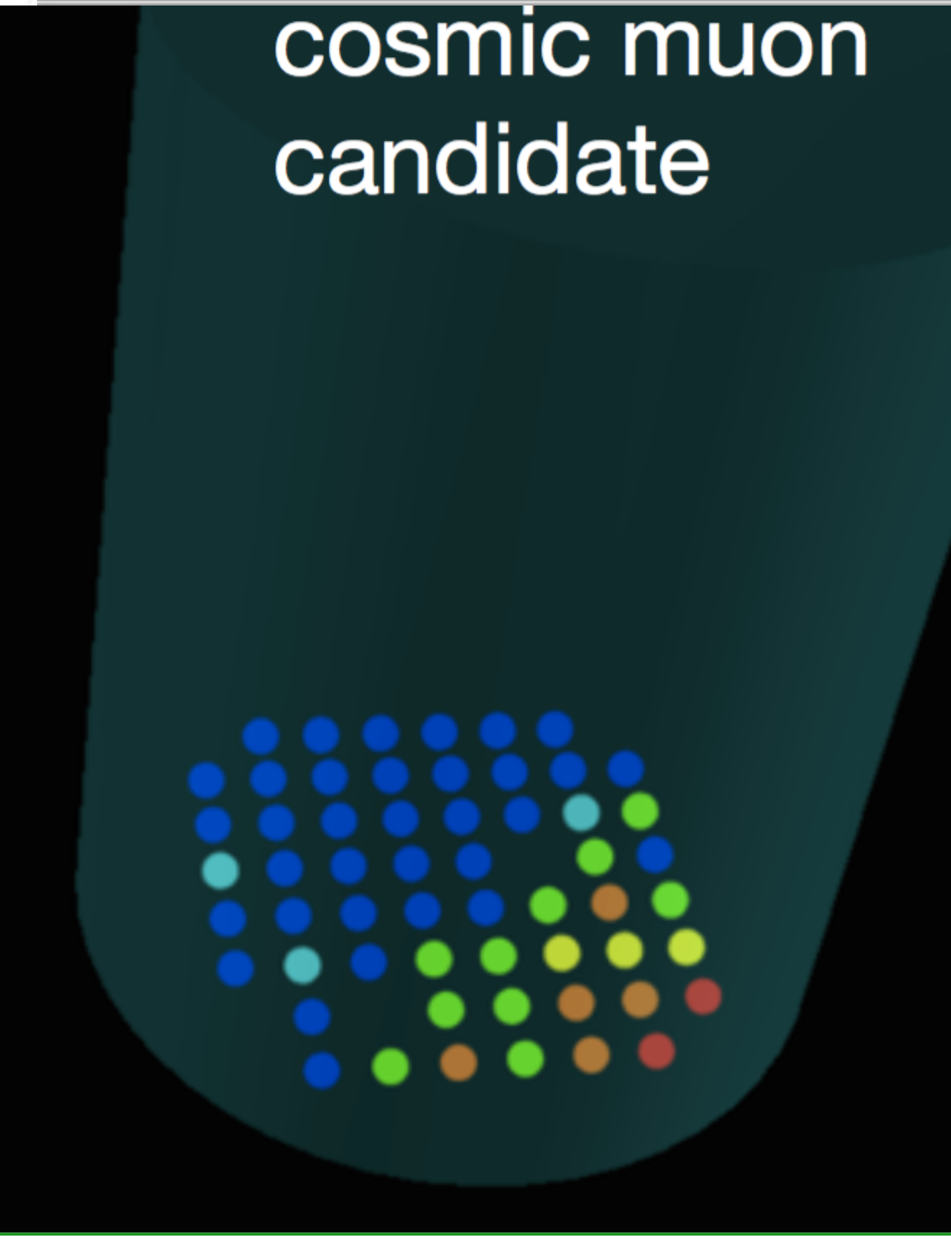


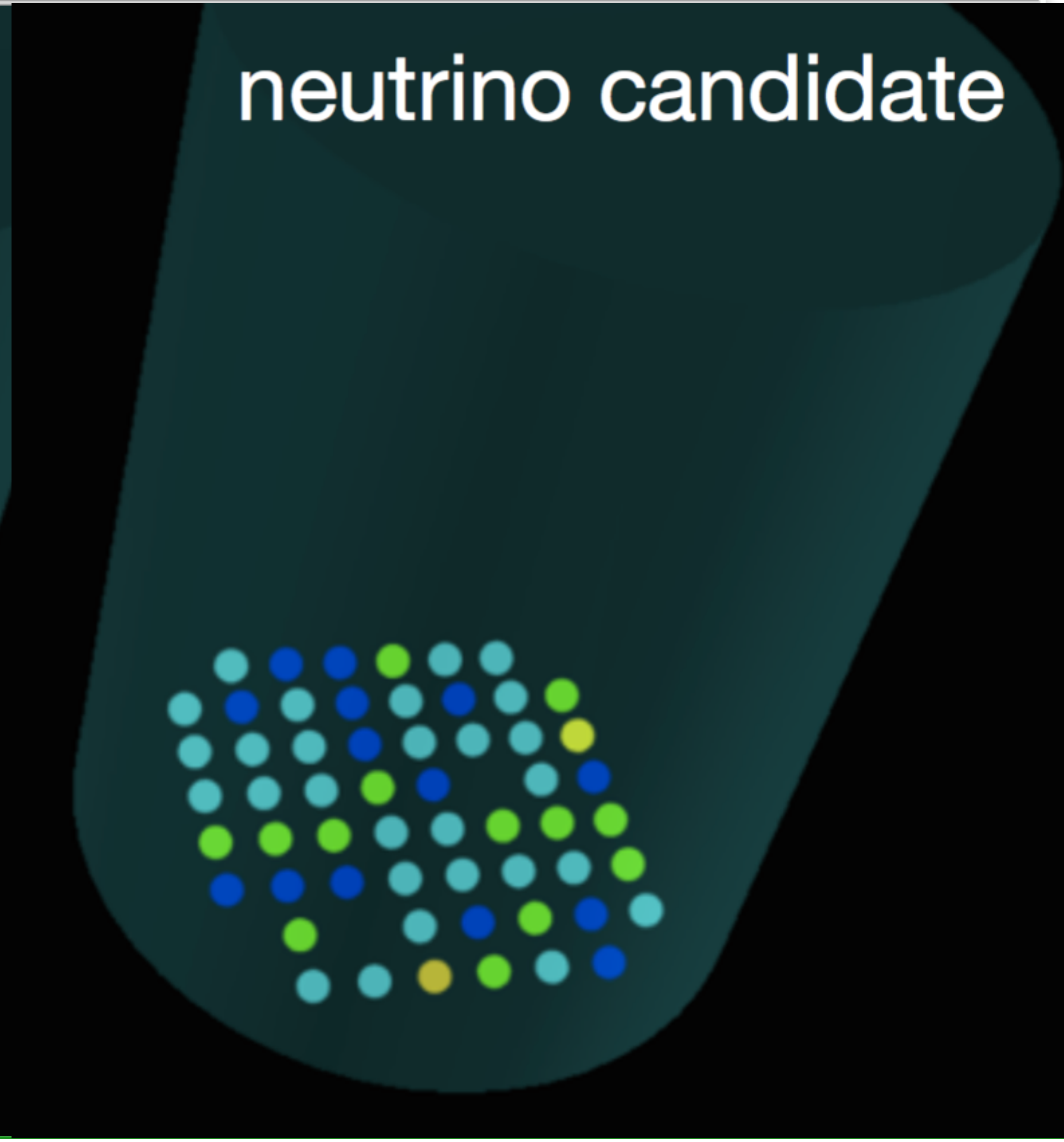
- Neutron capture volume (NCV) is an acrylic vessel.
- NCV can be moved vertically and along the beam axis.
- Filled with 100 liters of Gd-doped liquid scintillator
- EJ-335 contains pseudocumene and 0.25% Gd (weight)
- Peak wavelength 424 nm

Water Fill

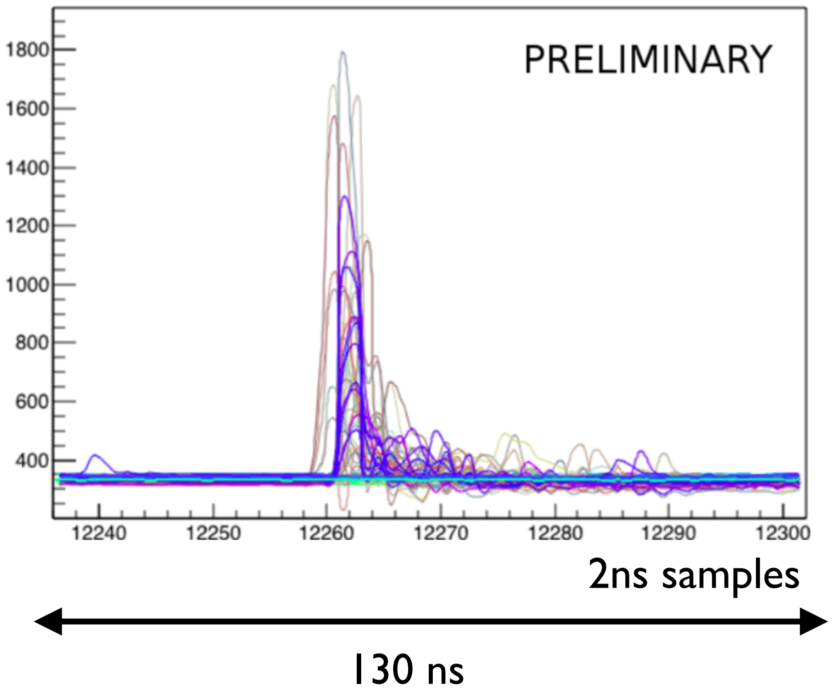


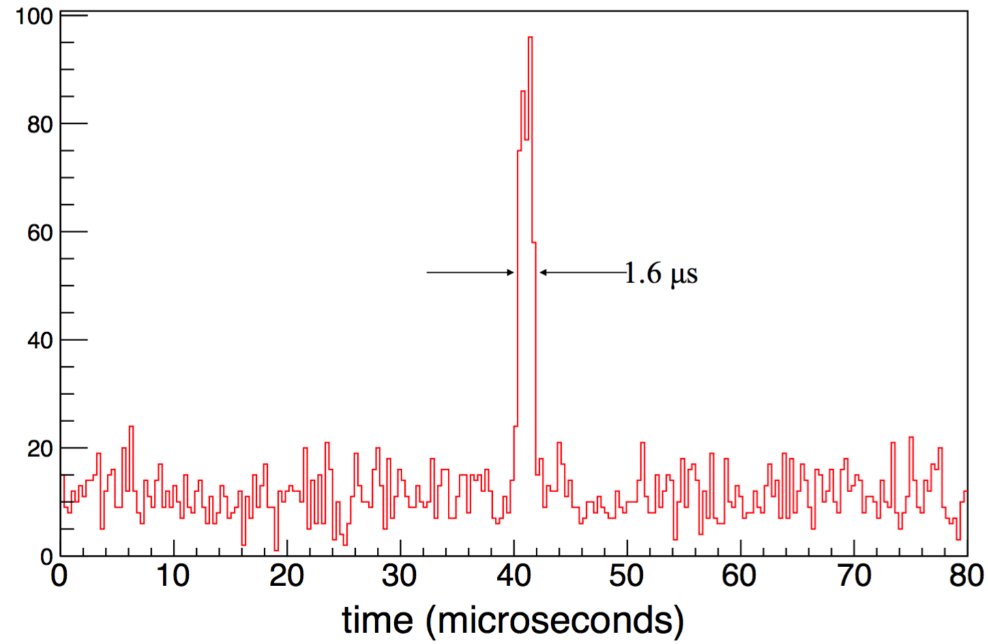
First Events





Found: Muons and Beam





- Muon traces from a large number of PMTs (2 ns sampling FADCs), with number of PMTs > 5 above threshold.

- Neutrino events correlated with beam trigger (relative to resistive wall monitor from BNB).

ANNIE Summary

- **Science**: measure **final state neutron abundances** (Gd-doped water) and provide critical **input for modeling multi-nucleon contributions to CCQE-like** neutrino interactions — augment multi-proton detection by liquid-Ar technique — help to improve energy resolution of oscillation experiments.
- **Science:** ANNIE results will provide a better understanding of neutron tagging techniques for reducing background from atmospheric neutrinos (proton decay, supernova neutrinos).
- **Technology**: breakthrough for water Cherenkov-technique by using high time/spatial resolution LAPPDs.
- **Operation of ANNIE Phase-I is underway**, data analysis has started to evaluate beam-correlated neutron background.
- ANNIE Phase-II (2017 - 2021) with the deployment of LAPPDs is in the planning stages.