Accelerator Neutrino Neutron Interaction Experiment

Run-I Experience and Run-II Plans

Frank Krennrich, Iowa State University
for the ANNIE Collaboration

ANNIE
Accelerator Neutrino Neutron Interaction Experiment

Collaboration

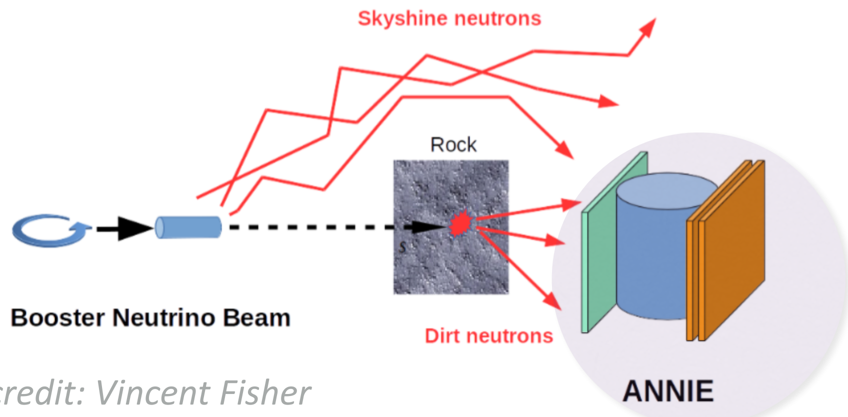
- Argonne National Laboratory
- Brookhaven National Laboratory
- Fermi National Accelerator Laboratory
- Imperial College of London
- Iowa State University
- Johns Hopkins University
- MIT
- Ohio State University
- Ultralytics, LLC
- University of California at Davis
- University of California at Irvine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

Outline

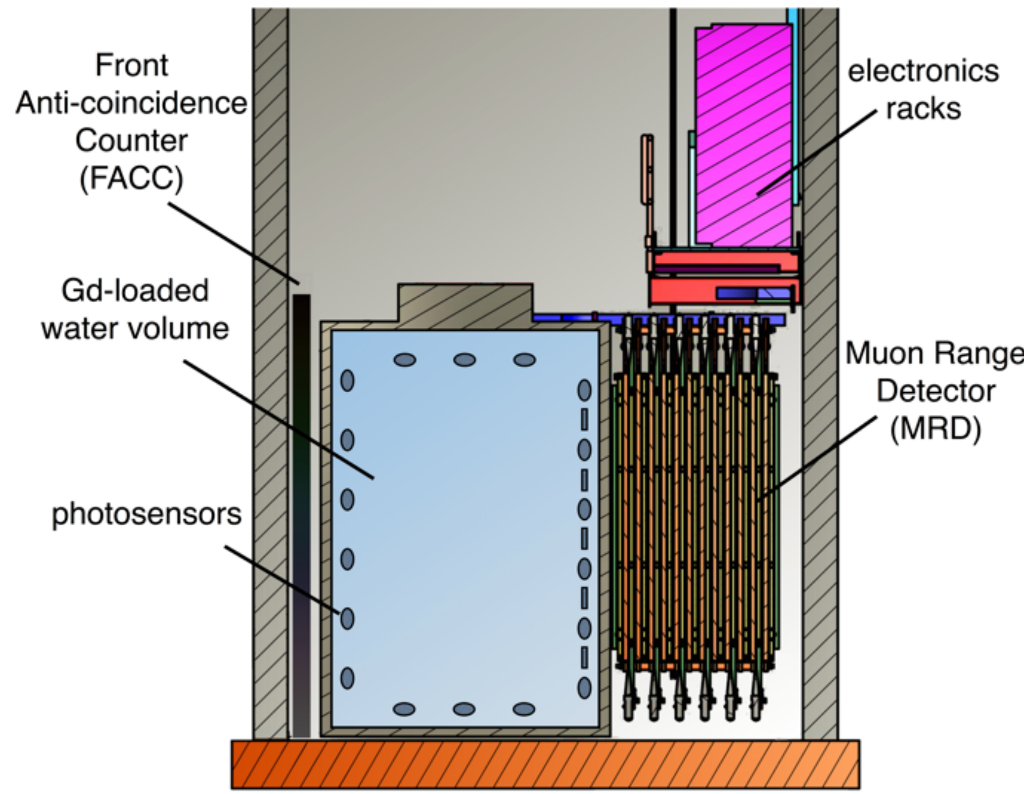
- What is ANNIE?
- Physics Motivations & Design Considerations
- Phase-I and Status
- Phase-II Plans

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.

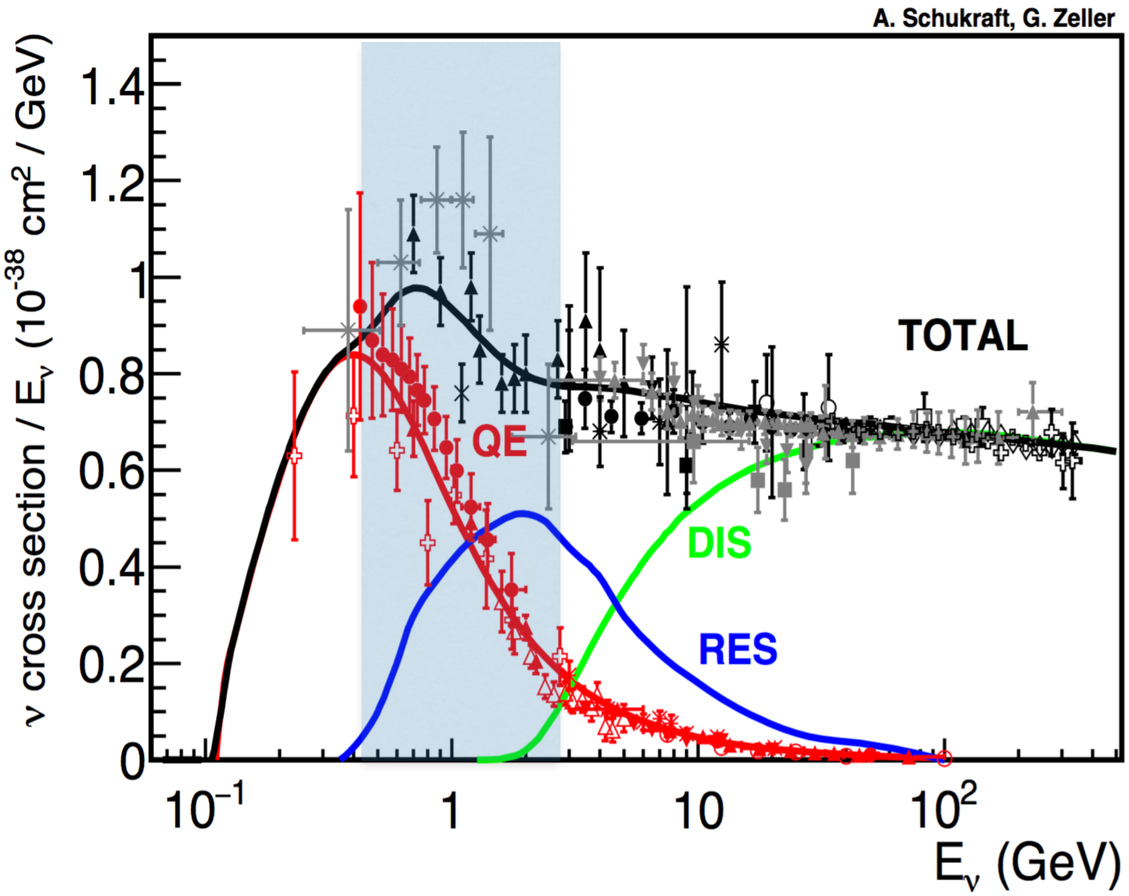


credit: Vincent Fisher



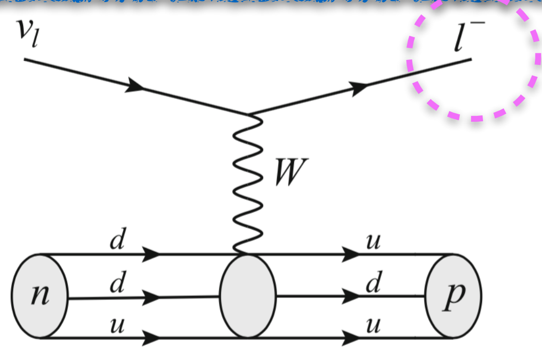
Physics Motivations: Nuclear Physics Effects

- **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.**
- **Cross 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**.



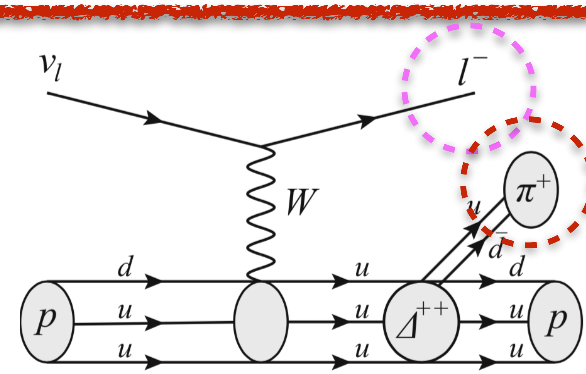
Relevant Neutrino Interactions

QE



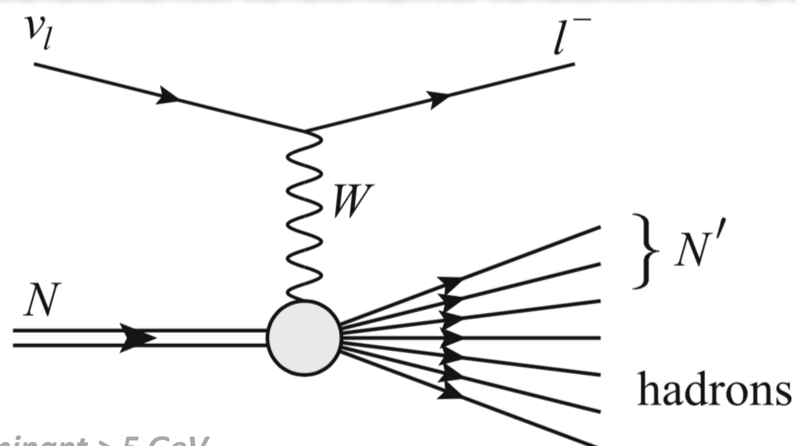
– ***dominant < 1 GeV*** *for CCQE, NCE*
– *lepton mostly in* ***forward direction***

RES



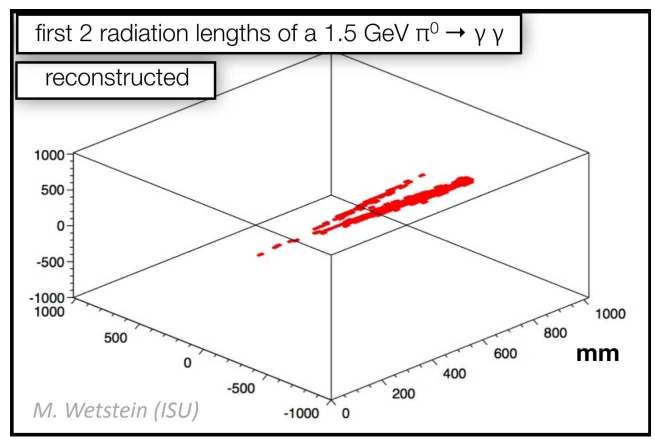
– *CC1pion, NC1pion*
– *can also produce FS* ***neutrons****, protons, …*

DIS

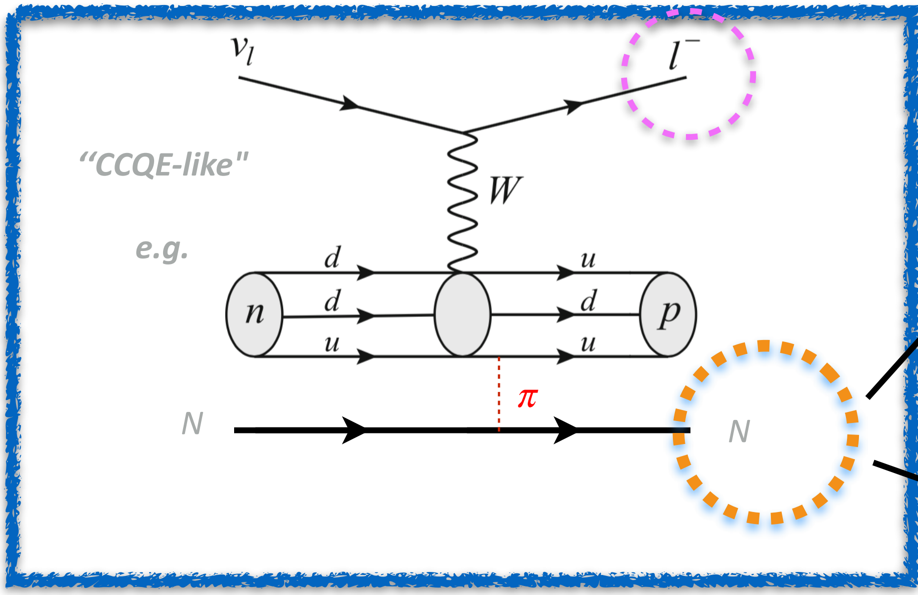


– ***dominant > 5 GeV***
– *interaction with quarks, high momentum transf.*

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

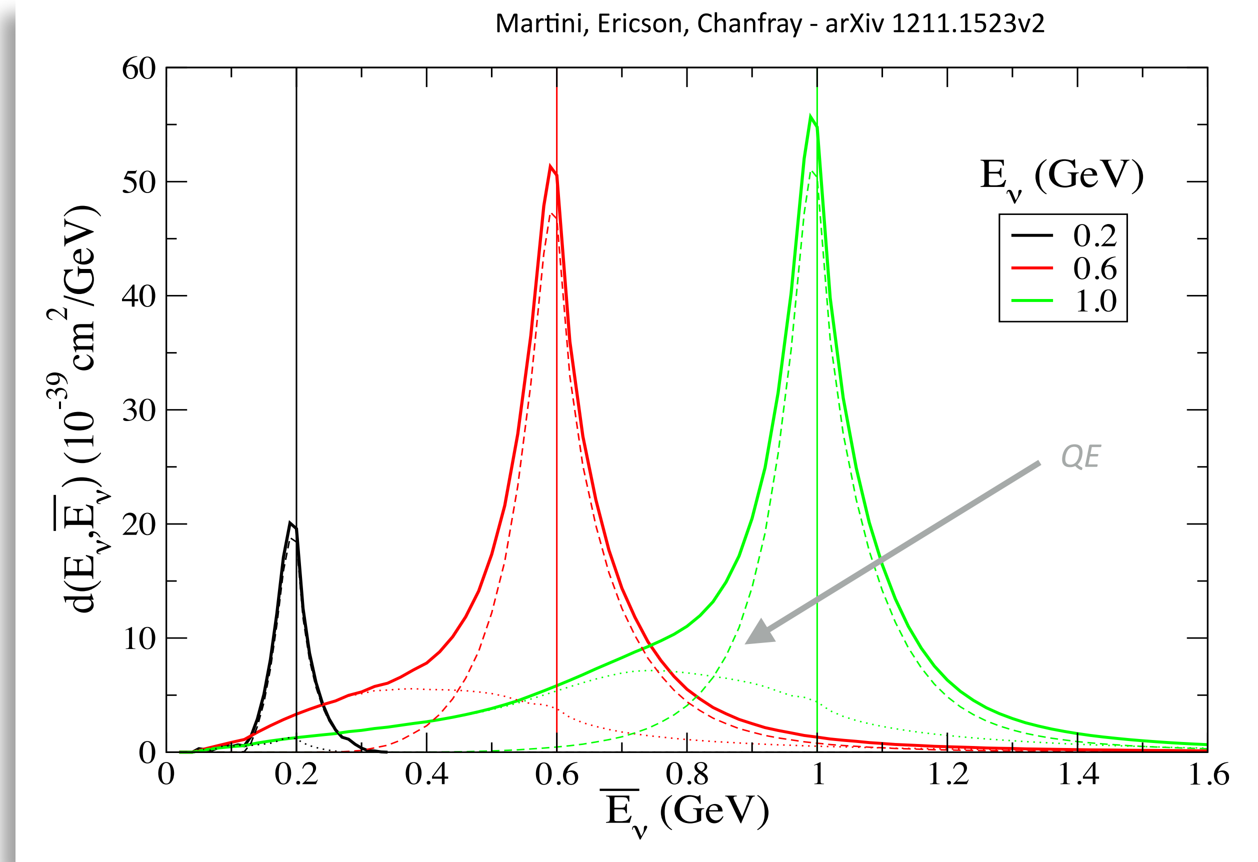
*i) **Initial state** nucleon-nucleon correlations: excitation of particles.*

*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.



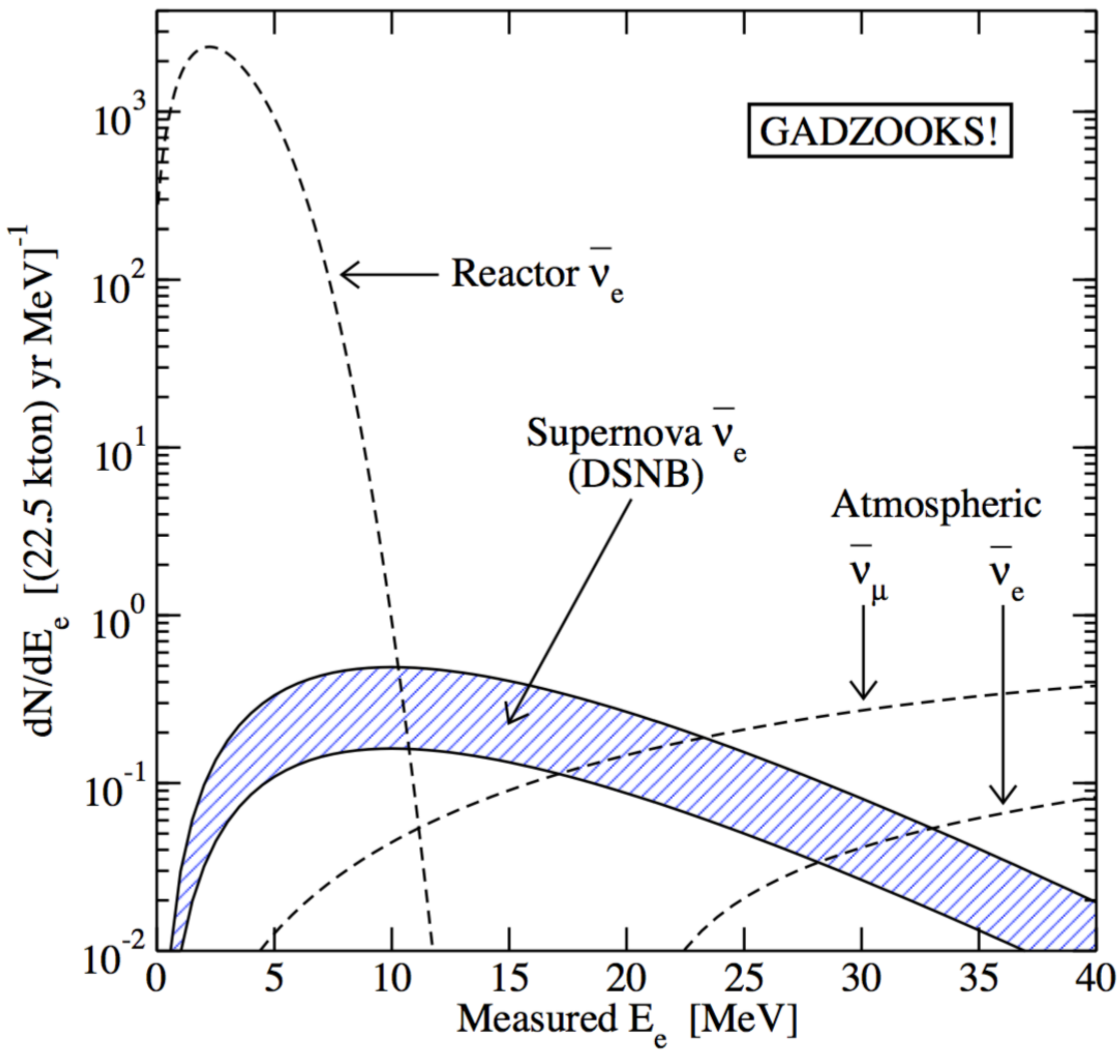
Physics Motivations: Supernova Neutrino Background

- 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

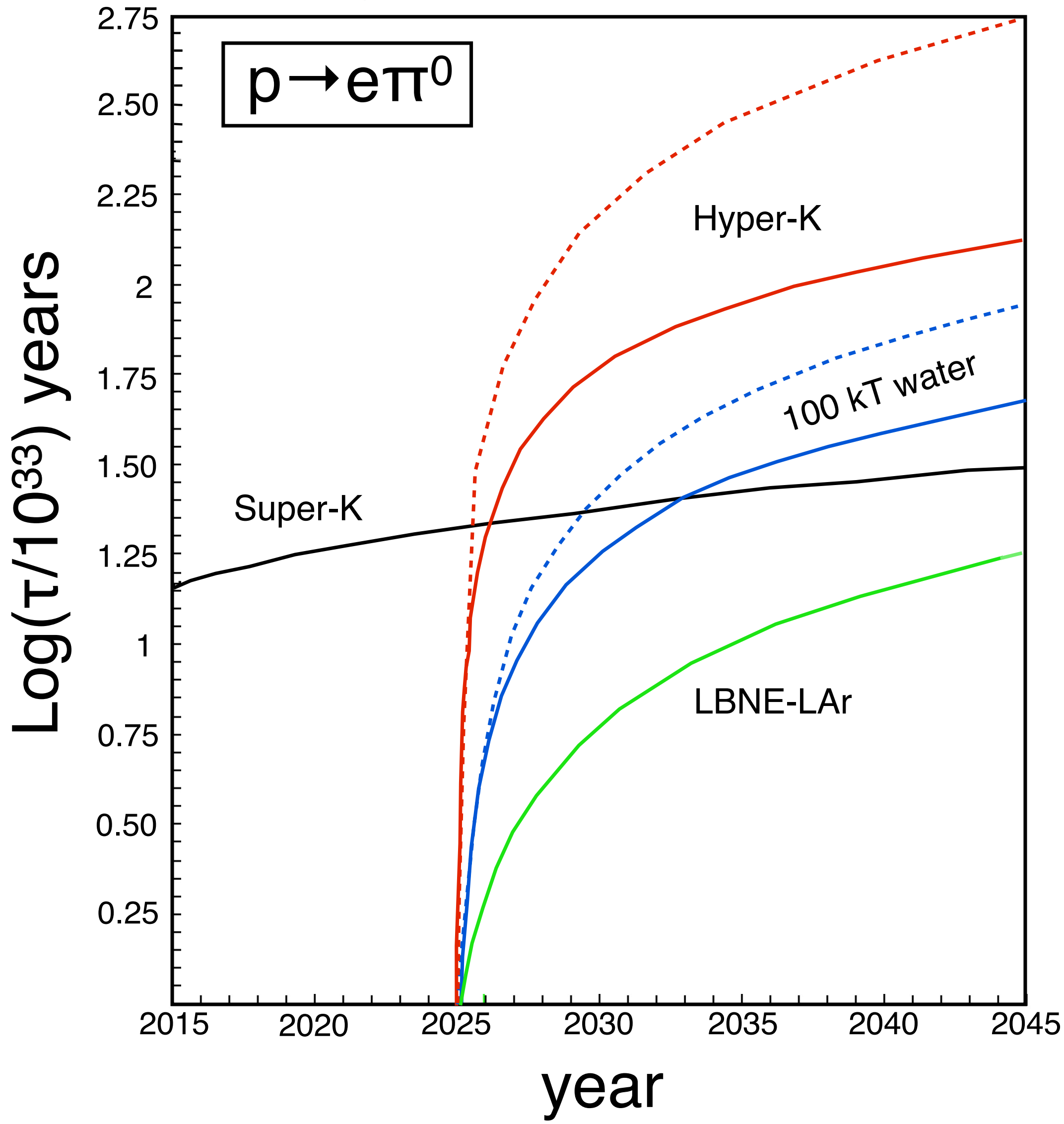


... ***very relevant for Super-K-Gd ...***

Physics Motivations: Proton Decay

- Proton decays, e.g., $p \to e^{+} + \pi^{0}$
- > **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 regime **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.

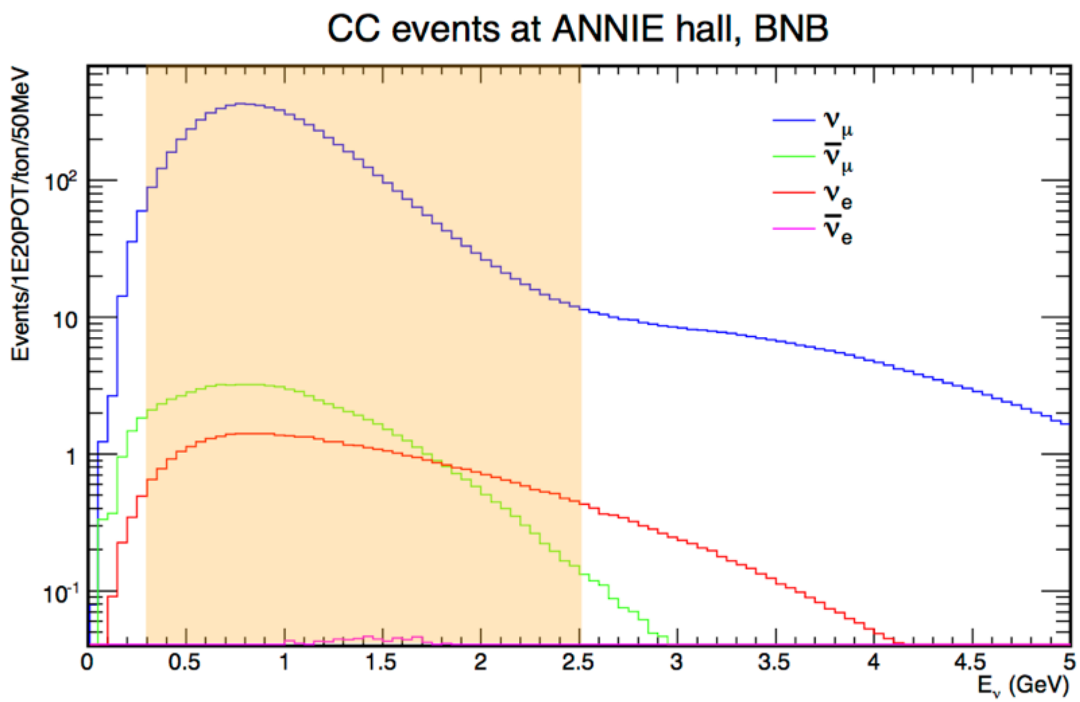
Anghel, I. et al., - arXiv 1504.01480



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.

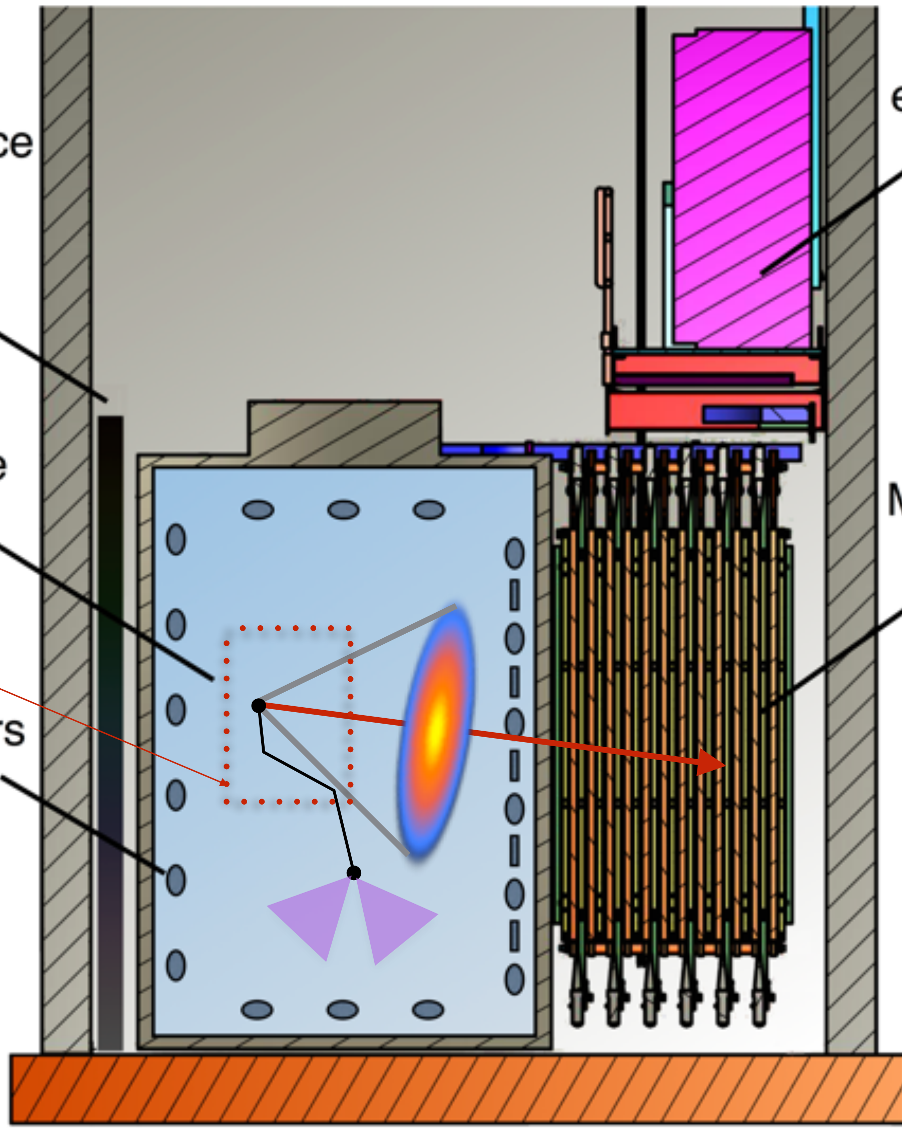
ν-type	Total Interactions	Charged Current	Neutral Current
ν_μ	9892	6991	2900
$\bar{\nu}_\mu$	130	83	47
ν_e	71	51	20
$\bar{\nu}_e$	3.0	2.0	1.0



- **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



Fiducial Volume (selectable in off-line analysis)

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%

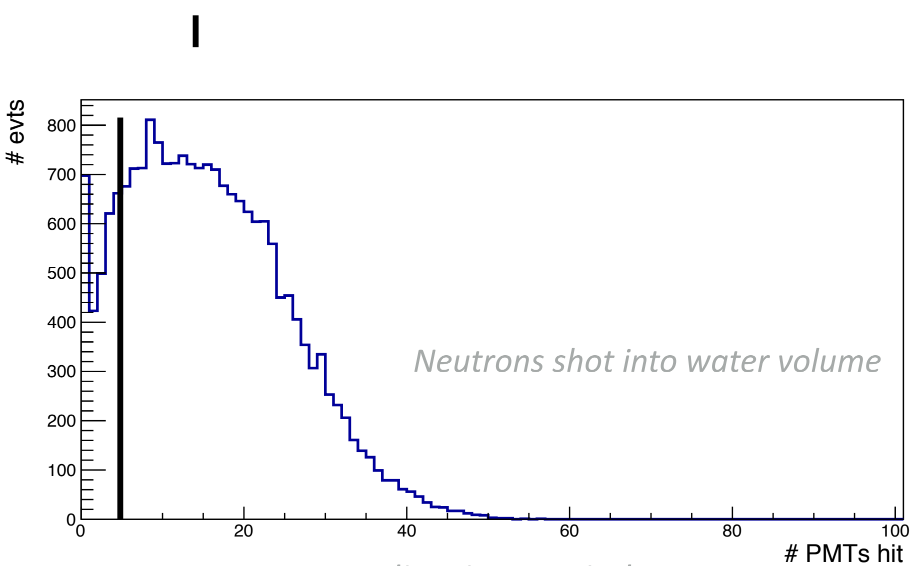
PMTs (8-inch)
- *neutron capture*

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 150 PMTs, 20% Q.E.)



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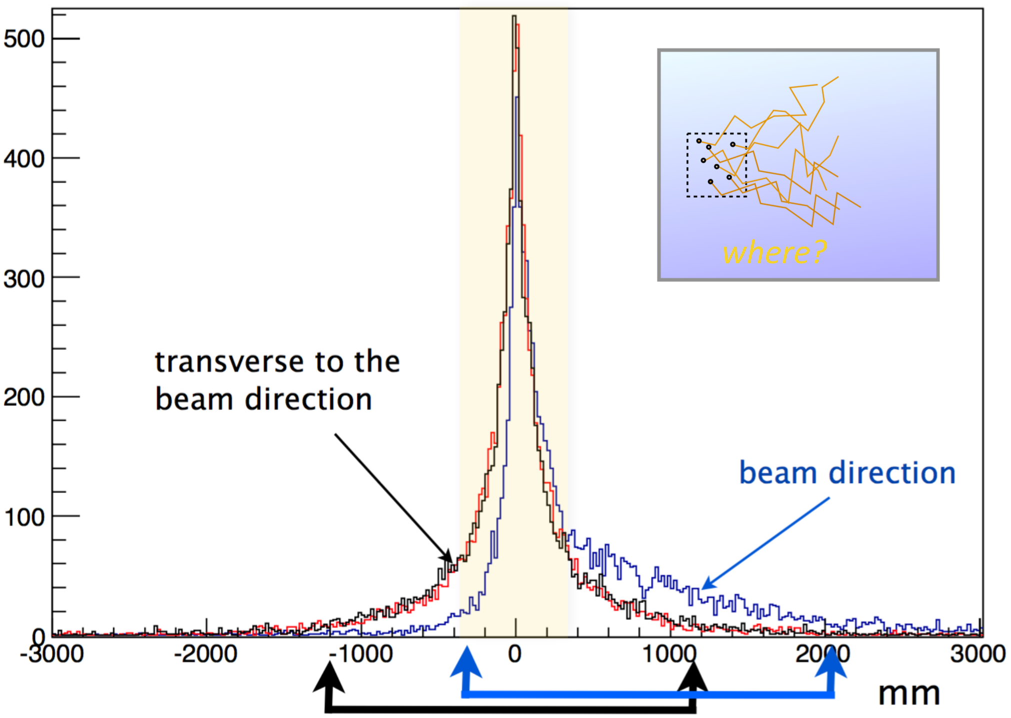

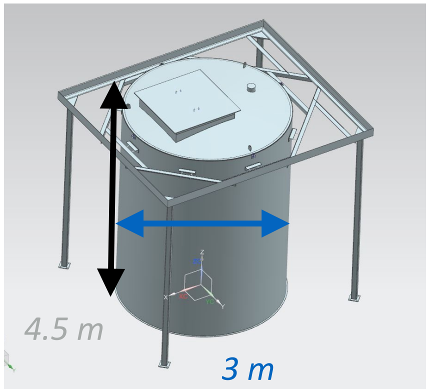

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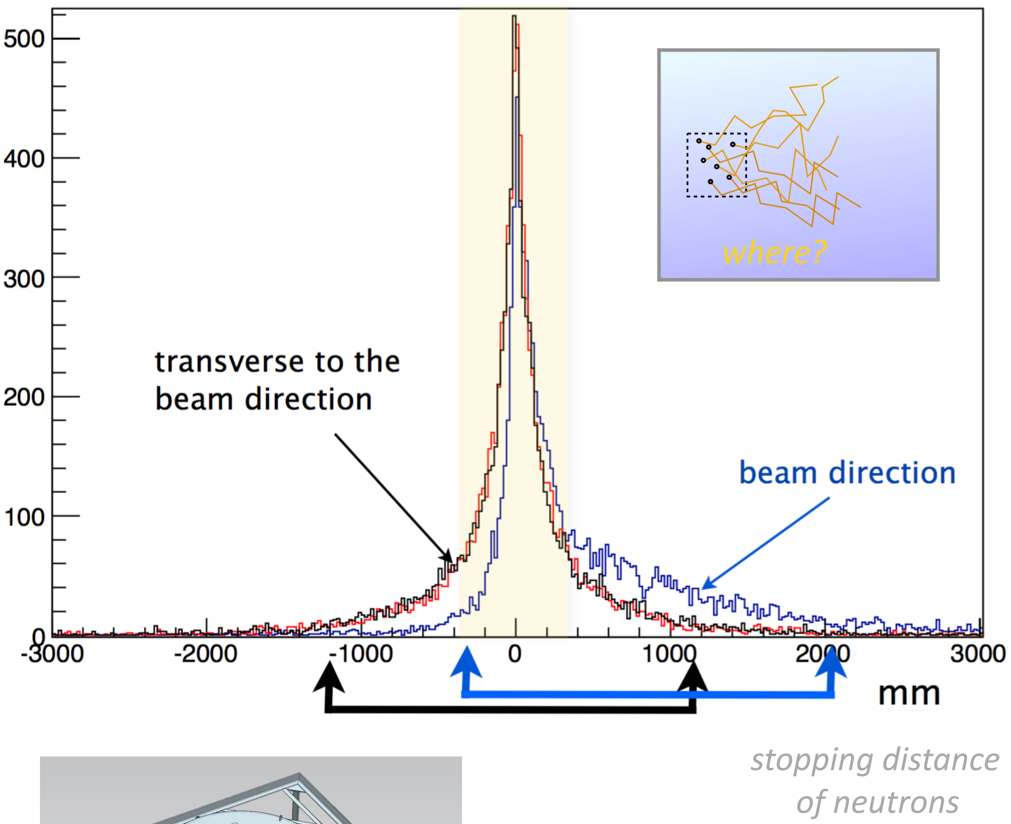

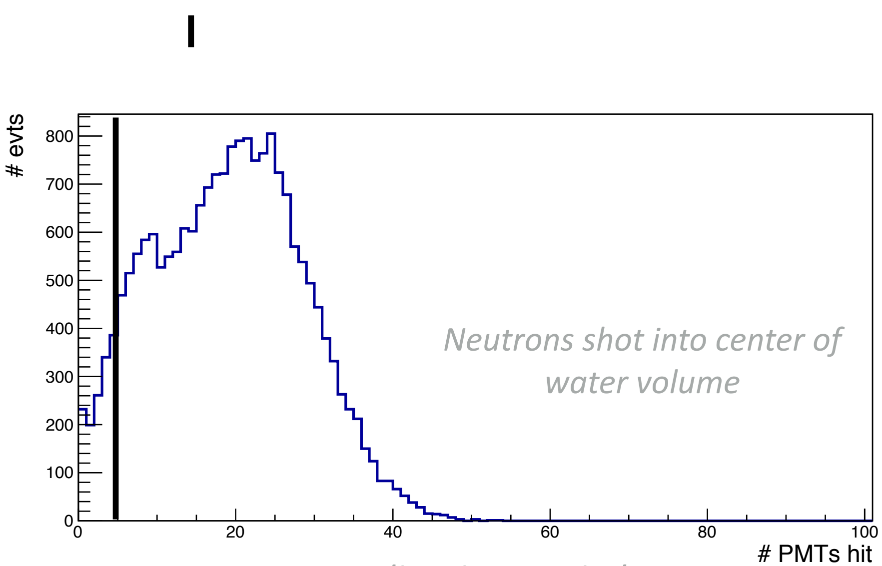

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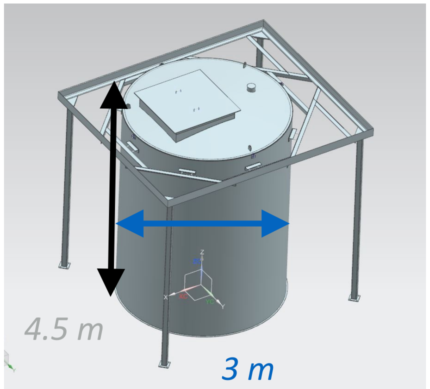
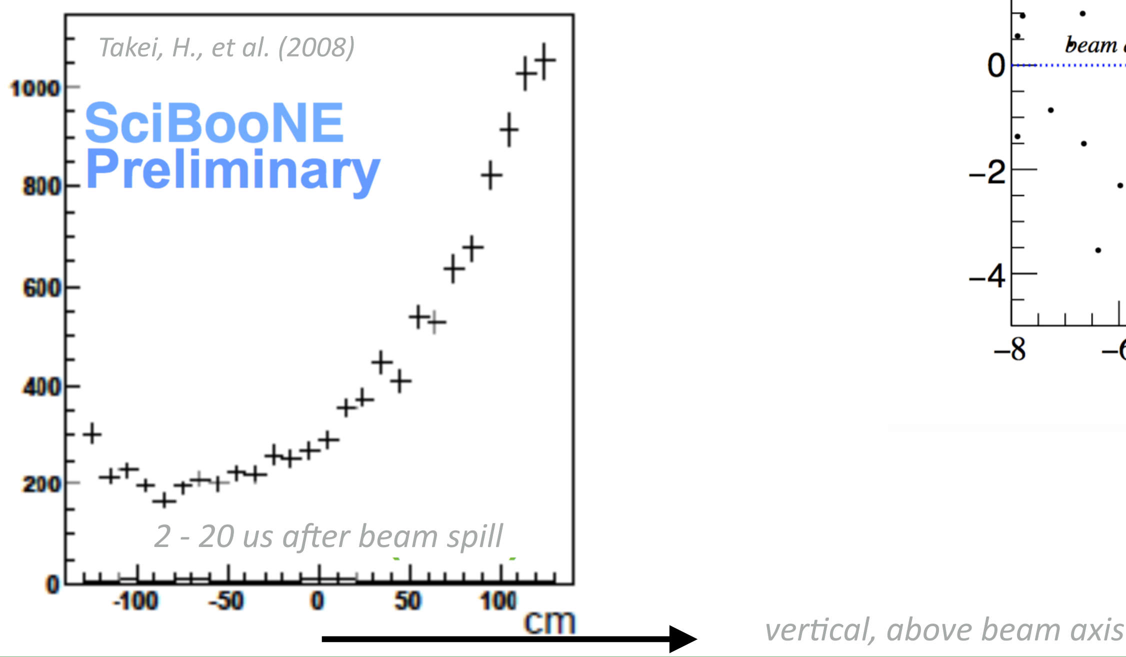
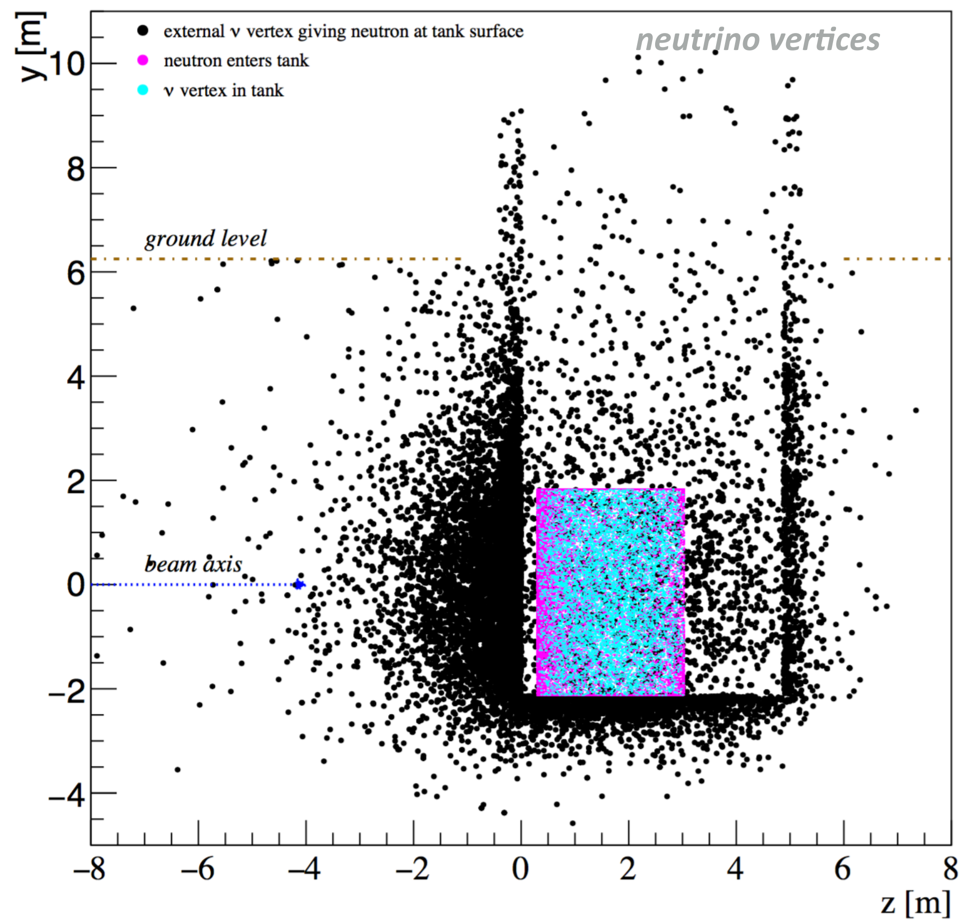


Neutron Background at ANNIE

- **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.





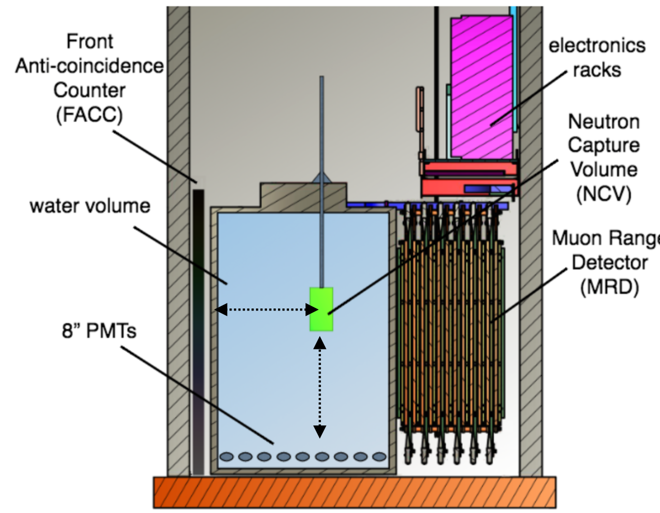
ANNIE: Phased Approach

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**.



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

c) Preparation for Phase-III.

proposal stage

simulations of optimal configuration under way

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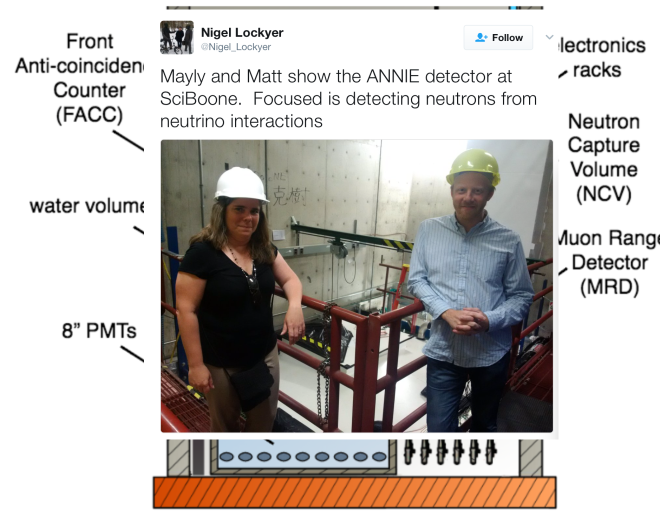

Funded, approved by Fermilab

first light in May 2016

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c) Preparations & Readiness for Theia R&D.

proposal stage

simulations of optimal configuration under way

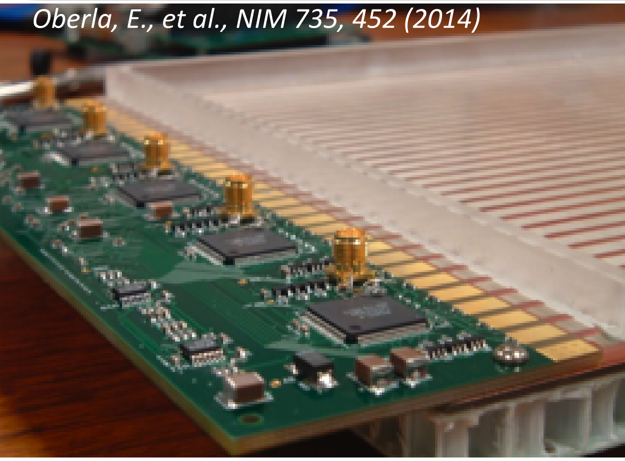
Veto, MRD, HV

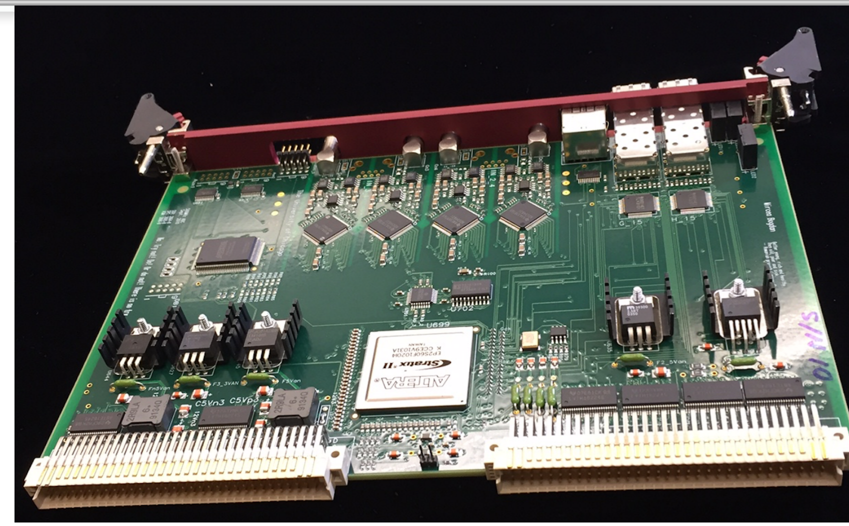

Veto:
2 layers
26 channels


2 layers
of MRD
refurbished
55 channels
(Phase I)


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

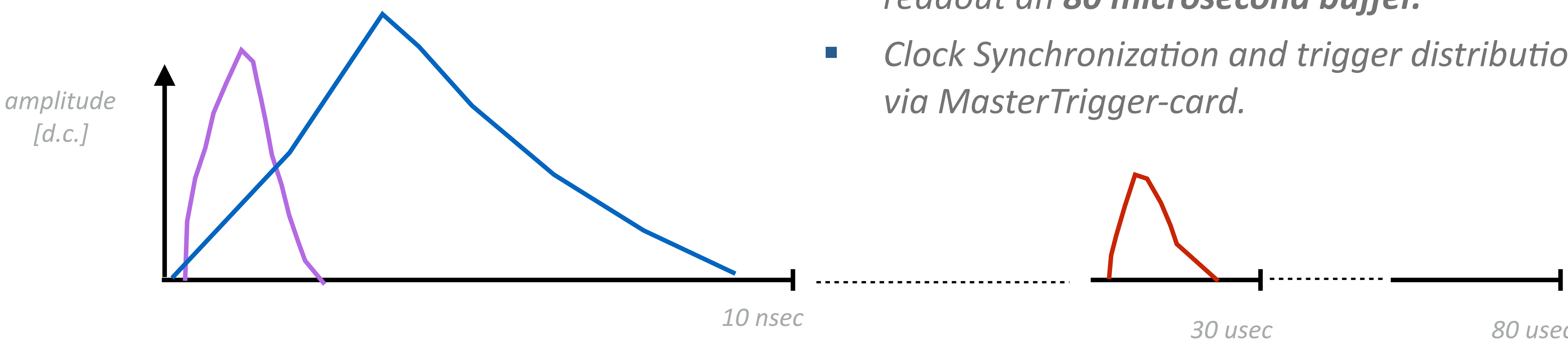
Readout Electronics





- ***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.*

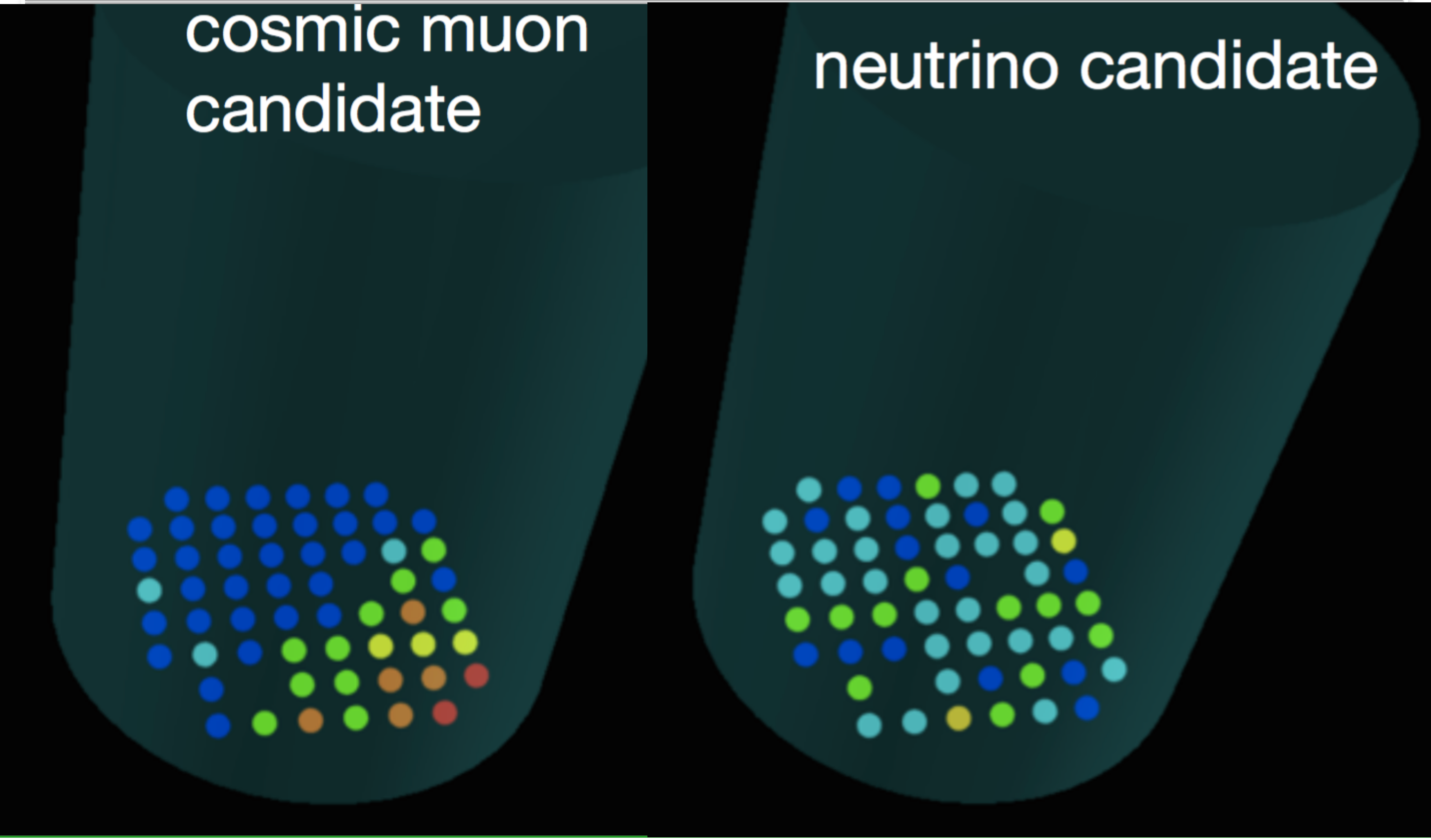


Water Fill

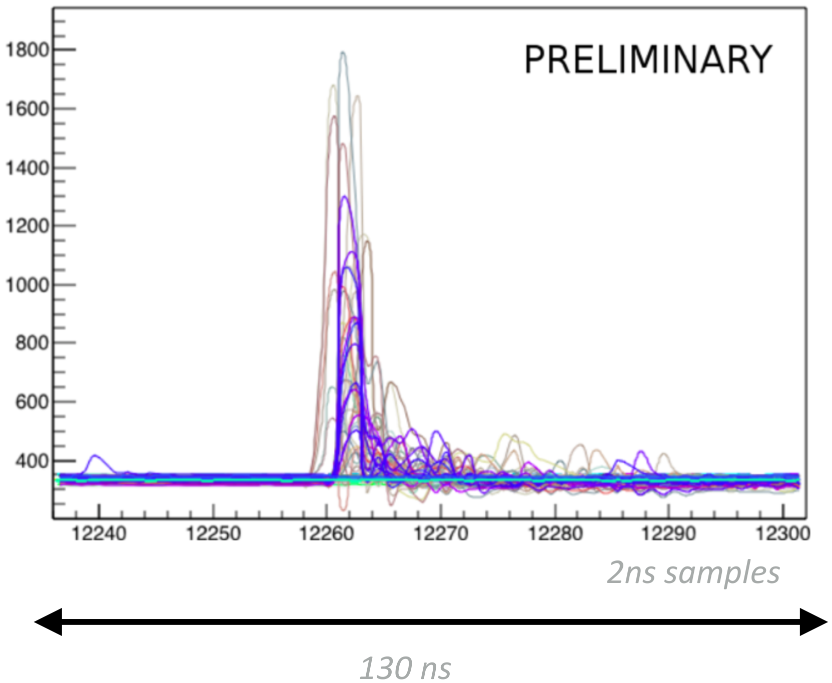
The ongoing and near-term program hosted by Fermilab was an important topic at the meeting. The excerpts on ANNIE from the PAC report are attached. As you can see, the committee "… *commends the ANNIE Collaboration's success in commissioning its detector.*" The PAC endorses the request to proceed with the Phase 1b plan, and for Phase II "… *expects that a formal proposal will be submitted at an appropriate time determined by Fermilab.*"

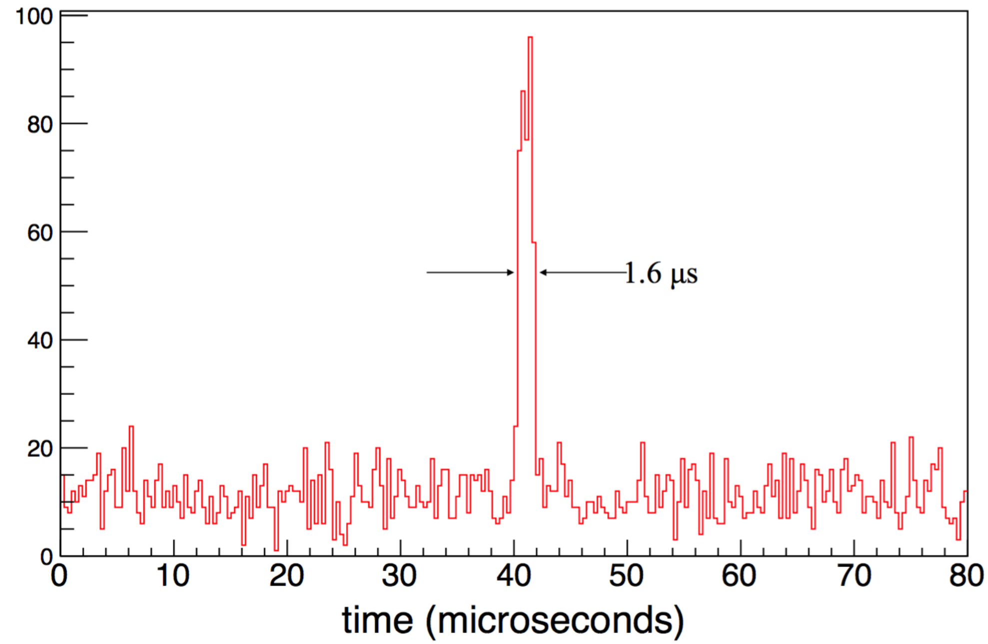
letter to ANNIE from Nigel Lockyer, July 19 2016

First Events



Muons and Beam

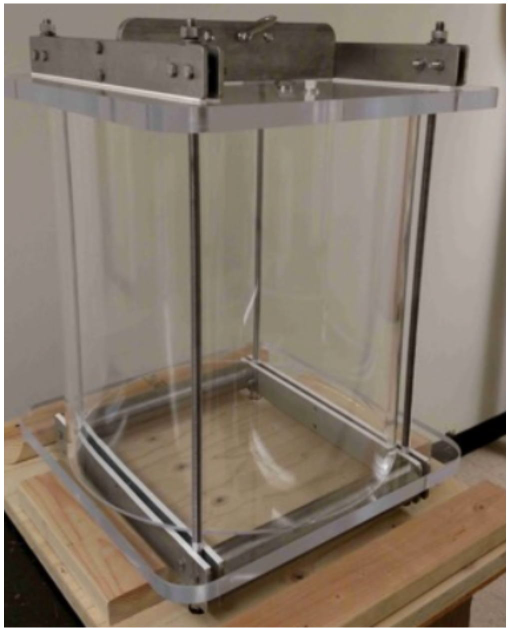


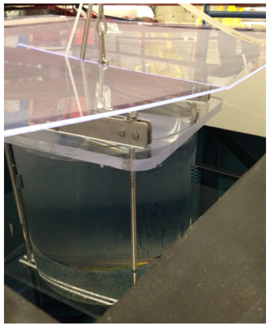


- Muon traces from a large number of PMTs (2 ns sampling FADCs), with number of PMTs > 5 above threshold.
- Neutrino events correlated with beam trigger (relative to resistive wall monitor from BNB).

Water Purification, Neutron Capture Volume

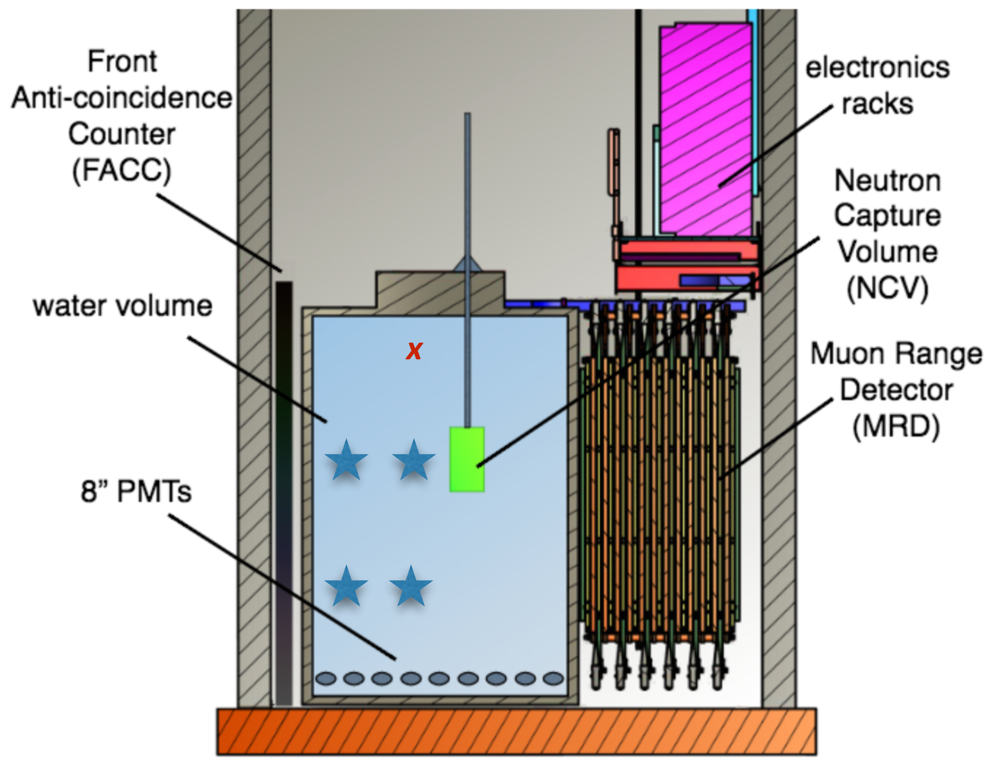
- Ultra pure water (0.5 ppm).
- Resistivity > 10 MOhm/m.
- 7,000 Gallons are continuously flushed with nitrogen and filtered through a deionizing purification system.

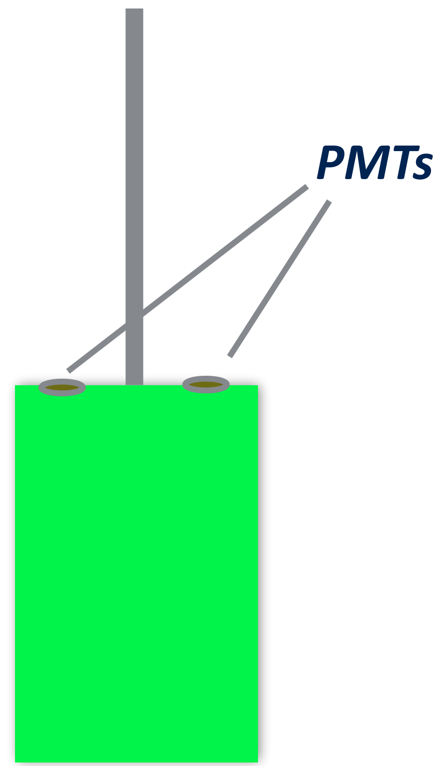




- Neutron capture volume (NCV) is an acrylic vessel.
- NCV can be moved vertically and along the beam axis.
- Filled with 100 liters of Gd-doped liquid scintillator
- EJ-335 contains pseudocumene and 0.25% Gd (weight)
- Peak wavelength 424 nm

Phase-I with NCV

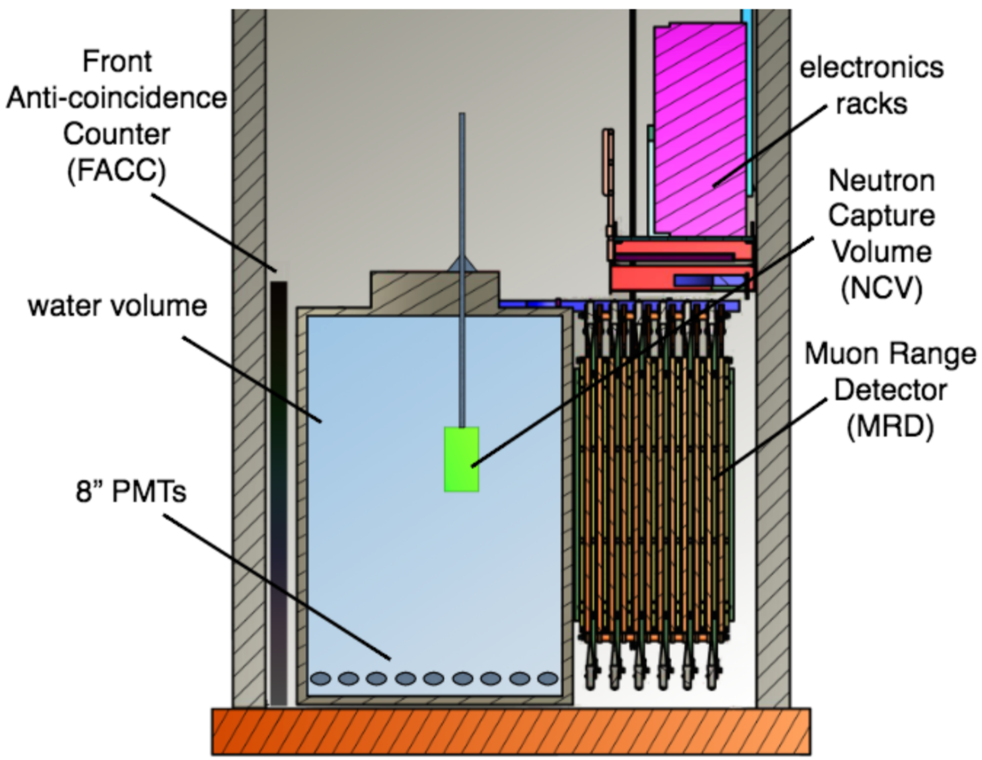


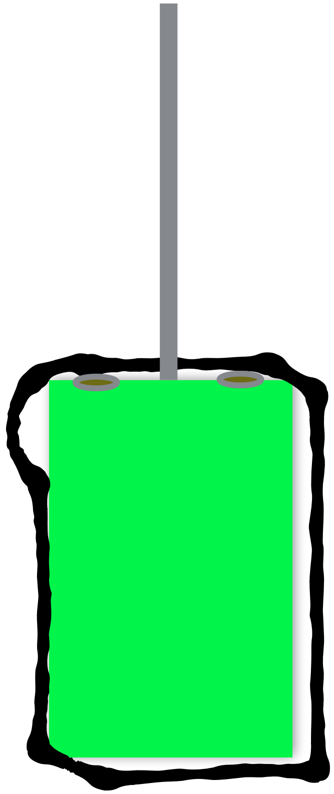


- NCV is moved to several locations to measure the neutron background.
- Guide for selecting fiducial volume.

- NCV filled with EJ-335 (pseudocumene and 0.25% Gd (weight).
- 2 PMTs sensitive to light from within NCV and from water tank.

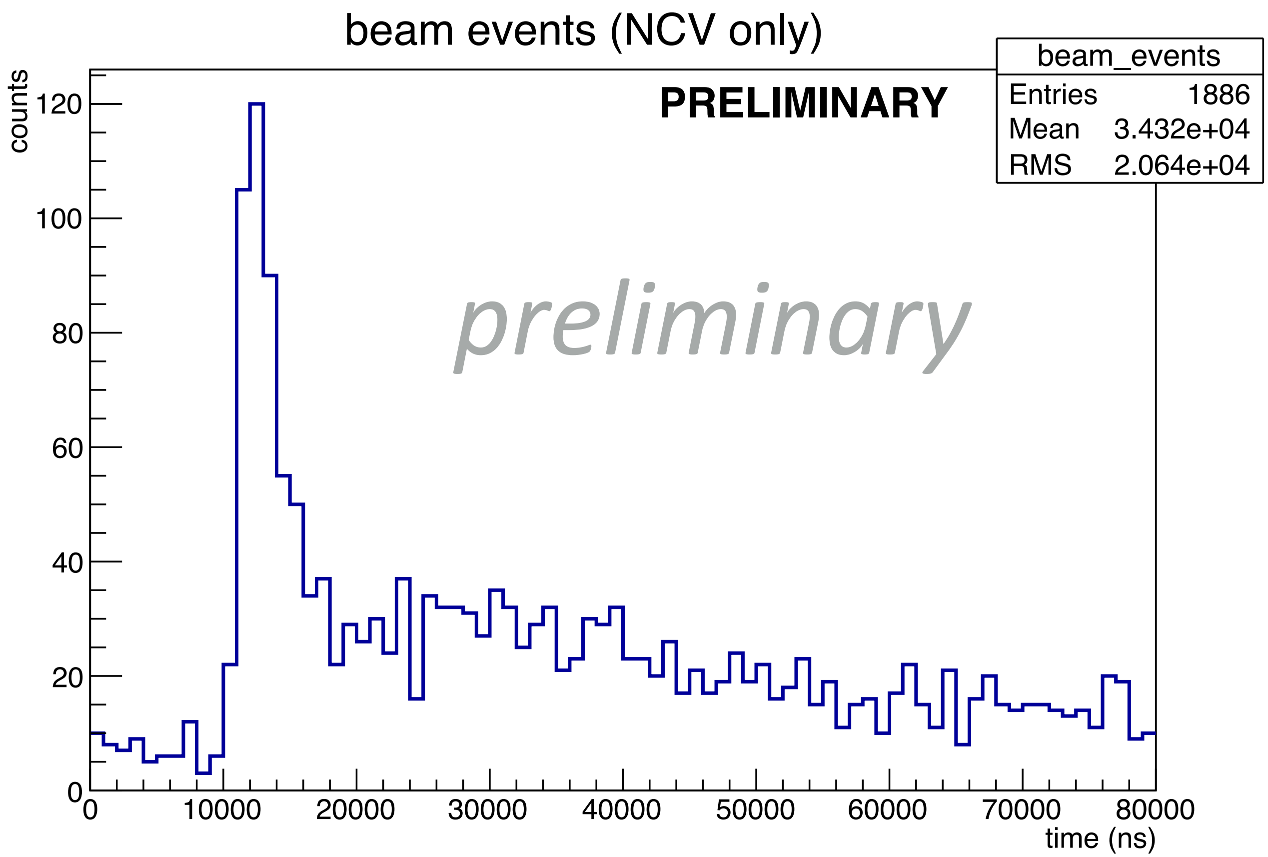
Phase-I with NCV





- NCV is optically isolated from the water volume (**"Hefty-mode"**, credit: Jonathan Eisch).
- Separate neutron capture inside NCV from cosmic-ray muons.

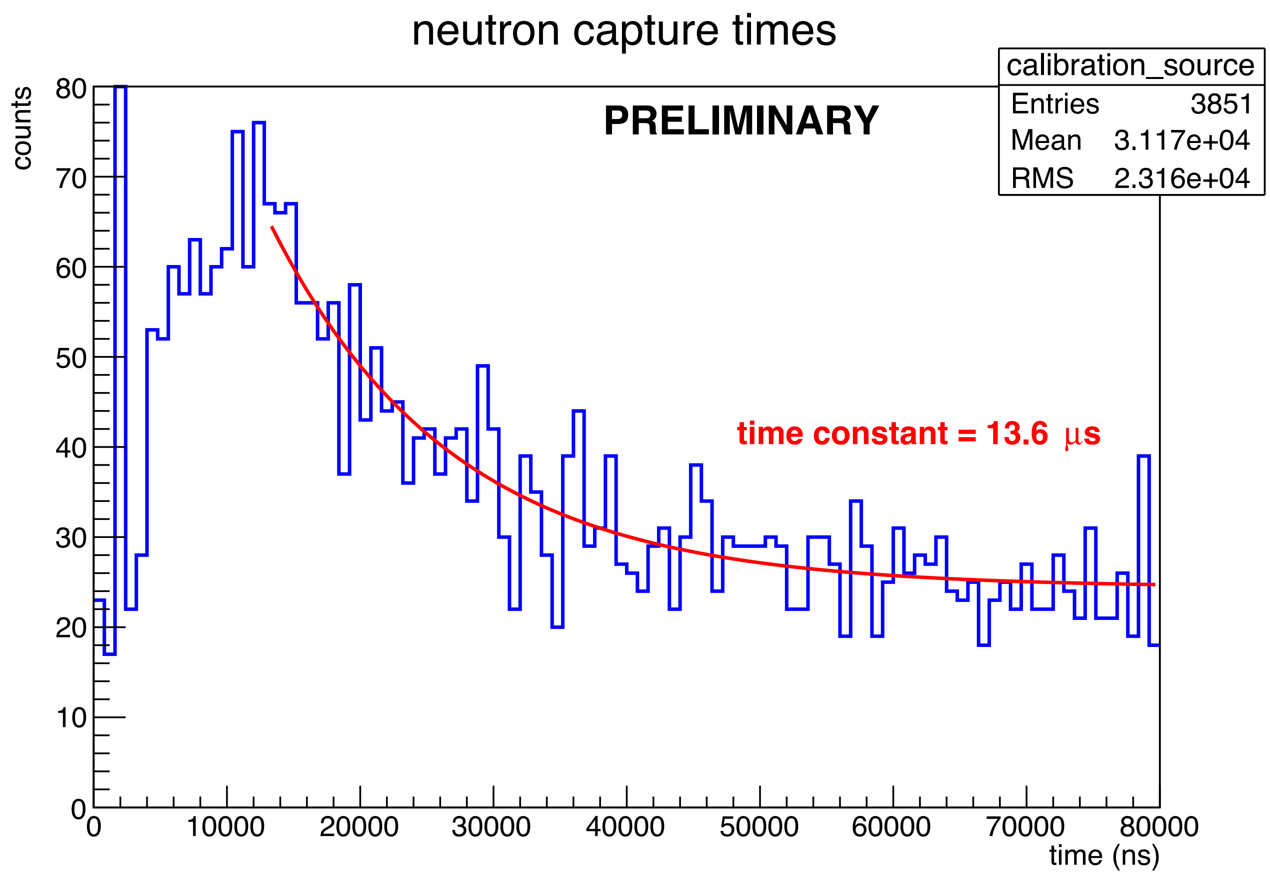
Evidence for Neutron Captures correlated with the beam



credit: Steven Gardiner & Vincent Fischer

- Rate of neutrons will depend on NCV position inside water tank.
- Triggered on beam, FACC/MRD veto, #PMTs in water volume < 4.
- More efficient DAQ "Hefty mode" is currently being tested to increase statistics rapidly.

Neutron Captures: Calibration Source



credit: Steven Gardiner & Vincent Fischer

- 252-Cf source, 0.5 mR/hr at 1 foot.
- Triggered on the gammas from the neutron calibration source: on top of the tank/NCV.
- Used a LYSO crystal (Lutitium-ytrium-oxyorthosilicate), peak at 375 nm + small PMT.

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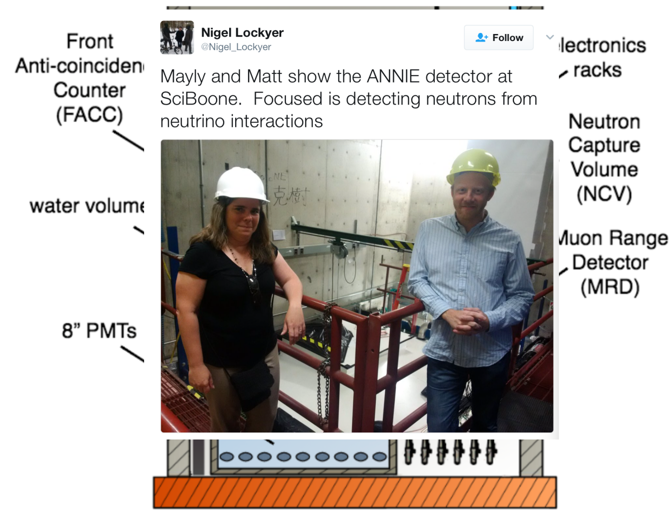

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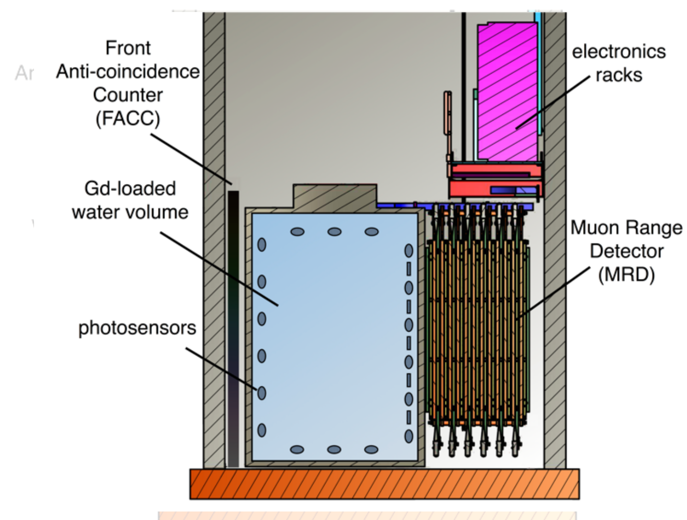
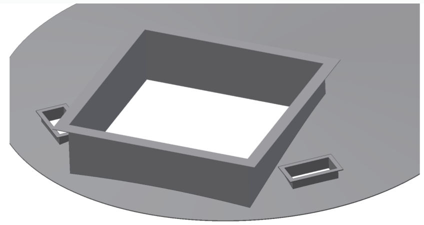


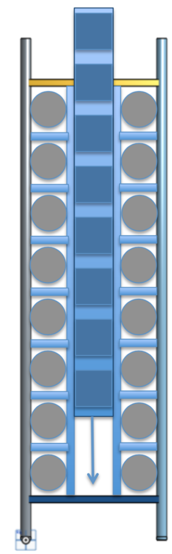
proposal stage

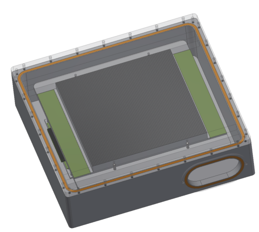
simulations of optimal configuration under way

ANNIE Phase-II Plans

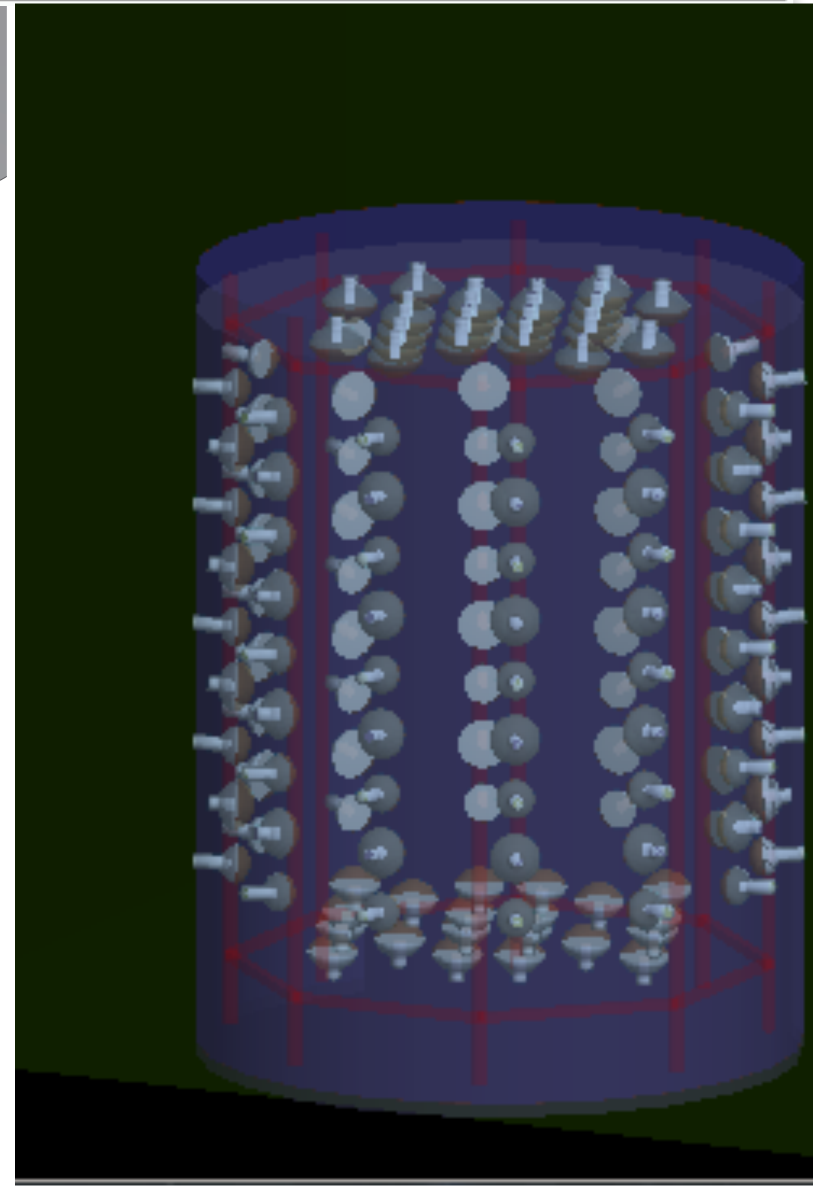


cassette - slot



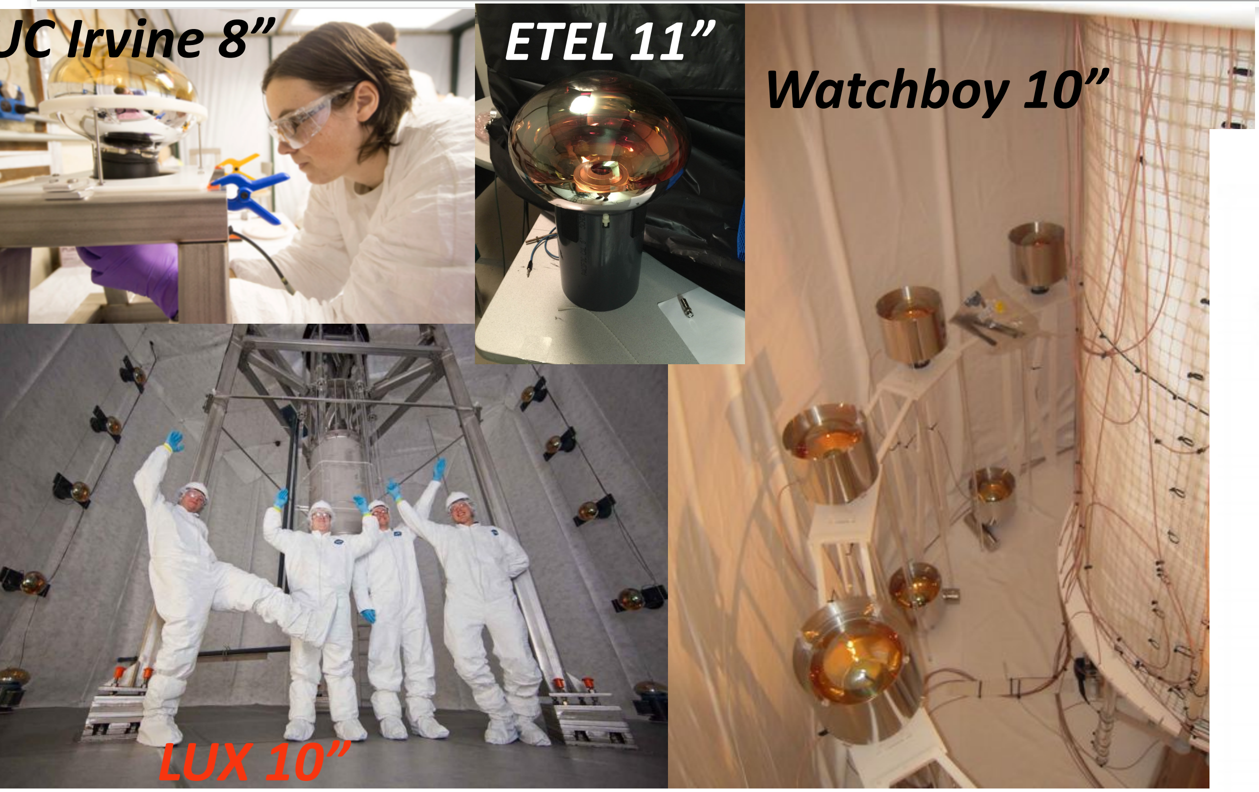


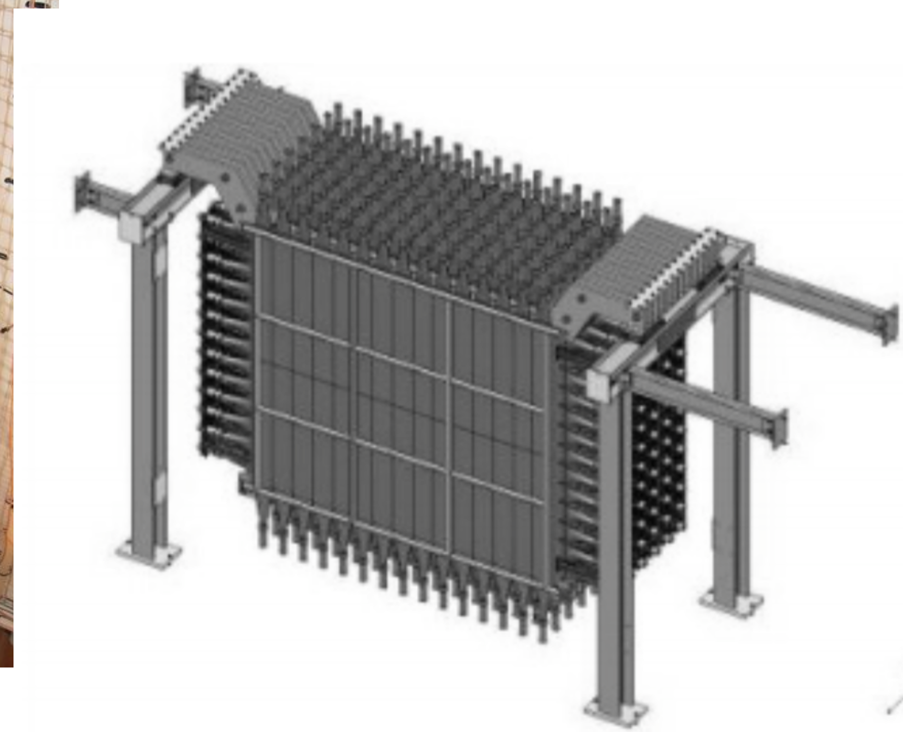
LAPPD housing



- Move the tank to staging area.
- Reconfigure the inner structure to install full complement of PMTs and LAPPDs.
- Install mail slot/cassette system for in-situ deployment of LAPPDs (in water).

ANNIE Phase-II Plans



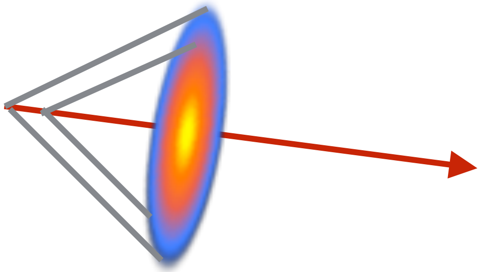


- PMTs largely in-kind contributions.
- 8-, 10- or 11-inch tubes (incl. HQE).
- Could use another 50 - 60 PMTs.
- PMTs are important contributions to ANNIE (new collaborators).

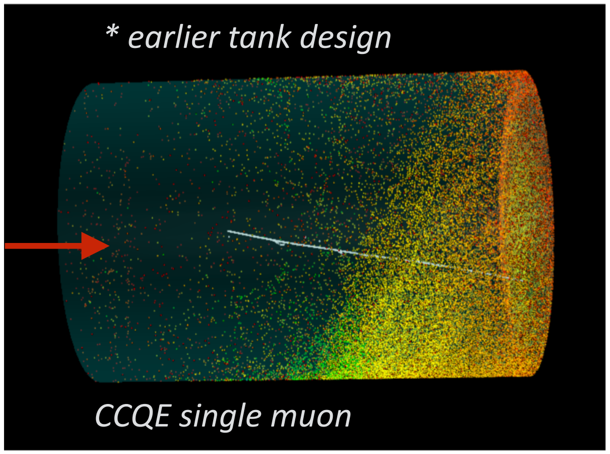
- Refurbish MRD.
- Test all components for Gd compatibility.
- Staging of water fill and Gd deployment.
- Electronics work: PSEC-4, FADC firmware, MRD electronics, HV, …

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.

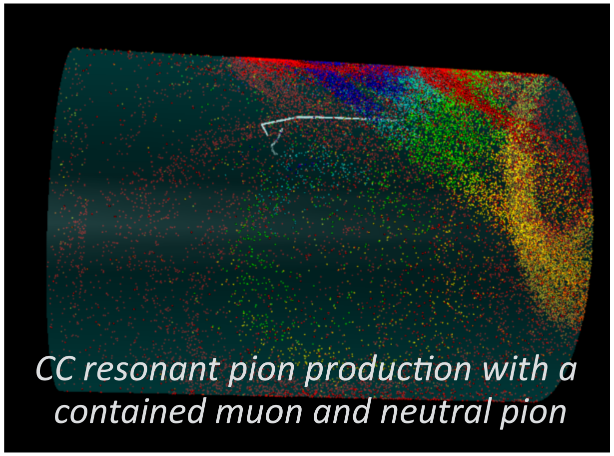


- **Find edge** of Cherenkov cone, LAPPDs (if cone edge crossed sensor), and/or use MRD, PMTs.
- **LAPPDs**: excellent timing and spatial resolution to separate single/multiple tracks.

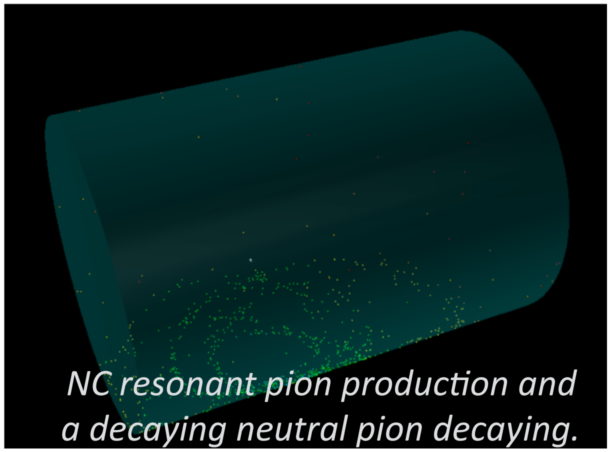


** earlier tank design*

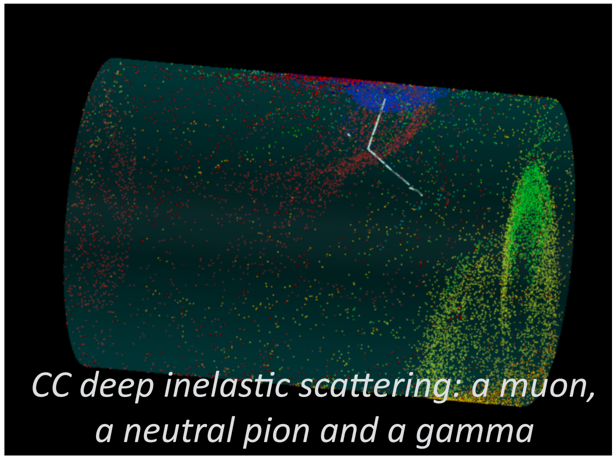
CCQE single muon



CC resonant pion production with a contained muon and neutral pion



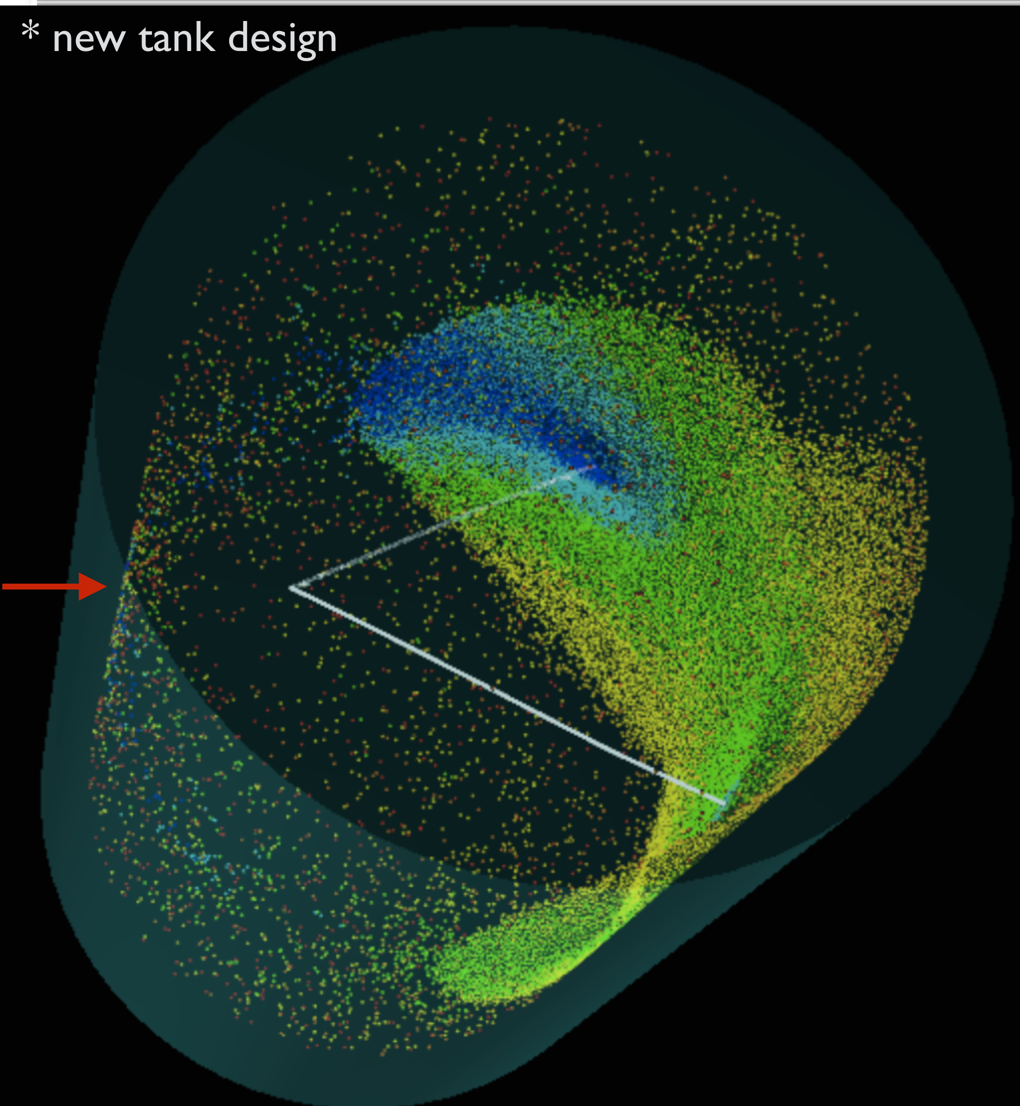
NC resonant pion production and a decaying neutral pion decaying.



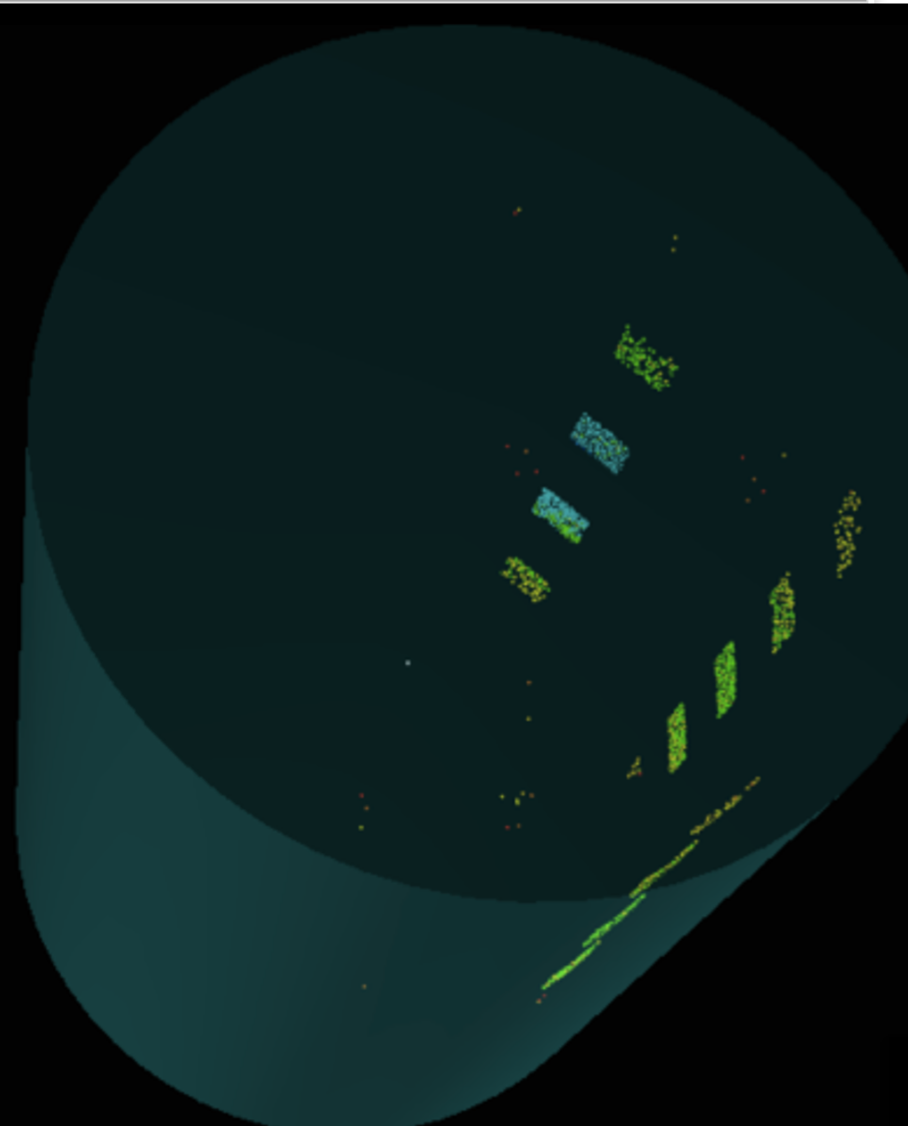
CC deep inelastic scattering: a muon, a neutral pion and a gamma

Photodetector Coverage

* new tank design



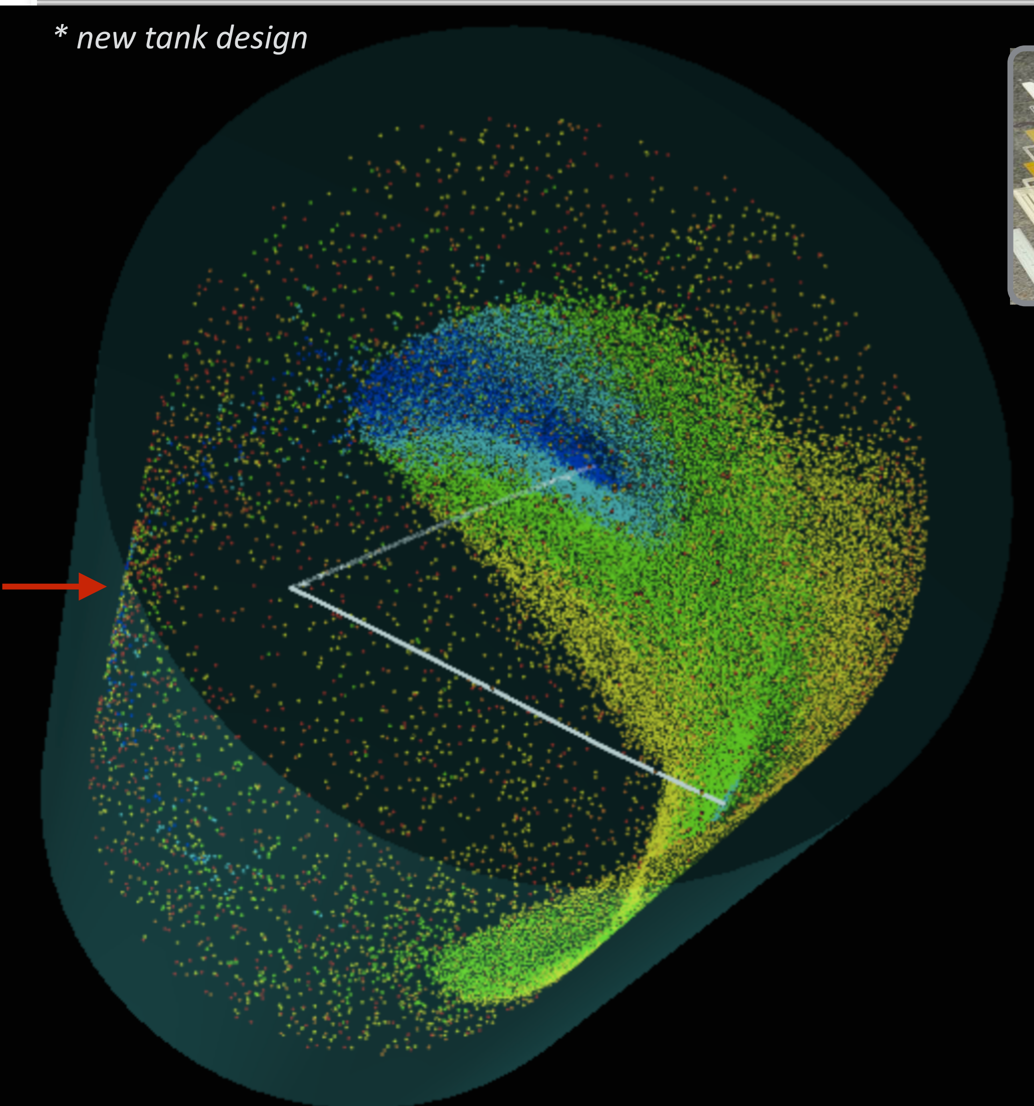
CC resonant pion production, a muon and a pion.



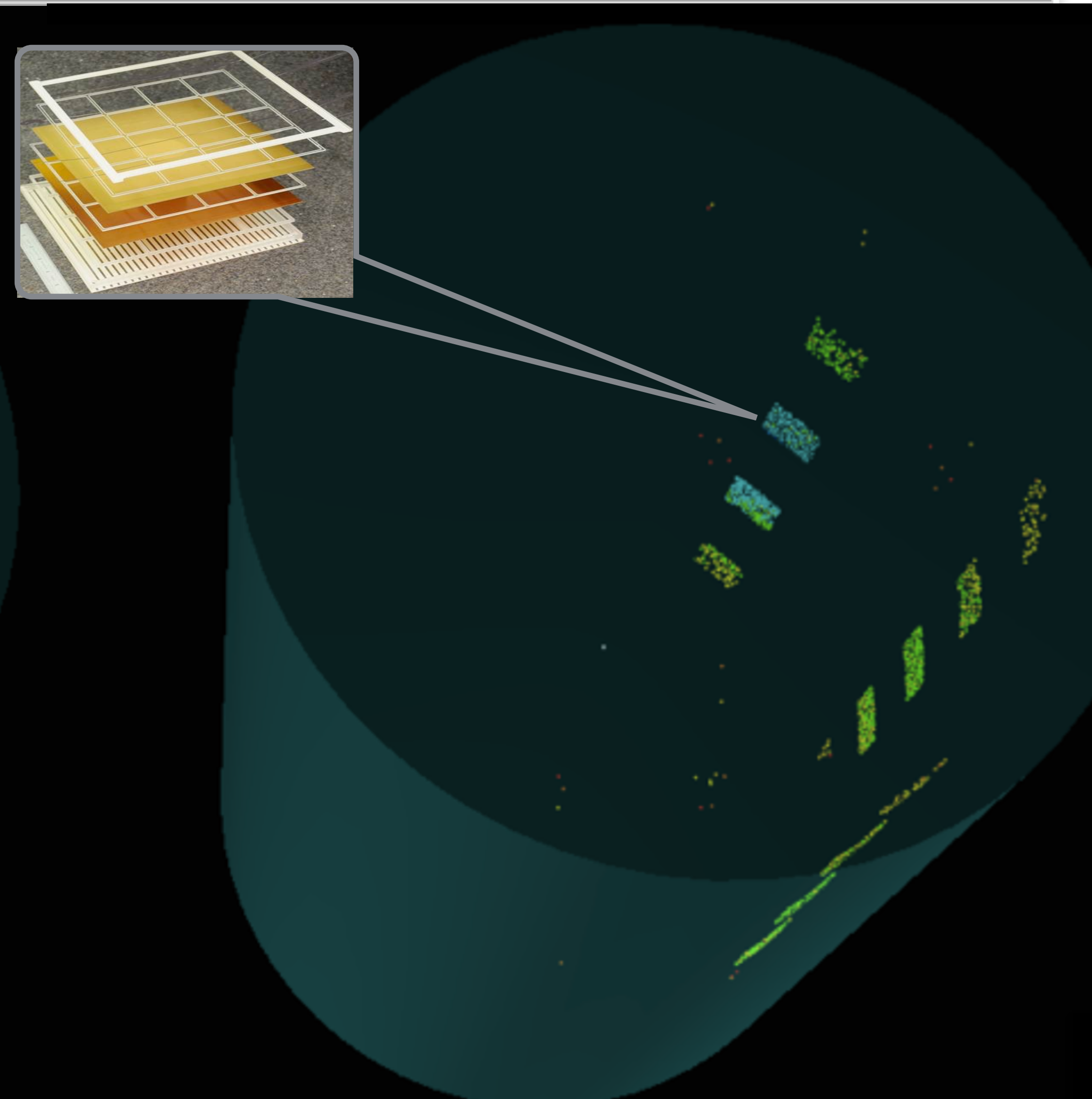
Coverage by 20 LAPPDs.

Photodetector Coverage

* new tank design

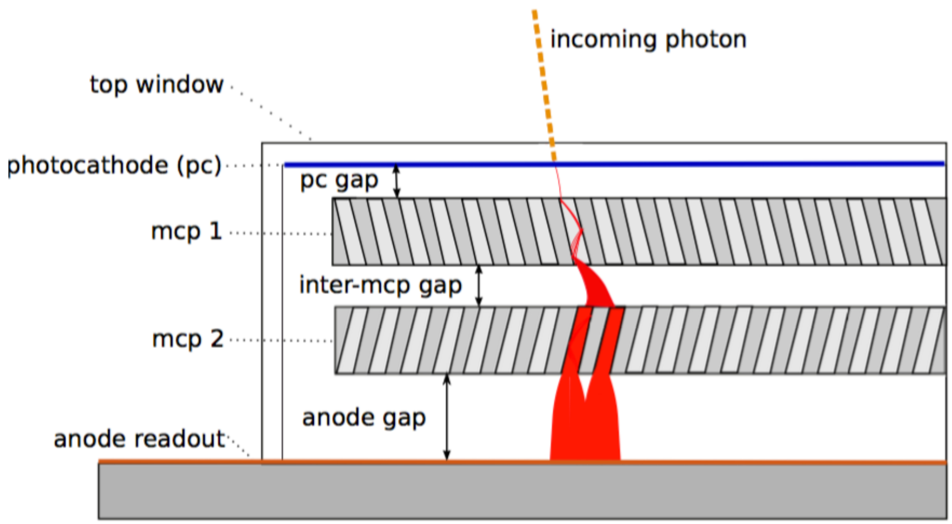


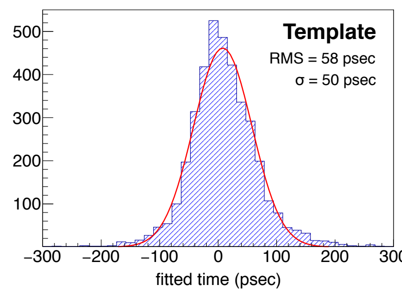
CC resonant pion production, a muon and a pion.



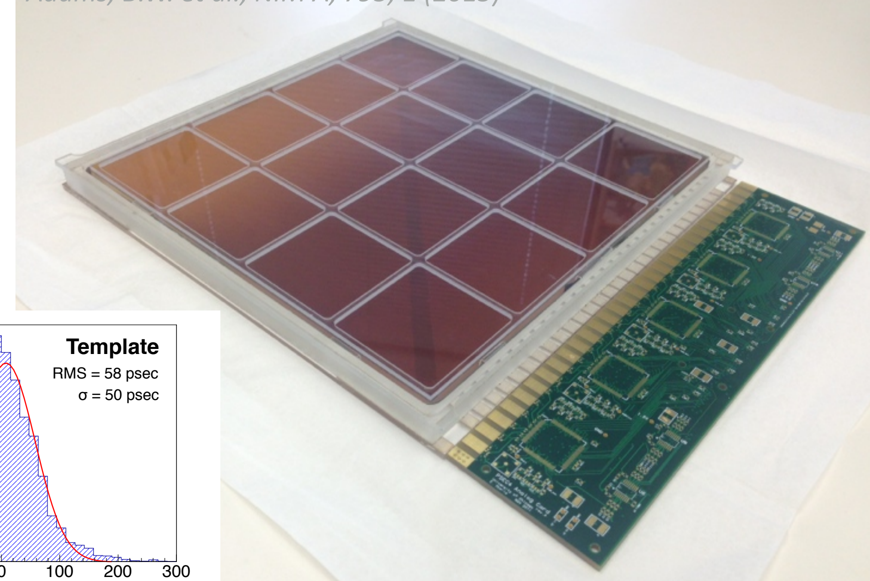
Coverage by 20 LAPPDs.

LAPPDs





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



See Matt Wetstein's Talk on LAPPDs

- LA[illegible]D (La[illegible]ge Ar[illegible]a Pi[illegible]ec[illegible] Ph[illegible]tect[illegible]r): [illegible] cm x 20 c[illegible] (8" [illegible]til[illegible] fla[illegible] p[illegible]n[illegible] p[illegible]ocath[illegible]de.
- 2 MCP[illegible] (ALD): **[illegible]00[illegible]s t[illegible]m[illegible] r[illegible]ol[illegible]tio[illegible]** multi[illegible]no[illegible] re[illegible]dout [illegible]ives [illegible] **1 cm spati[illegible]l [illegible]so[illegible]ution**
- ANNIE: minimal pileup and **single photon resolution** are the basis for cm scale vertex reconstruction, single-/multi-particle separation, …
- Incom Inc[illegible] has set u[illegible] commercial production f[illegible]cility [illegible] ANN[illegible] w[illegible]l [illegible]et [illegible]p [illegible]o 2[illegible] LA[illegible]PDs (3-years).
- ANNIE p[illegible]ys[illegible]s [illegible]o[illegible]ra[illegible] [illegible]enef[illegible]s f[illegible]r **L[illegible]PPD [illegible]apa[illegible]s** [illegible]ut is a[illegible]so de[illegible]elo[illegible]ing [illegible]eir **first use in an experiment**; experience in a liquid environment and physics data.

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.*
- ***First results*** *from* ***ANNIE Phase-I indicate a neutron signature*** *correlated with the beam.*
- *Operation of ANNIE Phase-I is going into its final stage:* ***optical isolation mode with multi-stage triggered DAQ*** *("Hefty mode").*

ANNIE Summary

- ***LAPPD readiness*** *is well underway:* ***first few tiles produced****, and are currently being tested, water proof housing design available.*
- ***ANNIE Phase-II (2017 - 2021)*** *with the deployment of LAPPDs is in the planning stages. Simulations are under way to determine the track reconstruction resolution as a function of # of LAPPDs and positioning.*
- *Construction efforts for Phase-II are planned to start summer 2017, and operation will start in 2018.*
- ***ANNIE is also an excellent proof-of-principle facility*** *for a* ***THEIA prototype setup*** *(see Bob Svoboda's talk).*
- *ANNIE Phase-III can be tailored to THEIA R&D needs.*