Measuring Neutrino-Nucleus interaction using ANNIE

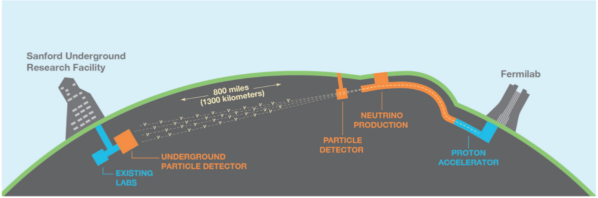
Navaneeth Poonthottathil

IIT Kanpur

Frontiers in Particle Physics 2024, IISc Bengaluru

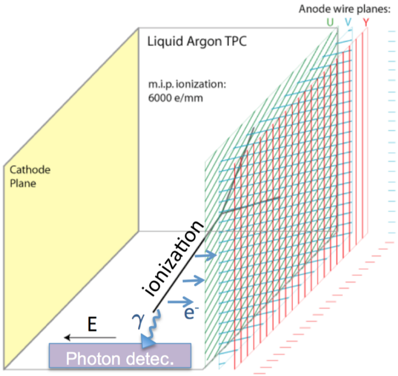
Long Baseline Neutrino Experiment

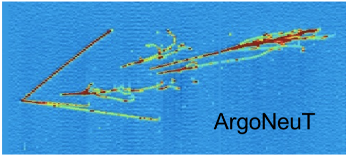
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



- 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.

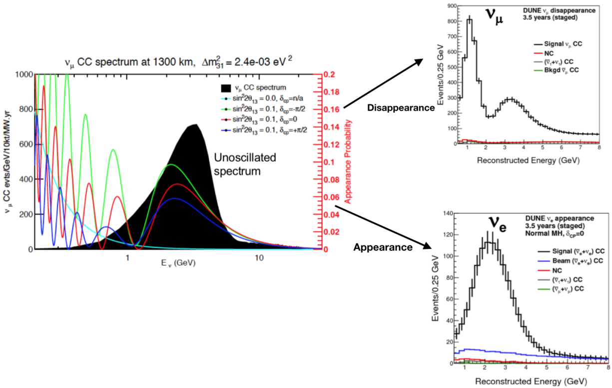
Liquid Argon TPC





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

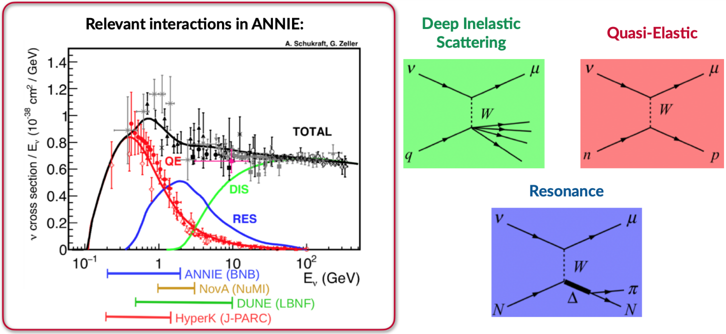
Neutrino Oscillation Measurement



- 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.

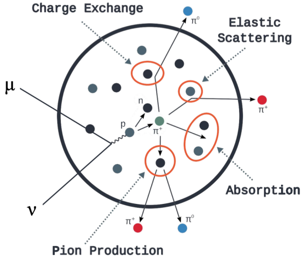
The Accelerator Neutrino Neuclues Interaction Experiment

GeV-scale neutrino interactions



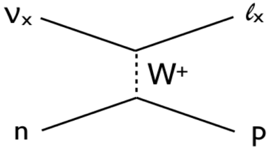
- Across the GeV-energy range, there are multiple possible interaction types (and particles produced).
- Final-state interactions for different events could lead to different neutron multiplicities.
- Additional cross-section measurements can help refine neutrino interaction models.

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

True CCQE interaction

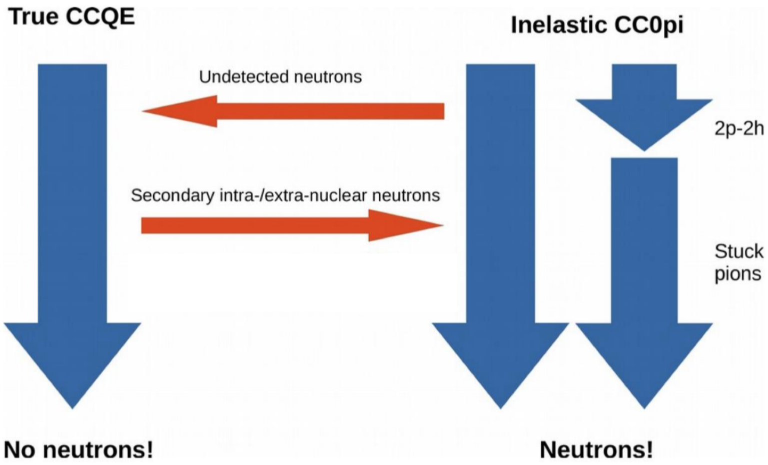


$$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

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

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

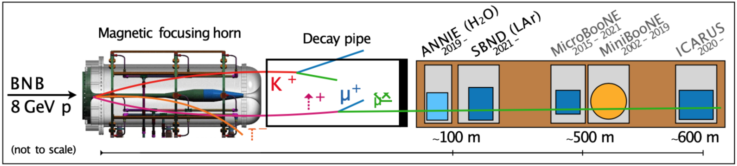
Neutron multiplicity identification (and confusion)

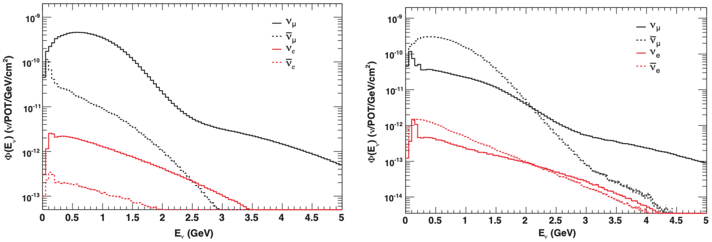


Goals of ANNIE

- 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.
- 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

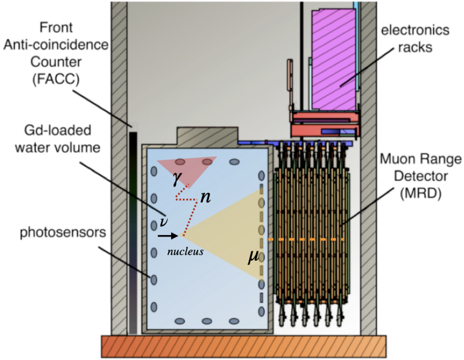
Booster Neutrino Beam

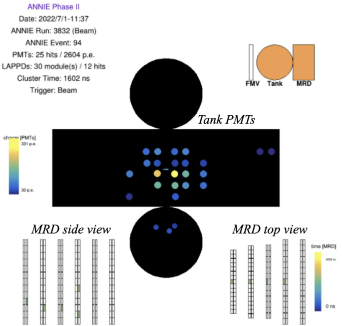




- 8 GeV protons8 GeV protons on Beryllium target
- Mean neutrino energy of 700 MeV.
- Composition: 93 % of ν_μ, 6.4 % $\bar{\nu}_\mu$ and 0.6 % of ν_e and $\bar{\nu}_e$

ANNIE Detector in Phase II



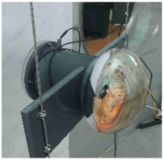
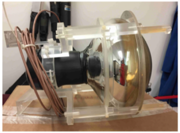
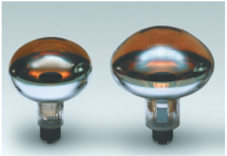


- In Phase I background neutron is measured especially skyshine component
- Background rate less than $0.02/m^3/spill$ - *A.R. Back et al 2020 JINST 15 P03011*

ANNIE Detector during Installation

- Equipped with 132 photomultipliers.

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

ANNIE Event Rates

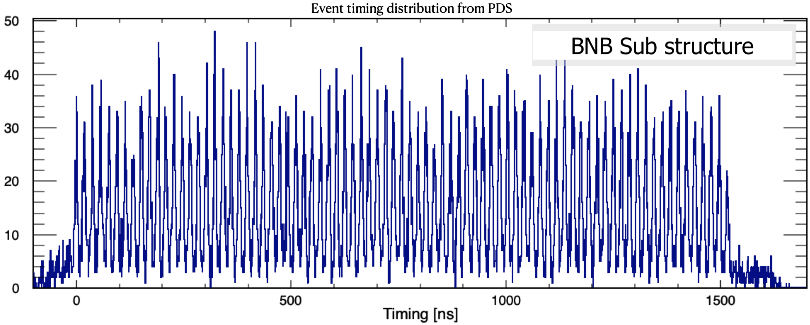
- BNB delivers 4×10^{12} POT per $1.6\mu s$ at 5Hz.
- Mean Energy 700 MeV
- Average 1CC ν_μ interaction in every 150 spill - no pileup

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

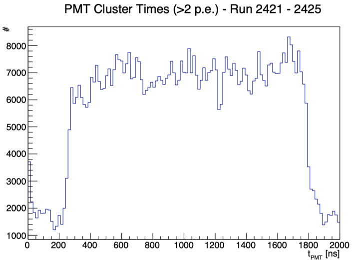
Table: Event counts in 2.5-ton fiducial volume over 2×10^{20} POTs $\sim$1year

BNB Beam structure

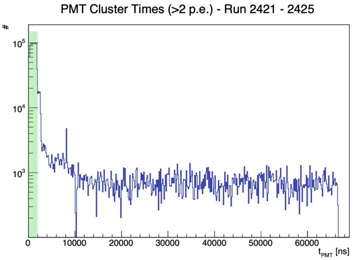
- 1.6 us wide, 53.1Hz, 2ns width, 82 Bunchs



Do we see Neutrinos - Phase II



Prompt window

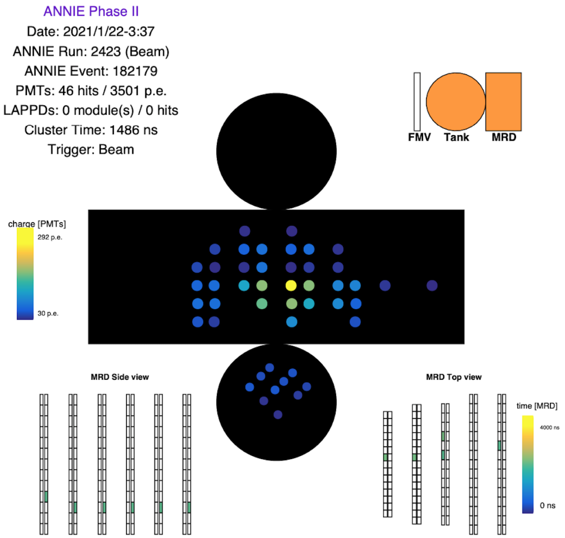


Extended window

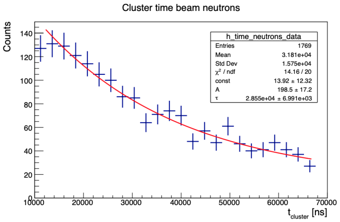
1.6us beam spill window visible

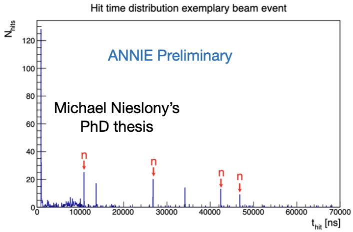
Less statistics for extended readouts

Neutrino candidate



Neutron Capture

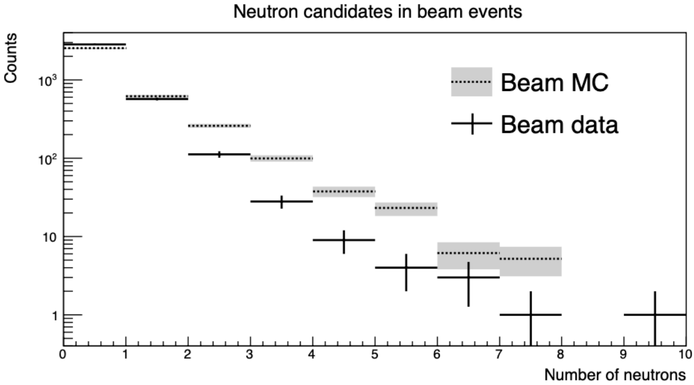




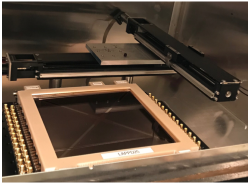
- Gadolinium's average neutron capture cross-section is high compared with pure water. Cross-section: - Gd: 49000 barns. - H: 0.3 barns.
- Neutrons after thermalization, capture time: - Gd: 30 μs. - H: 200 μs.
- Signature: - Gd: 8 MeV cascade. - H: 2.2 MeV .

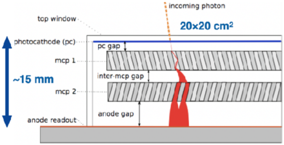
Neutron Multiplicity - Very Preliminary

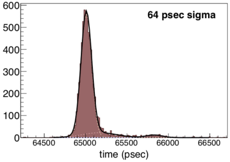
- Neutron multiplicity distribution in data for beam neutrino.
- These are events featuring a stopping muon track in the MRD.



ANNIE Detector R&D: LAPPDs Developments



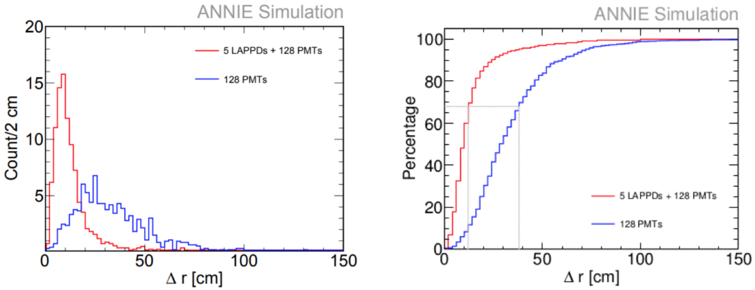




- LAPPDs are 8" × 8" MCP-based imaging photodetectors, with target specifications of:
  - $\sim$ 50 picosecond single-PE time resolution
  - $<$1 cm spatial resolution
  - $>$ 20% QE
  - High gain and low dark noise rate
- Opportunities to work on new detector technology

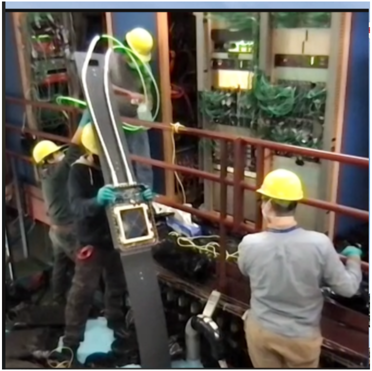
ANNIE vertex resolution improvement with LAPPDs

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



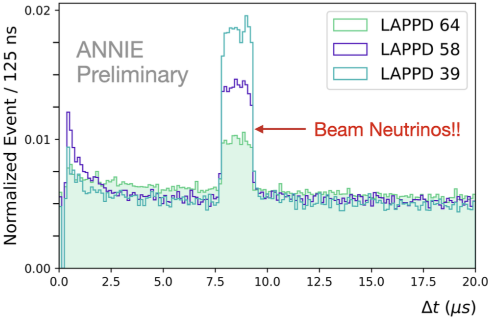
- 128 PMT-only : 38 cm
- 5LAPPDs+128PMTs: 12cm(more than a factor of 3!)

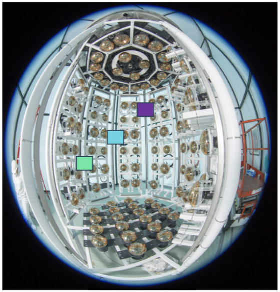
LAPPD Deployment



- LAPPD system has been fully tested and validated .
- Successfully deployed LAPPDs in the ANNIE tank.

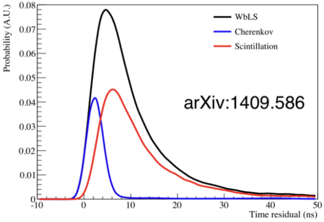
First Neutrinos in LAPPD

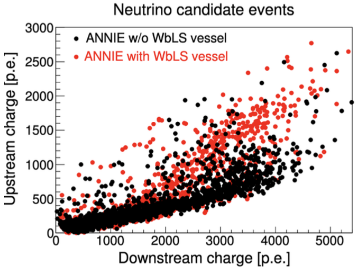




- World's first: neutrinos observed with an LAPPD

Phase III Water based Liquid Scintillator





- 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

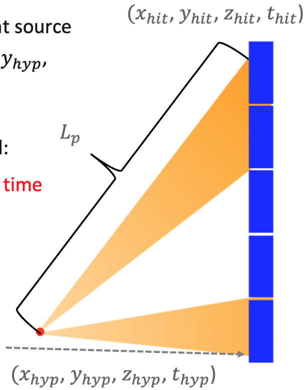
four parameter fit: (x, y, z, t)

- 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:

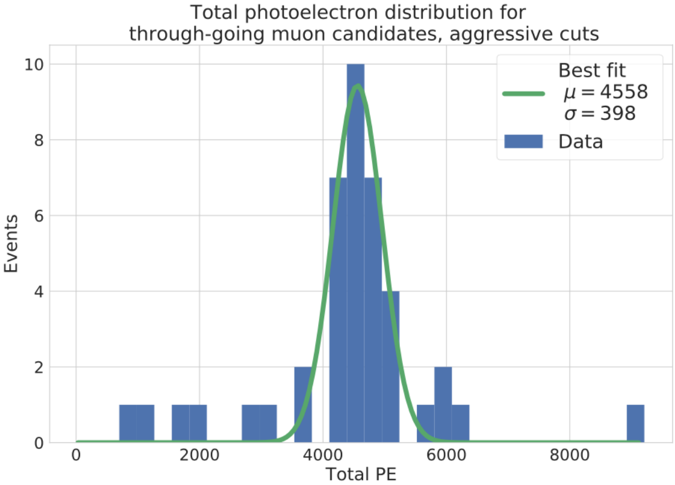
$$\Delta t = t_{hit} - \frac{L_p}{c/n}$$

Photon travel time

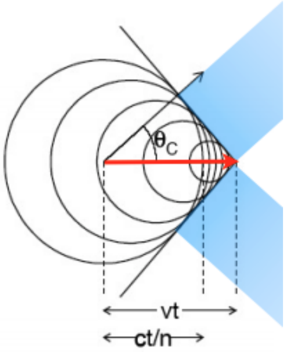
- **For all the hits, calculate the timing-based Figure-of-Merit (timing likelihood)**
- **Adjust four parameters** to maximize time FOM. FOM takes the maximum value when the width of the time residual distribution is minimized

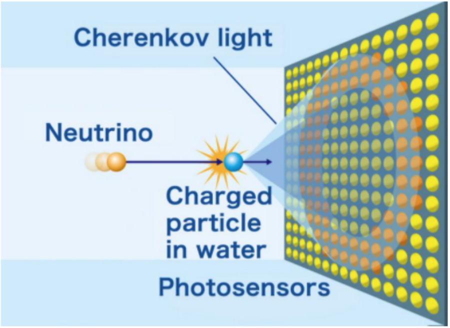


Energy Resolution

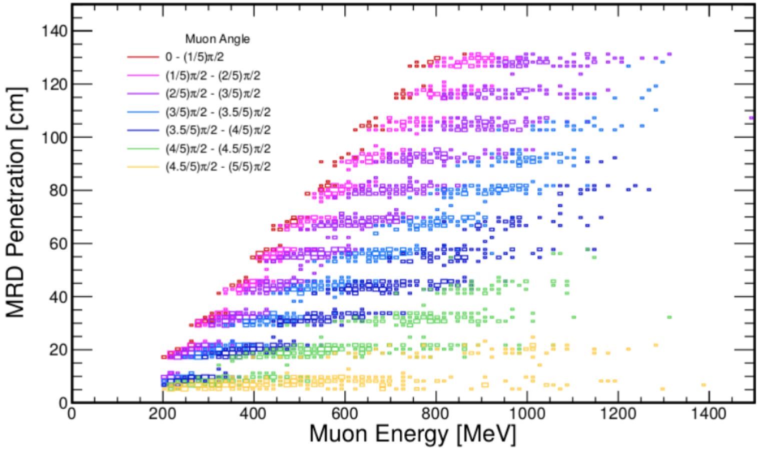


Detection of Cherenkov Photons

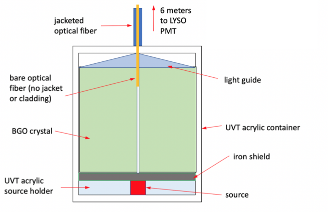


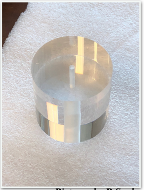


Muons at MRD


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]
Muon Energy [MeV]
0
20
40
60
80
100
120
140
200
400
600
800
1000
1200
1400

Detector Calibration

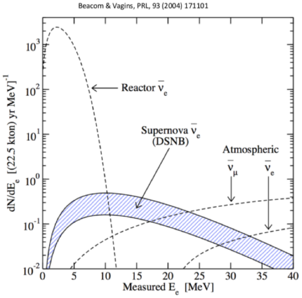




Pictures by R.Svoboda, UC Davis

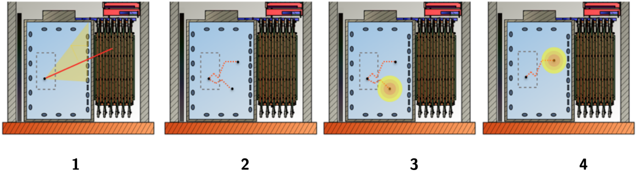
- PMT single p.e calibration
  - LED fibers with attached diffuser tip
- LAPPD timing calibration
  - 405nm picosecond laser
- Neutron Calibration
  - AmBe source, tag neutron events by using coincidentally emitted gamma
  - 100 us detection window $\sim$ 100 tagged neutrons per second

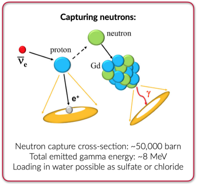
Rare Physics searches



- 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

How ANNIE Works





- 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 .

Phase I

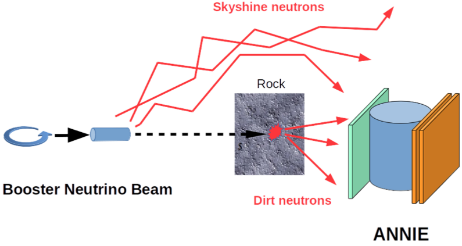
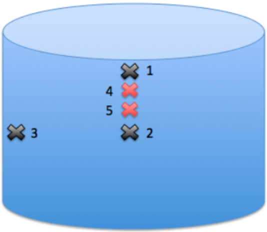
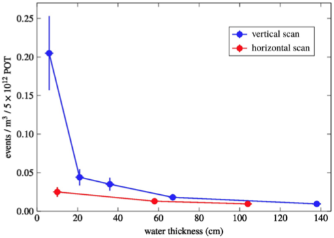


Image: Vincent Fischer

- 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*