Prospects of Neutron Multiplicity Measurements in Neutrino Interaction

Navaneeth Poonthottathil

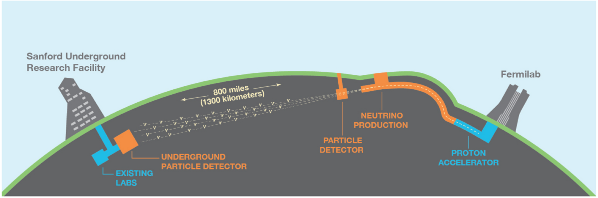
IIT Kanpur

In-house Symposium 2024

February 2, 2024

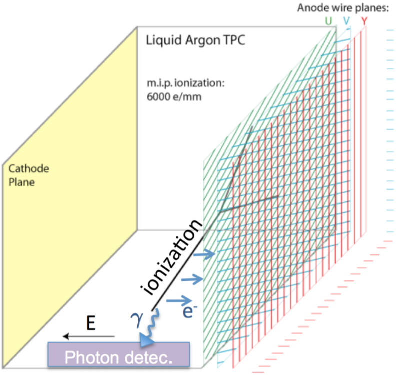
Next Generation Neutrino Experiment

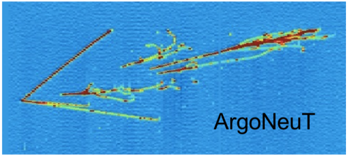
DEEP UNDERGROUND NEUTRINO EXPERIMENT



- Shoot a neutrino beam from Fermilab (IL) to SURF (SD), 1300 km baseline.
- Four 10 kt liquid argon detectors, very promising detector technology.
- Physics goals to measure CP violation (matter-antimatter asymmetry), mass hierarchy of neutrino, proton decay.

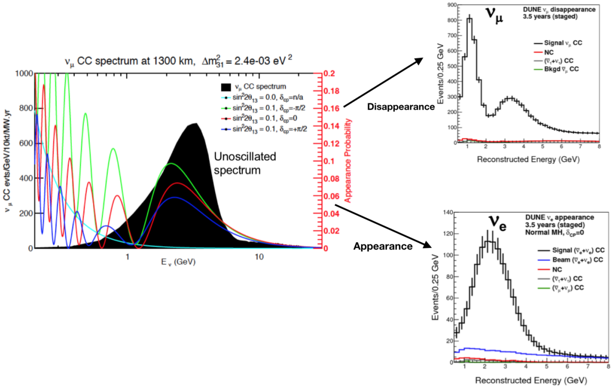
Liquid Argon TPC





- DUNE uses Liquid Argon Time projection chambers for detecting neutrinos.
- High energy particles ionize liquid argon atoms along their paths.

Neutrino Oscillation Measurment



- Produce a pure on-axis ν_μ beam with spectrum matched to oscillation pattern at the chosen distance.
- Compare the near and far detector spectrum, obtain the neutrino oscillation parameters.

The Accelerator Neutrino Neutron Interaction Experiment

Detector

Collaboration

New technologies:
LAPPDs/WbLS
Gd-loaded water

- More than 30 Collaborators from 5 Countries
- US, Germany, India, UK, Turkey, Greece

IITK Application to join ANNIE - 2023, Januray

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To : ANNIE Collaboration 3 November 2022

Dear ANNIE Institutional Board Chair and Members,

This letter is to support my application to join ANNIE Collaboration with my new institution, the Indian Institute of Technology Kanpur (IITK), India. I completed my M.Sc. in Physics from the Cochin University of Technology, India, in 2011 and my Ph.D. through the India-Fermilab Neutrino collaboration program in 2017. I joined the Physics Department at Iowa State University (ISU) in February 2018 as a full-time postdoctoral researcher contributing to the neutrino physics efforts on ANNIE and DUNE. As of September 14, 2022, I started a new faculty position in the Department of Physics, Indian Institute of Technology Kanpur.

IIT Kanpur is one of the prestigious public-research institutes in India, situated in Kanpur (400km south of New Delhi), India. It was founded in 1959. The institute now has around 4500 undergrads and ~4500 graduate students (Master's + Ph.D.). The physics department was founded in 1960 and accepted the first undergrads in the same year. There is 50 faculty staff in the Physics Department, and the department has strong research groups focusing on Complex Systems, Condensed Matter Theory & Experiment, High Energy Physics, Laser Physics, and Ion Beam Plasma & Nuclear Solid State. We have a strong theoretical High Energy Physics group (12 faculties) working on aspects such as QCD, String theory, Collider Physics, and Effective field theory. Most of our colleagues are working on theoretical high-energy physics and cosmology. For now, I am the only neutrino physicist in the department, but we will expand the experimental neutrino group in the following years. The institute is now planning to strengthen the experimental HEP group by hiring more faculties for the collider physics experiments as well as for the neutrino physics program in the coming years.

My association with the Fermilab neutrino experiment started in 2011 when I joined the MINOS collaboration during my Ph.D. As a Postdoctoral Fellow at ISU, I served as in charge of the ISU test stand for the last few years and was involved in commissioning the phase II data during 2020, especially validating the trigger system. During the Phase II detector hardware building, I was stationed at Fermilab in the summer and contributed towards the detector upgrade of the ANNIE Detector for the Phase II data taking. In addition to my work on ANNIE. I have contributed to the MINOS experiment. I did my Ph.D. thesis on a Sterile neutrino disappearance search in MINOS using the antineutrino data. In MINOS, I served as a DAQ expert for two years. My DUNE efforts at Iowa State include developing the techniques for the quality control of DUNE cold electronics components. I have set up a DUNE functional test facility at Iowa State, which will be a site for DUNE cold electronics component (Front End Mother Board) testing in the future. In the future, I am interested in working on neutron multiplicity studies and LAPPD data analysis in ANNIE. I am also interested in detector R&D studies for future WbLS.

The Institute has a provision for funding for postdoctoral research associates (up to 3 years). I am planning to hire one postdoc early next year. The Institute also provides a fellowship for Ph.D. students, and I expect to have someone in the next batch of Ph.D. admission to our Institute. IIT Kanpur has provided me with a small startup grant which I will use to set up a workstation along with the facilities to do ANNIE remote shifting. I am also planning to submit a research grant proposal to funding agencies of the Government of India. This proposal would include a plan to set up a HEP detector R&D lab for various detector component testing, including those for DUNE ND development. Also, some of my colleagues at IIT Kanpur working on HEP phenomenology expressed their interest in joining neutrino experiments at Fermilab.

For service work, In the beginning, I, along with students (MS and Ph.D.) and our post-doc (planning to hire early next year), will contribute to the shift operations, and I will also be continuing as a shift expert. I hope we can set up a remote control shift center relatively sooner at IIT Kanpur. The new proposal to the Indian funding agency includes some money for international travel support and will help students to spend at least a few months in the summer at Fermilab. I will talk to our physics analysis coordinator for the analysis topic discussion for one Ph.D. student, and I will also talk with spokespeople about more service contributions to the experiment to make sure our group continues to provide the best support to the ANNIE experiment.

I am looking forward to continuing my contributions to ANNIE through IIT Kanpur.

Thank you for your time and consideration.

Sincerely,

Navaneeth Poonthottathil

Navaneeth Poonthottathil

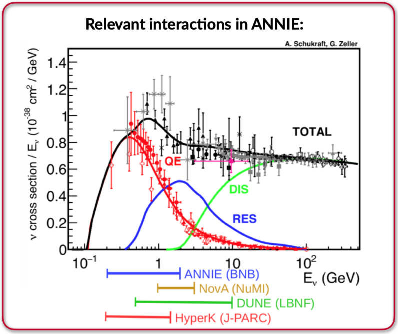
Department of Physics
Indian Institute of Technology Kanpur
Kanpur, India

Forwarded and Recommended

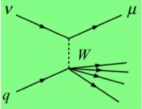
Harsha

Head, Department of Physics
Indian Institute of Technology Kanpur
Kanpur, India

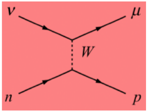
GeV-scale neutrino interactions



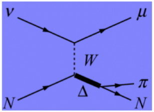
Deep Inelastic Scattering



Quasi-Elastic

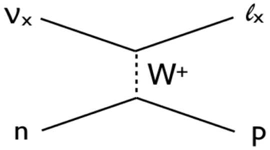


Resonance



- Across the GeV-energy range, there are multiple possible interaction types (and particles produced).
- Final-state interactions for different events could lead to different neutron multiplicities.
- Additional cross-section measurements can help refine neutrino interaction models.

True CCQE interaction

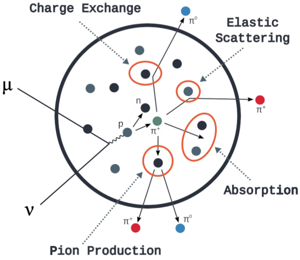


$$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

$$Q_{QE}^2 = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

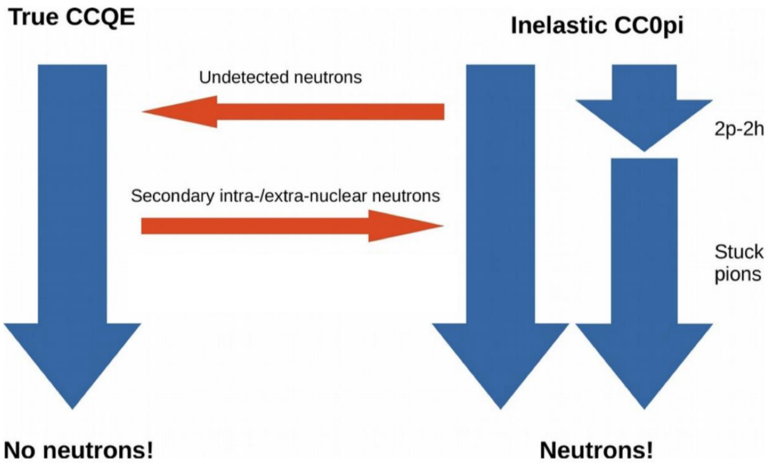
- Two body scattering with an outgoing lepton.
- Target nucleon assumed at rest.
- Calculate kinematics from the outgoing leptons

Role of Understanding the Interaction

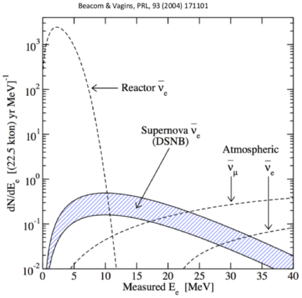


- Knowledge of neutrino-nucleus scattering cross sections is crucial to the global neutrino physics program.
- We still have a long way to understand the nuclear effects that define what we see in our detectors..
- **Final State Interactions (FSI)** and other **nuclear effects** make different interaction channels have the same final topology

Neutron multiplicity identification (and confusion)



Rare Physics searches

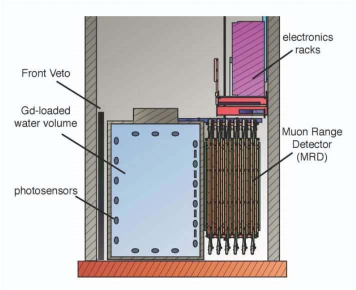


- Diffuse Supernova neutrino search from accumulation of all past supernova explosion.
- Small but steady source of supernova neutrinos.
- Never observed, challenging due to significant background
- Tagging atmospheric neutrinos helps ∼ more likely to produce neutrons

Goals of ANNIE

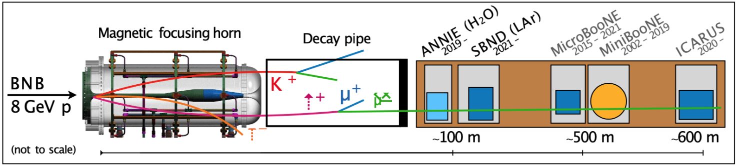
- Primary physics goal is to measure neutrino induced neutron yields in water as a function of outgoing lepton kinematics.
- Demonstrate new technologies that will be helpful for physics analysis.
- Perform a measurement of the CC inclusive cross section as a function of momentum transfer
- ANNIE's in collaboration with SBND would able to compare cross-sections measurements on water (oxygen) and argon nuclei.
- Gadolinium loaded water for high efficiency neutron tagging
- Large Area Picosecond Photodetectors (LAPPDs) for precise event reconstruction
- Use of Water-based Liquid Scintillator
- ANNIE will provide R&D for future large-scale experiments

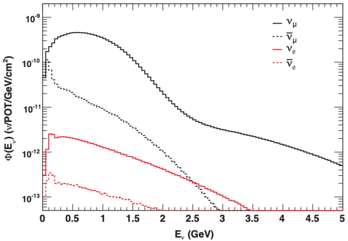
Overview of ANNIE

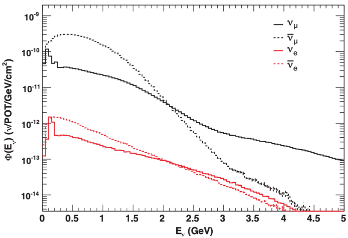


- Gd-loaded water based detector placed downstream of the Booster Neutrino Beam at Fermilab.
- 4m height and 3m radius - small detector
- Aims at measuring the production rate of neutrons from neutrino interactions in water.
- Close proximity to beam target, hight flux of neutrino, 10000 CC/ton/year

Booster Neutrino Beam







- 8 GeV protons8 GeV protons on Beryllium target
- Mean neutrino energy of 700 MeV.
- Composition: 93 % of ν_μ, 6.4 % $\bar{\nu}_\mu$ and 0.6 % of ν_e and $\bar{\nu}_e$

Phase I

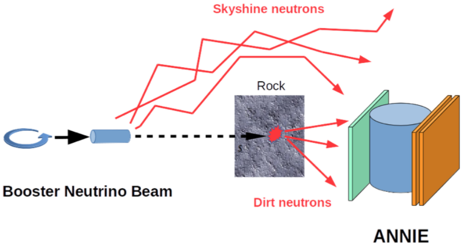
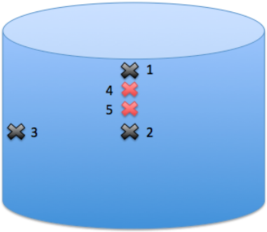
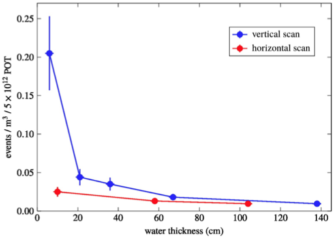


Image: Vincent Fischer

- Measurement of the neutron background rate is very important
- Source of neutron background:
  - **Skyshine neutrons** $\rightarrow$ Neutrons from the beam dump entering the detector
  - **Dirt neutrons** $\rightarrow$Neutrons originating from neutrino interactions downstream of the dump

Phase I





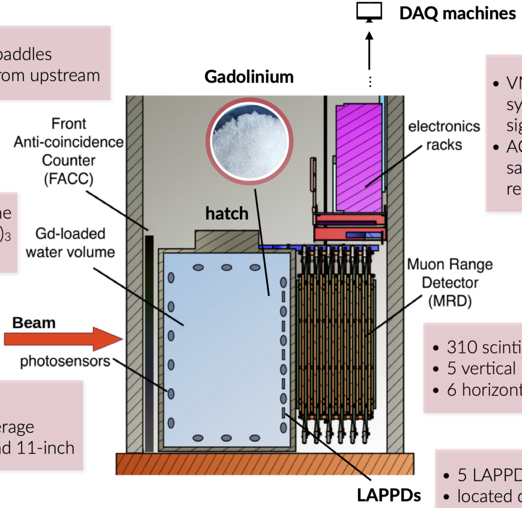
- Background neutron flux is different at each position, especially the skyshine component
- Background rate less than $0.02/m^3/spill$
- Not an issue for Phase II physics measurments
- Published - *A.R. Back et al 2020 JINST 15 P03011*

Phase II

Phase II detector

- 26 scintillator paddles
- reject muons from upstream

- 26 tons water volume
- loaded with $Gd_2(SO_4)_3$ (0.1% by weight)



- VME acquisition system for PMT signals (500MHz)
- ACDC cards sampling LAPPD response (10 GHz)

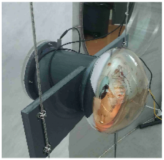
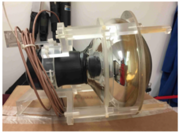
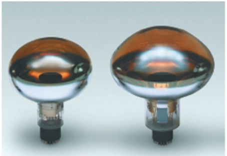
- 134 PMTs
- 20 % coverage
- 8-, 10-, and 11-inch

- 310 scintillator paddles
- 5 vertical layers
- 6 horizontal layers

- 5 LAPPDs
- located downstream

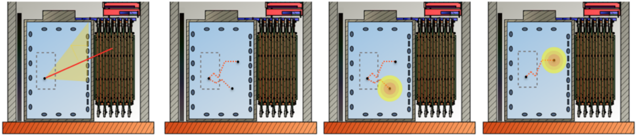
Picture from M.Nieslony

PMT types

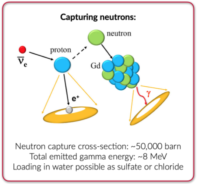





Manufacturer	ETEL	Hamamatsu	Hamamatsu	Hamamatsu	Hamamatsu
Origin	LBNE R&D	LUX	Watchboy	New	WATCHMAN
Type	D784KFLB	r7081	r7081	r5912	r7081
“Name”	LBNE (LB)	LUX (LX)	Watchboy (WB)	New (HM)	Watchman (WM)
Size	11”	10”	10”	8”	10”
HQE?	Yes?	No	No	Yes	Yes
Quantity	22	20	45	40	10

How ANNIE Works



1 2 3 4



- 1 - CC interaction in the fiducial volume
- 1 - Muon direction reconstructed using LAPPDs & momentum reconstructed with the MRD.
- 2- Neutrons are getting thermalized in the water volume
- 3-4 Neutron capture on Gd detected by the PMTs .

ANNIE Event Rates

- BNB delivers 4×10^{12} POT per $1.6\mu s$ at 5Hz.
- Mean Energy 700 MeV
- Average 1CC ν_μ interaction in every 150 spill - no pileup

Category	NC	CC	CCQE	CC-other
All	11323	26239	13674	12565
Entering MRD	2	7466	4279	3187
Stopping in MRD	2	4830	2792	2038

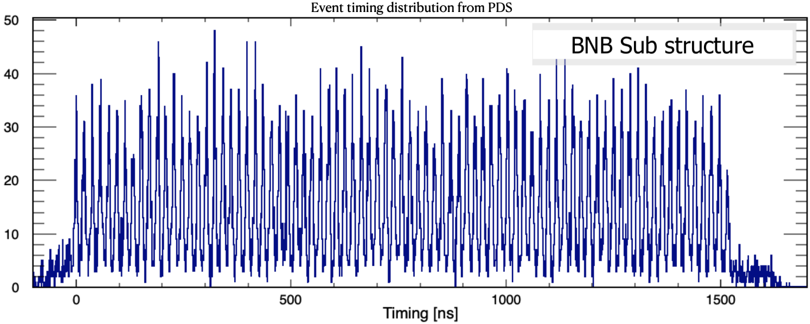
Table: Event counts in 2.5-ton fiducial volume over 2×10^{20} POTs $\sim$1year

ANNIE Detector during Installation

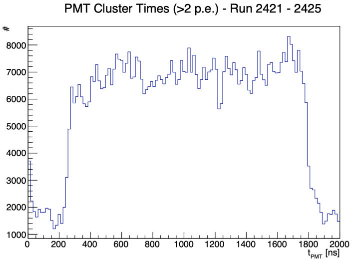
- Equipped with 132 photomultipliers.

BNB Beam structure

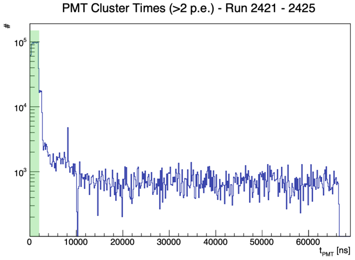
- 1.6 us wide, 53.1Hz, 2ns width, 82 Bunchs



Do we see Neutrinos - Phase II



Prompt window

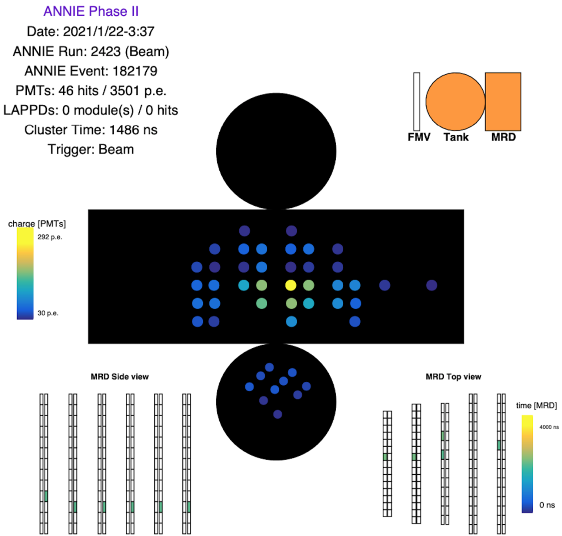


Extended window

1.6us beam spill window visible

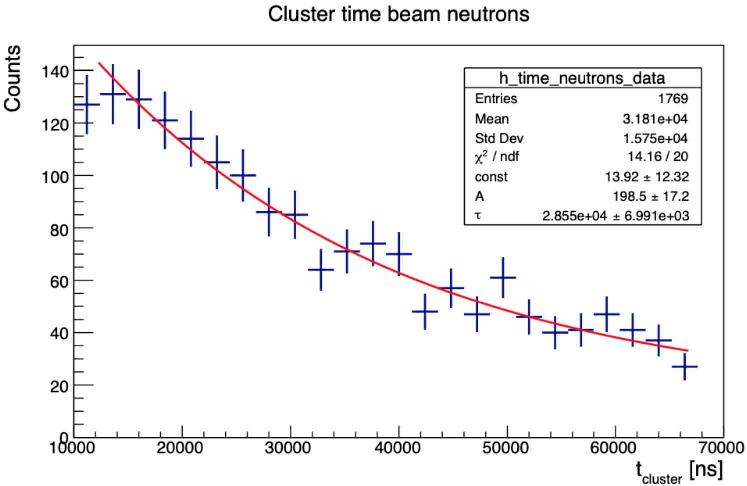
Less statistics for extended readouts

Neutrino candidate



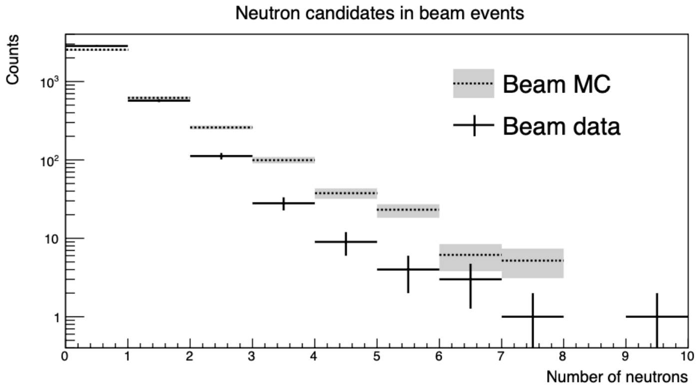
Neutron Capture Time- Very Preliminary

- The fit value is in agreement with theorectiocal prediction.

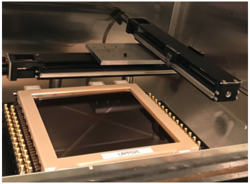


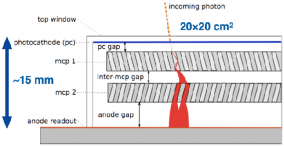
Neutron Multiplicity - Very Preliminary

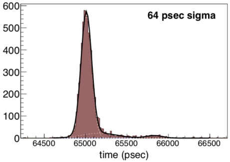
- Neutron multiplicity distribution in data for beam neutrino.
- These are events featuring a stopping muon track in the MRD.



ANNIE Detector R&D: LAPPDs Developments



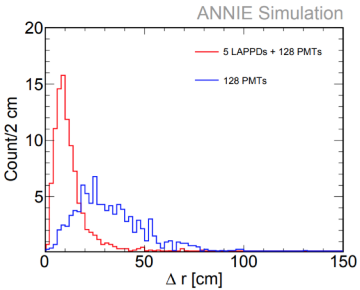


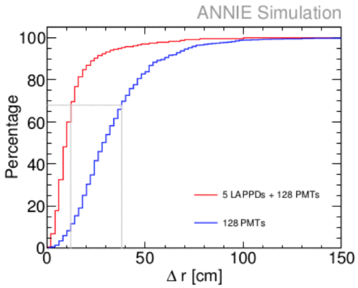


- LAPPDs are 8" $\times$ 8" MCP-based imaging photodetectors, with target specifications of:
  - $\sim$ 50 picosecond single-PE time resolution
  - $<$1 cm spatial resolution
  - $>$ 20% QE
  - High gain and low dark noise rate
- Opportunities to work on new detector technology

ANNIE vertex resolution improvement with LAPPDs

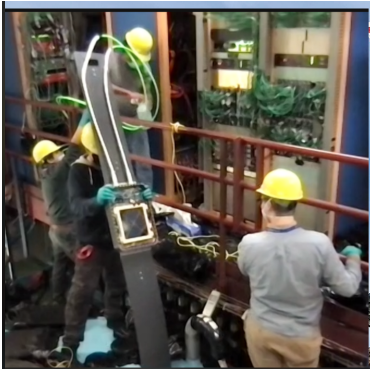
- Large improvement in the in the vertex resolution of reconstructed event.





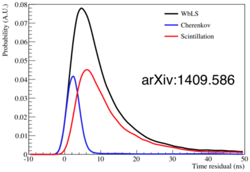
- 128 PMT-only : 38 cm
- 5LAPPDs+128PMTs: 12cm(more than a factor of 3!)

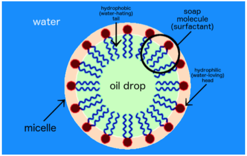
LAPPD Deployment



- LAPPD system has been fully tested and validated (tremendous amount of work during the pandemic)
- Successfully deployed the first LAPPD in the ANNIE tank.
- **Exciting results are coming soon!!! stay tuned.**

Phase III Water based Liquid Scintillator





micelle structure

- Combination of pure water and hydrocarbon liquid scintillator
- Directionality & kinematic reconstruction (Cherenkov)
- High light yield & calorimetric reconstruction (scintillation)
- Combines the advantages of water (low light attenuation, low cost) and liquid scintillator (high light yield)
- ANNIE demonstrated use of WbLs for the first time in neutrino beam - arXiv:2312.09335

Conclusions

- ANNIE will assess neutron multiplicity, offering data to validate models describing final states with multiple nucleons.
- Phase I measurement proves the off beam background is low $\sim$ good enough for physics measurement
- Data collection is currently in progress, made an initial measurement of neutron multiplicity
- ANNIE is the first neutrino detector that uses LAPPDs to detect accelerator neutrinos
- Additionally, we have examined the capabilities of a water-based liquid scintillator.
- More data is coming! stay tuned.

Thank you

Backup Slides

Reconstruction

Step1: "Simple vertex" fit

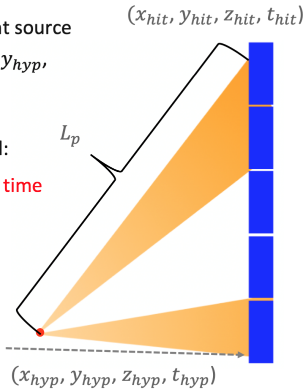
four parameter fit: (x, y, z, t)

- Conceptualize Cherenkov light as coming from a point source
- Assume a hypothesized point-source location $(x_{hyp}, y_{hyp}, z_{hyp}, t_{hyp})$
- For each photon hit, calculate the point time residual:

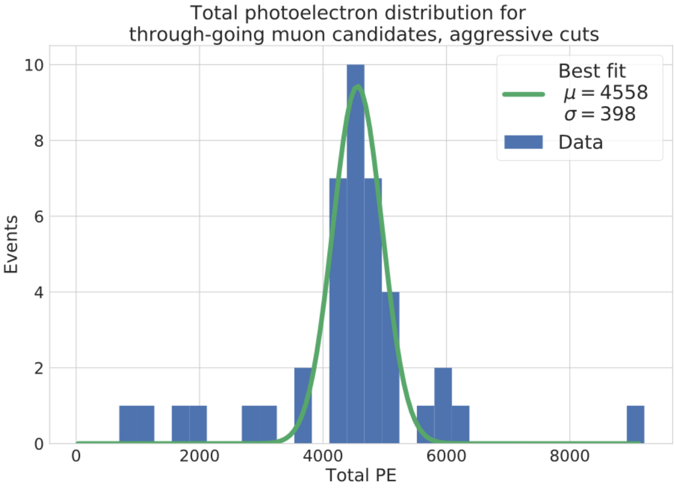
$$\Delta t = t_{hit} - \frac{L_p}{c/n}$$

Photon travel time

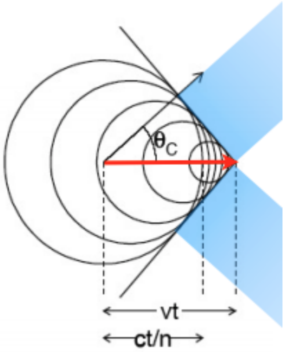
- **For all the hits, calculate the timing-based Figure-of-Merit (timing likelihood)**
- **Adjust four parameters** to maximize time FOM. FOM takes the maximum value when the width of the time residual distribution is minimized

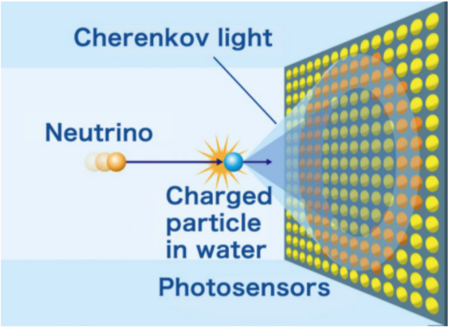


Energy Resolution

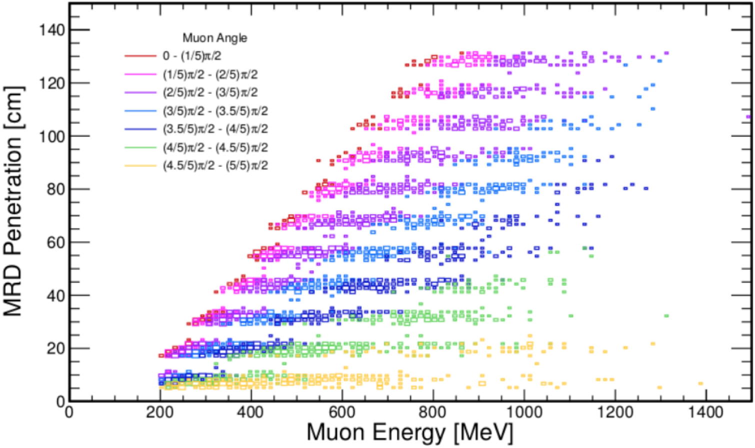


Detection of Cherenkov Photons

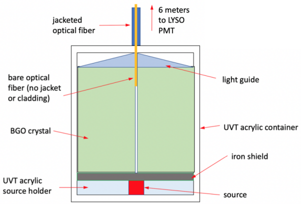


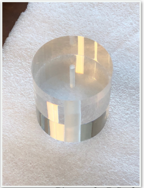


Muons at MRD


Muon Angle
0 - (1/5)π/2
(1/5)π/2 - (2/5)π/2
(2/5)π/2 - (3/5)π/2
(3/5)π/2 - (3.5/5)π/2
(3.5/5)π/2 - (4/5)π/2
(4/5)π/2 - (4.5/5)π/2
(4.5/5)π/2 - (5/5)π/2
MRD Penetration [cm]
0
20
40
60
80
100
120
140
0
200
400
600
800
1000
1200
1400
Muon Energy [MeV]

Detector Calibration





Pictures by R.Svoboda, UC Davis

- PMT single p.e calibration
  - LED fibers with attached diffuser tip
- LAPPD timing calibration
  - 405nm picosecond laser
- Neutron Calibration
  - AmBe source, tag neutron events by using coincidentally emitted gamma
  - 100 us detection window $\sim$ 100 tagged neutrons per second