The Accelerator Neutrino-Nucleus Interaction Experiment (ANNIE)

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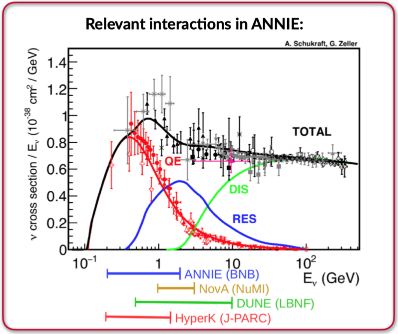
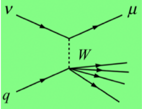
Outline of the Talk

- The ANNIE Experiment
  - Physics Motivation
  - Detector Technology
  - ANNIE Phase I Background measurement
  - ANNIE Phase II
  - Detector R&D and LAPPDs
  - ANNIE as potential path forward for Future Neutrino experiments

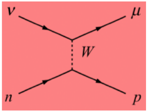
GeV-scale neutrino interactions



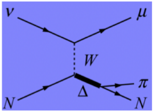
Deep Inelastic Scattering



Quasi-Elastic

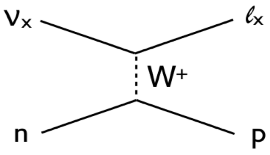


Resonance



- 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

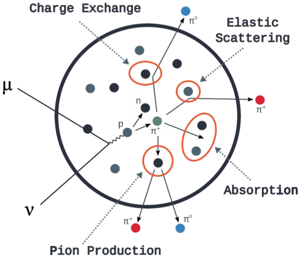


$$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

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

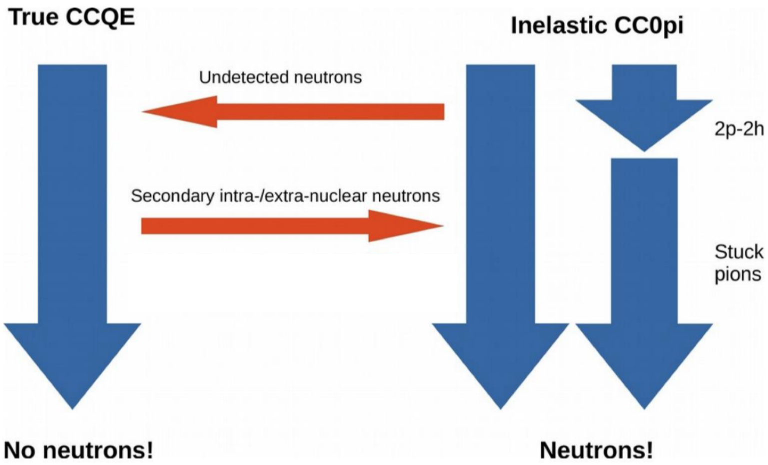
- Two body scattering with an outgoing lepton.
- Target nucleon assumed at rest.
- Calculate kinematics from the outgoing leptons

Role of Understanding the Interaction

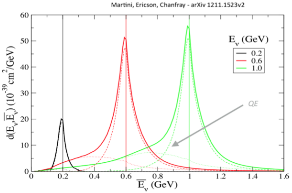


- Knowledge of neutrino-nucleus scattering cross sections is crucial to the global neutrino physics program.
- We still have a long way to understand the nuclear effects that define what we see in our detectors..
- **Final State Interactions (FSI)** and other **nuclear effects** make different interaction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

Neutron multiplicity identification (and confusion)

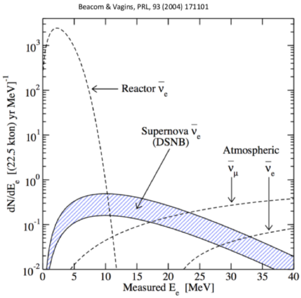


Physics Impacts



- Bias in reconstructed neutrino Energy.
  - This will affects the precise measurement of oscillation parameters
- Background measurements.
  - Neutron tagging is important to reduce background interaction rare event searches
- Accounting for these requires the knowledge of multiplicity and kinematic relations.

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 $\sim$ more likely to produce neutrons

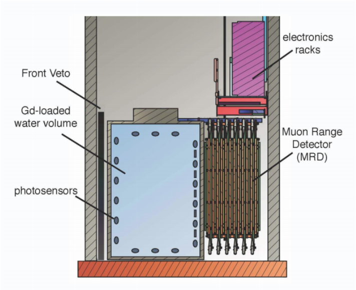
The Accelerator Neutrino Neutron Interaction Experiment

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

Goals of ANNIE

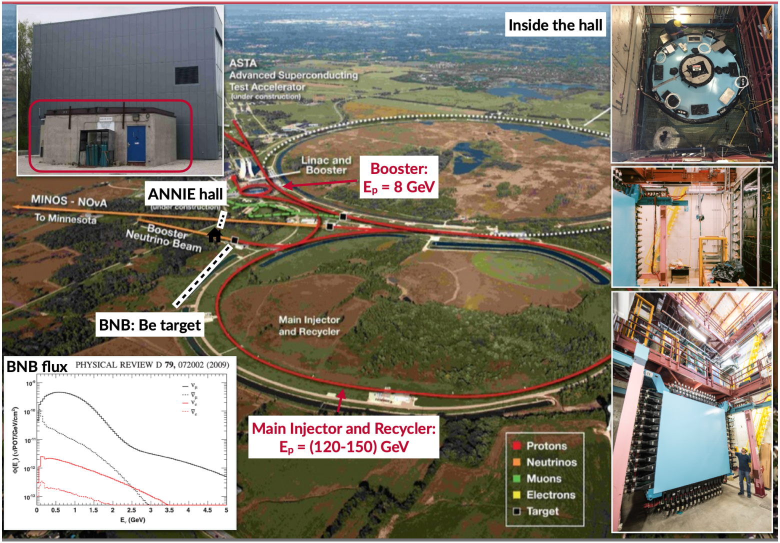
- Primary physics goal is to measure neutrino induced neutron yields in water as a function of outgoing lepton kinematics.
- Demonstrate new technologies that will be helpful for physics analysis.
- Perform a measurement of the CC inclusive cross section as a function of momentum transfer
- ANNIE's in 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

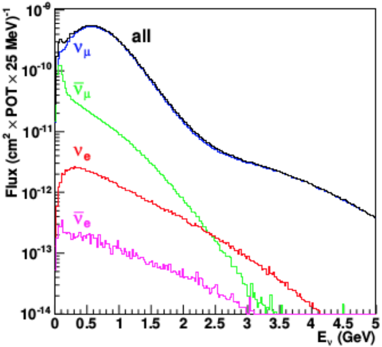


- Gd-loaded water based detector placed downstream of the Booster Neutrino Beam at Fermilab.
- 4m height and 3m radius - small detector
- Aims at measuring the production rate of neutrons from neutrino interactions in water.
- Close proximity to beam target, hight flux of neutrino, 10000 CC/ton/year

Fermilab Accelerator Complex



Beam Composition



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

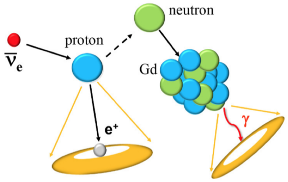
Neutron Multiplicity

- ANNIE will use Gadolinium to capture the neutrons
- 8MeV gamma, 4-5MeV visible energy
- 20us capture time $\sim$ minimize the background

Features of ANNIE's measurement:

- Close proximity to beam target
  → high flux of neutrinos
  (~10,000 CC-interactions / ton /year)
- Nearby SBND Liquid Argon detector
  → opportunity for combined
  argon/water cross-section analysis

Capturing neutrons:



Neutron capture cross-section: ~50,000 barn
Total emitted gamma energy: ~8 MeV
Loading in water possible as sulfate or chloride

Phase I

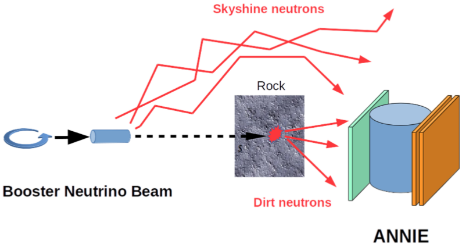
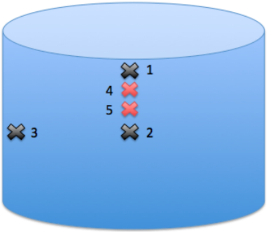
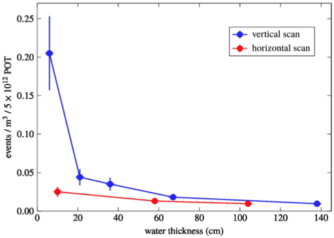


Image: Vincent Fischer

- Measurement of the neutron background rate is very important
- Source of neutron background:
  - **Skyshine neutrons** → Neutrons from the beam dump entering the detector
  - **Dirt neutrons** →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*

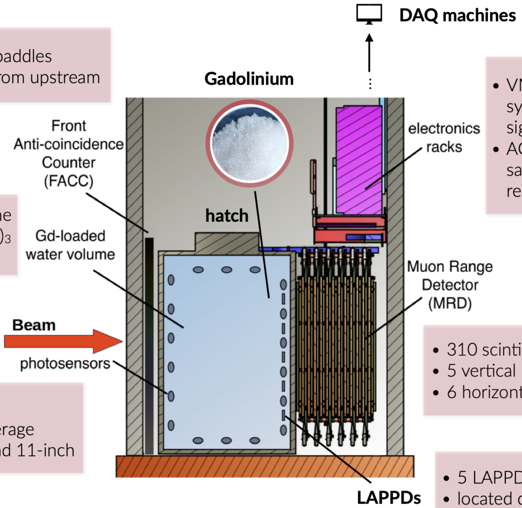
Phase II

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)

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



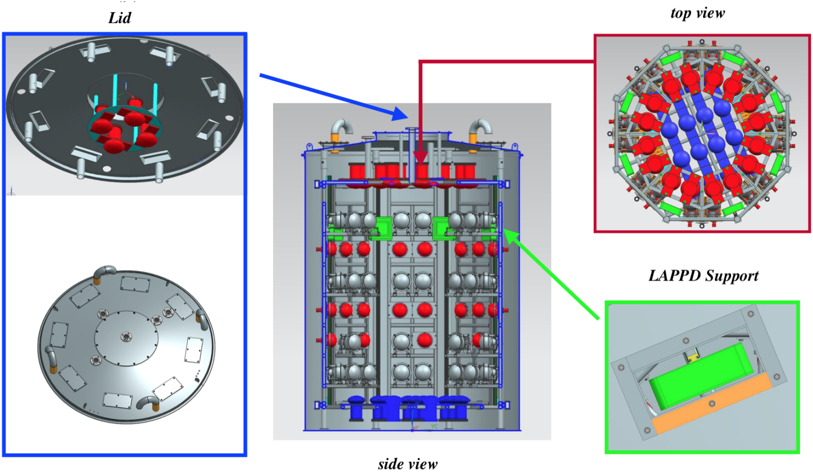
- VME acquisition system for PMT signals (500MHz)
- ACDC cards sampling LAPPD response (10 GHz)

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

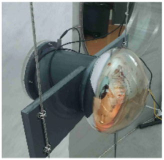
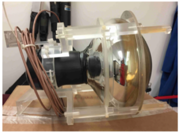
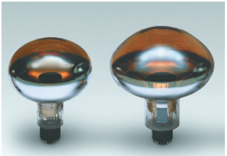
- 5 LAPPDs
- located downstream

Picture from M.Nieslony

Tank Design

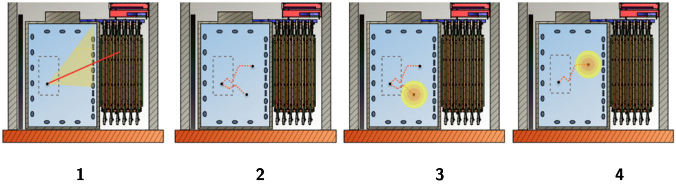


PMT types

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 - 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 .

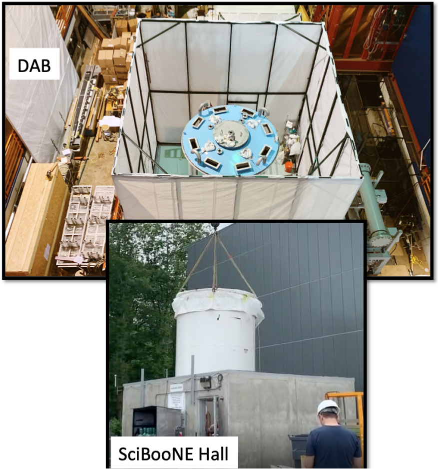
ANNIE Event Rates

- 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 ~1year

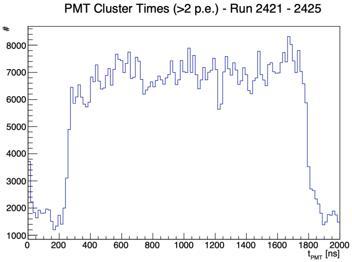
ANNIE Detector during Installation



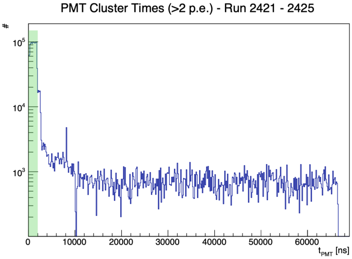
ANNIE Detector during Installation

- Equipped with 132 photomultipliers.

Do we see Neutrinos - Phase II



Prompt window

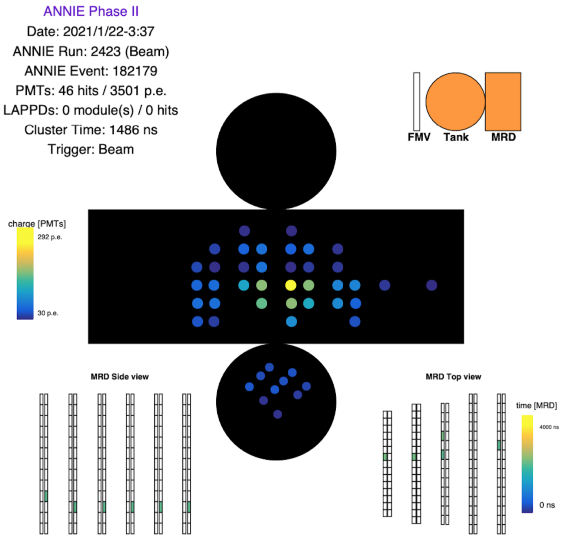


Extended window

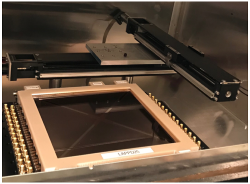
1.6us beam spill window visible

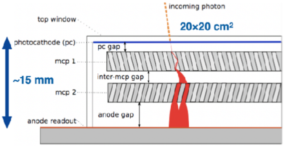
Less statistics for extended readouts

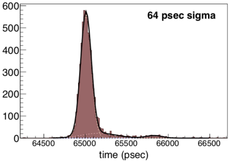
Neutrino candidate



ANNIE Detector R&D: LAPPDs Developments at Iowa State University



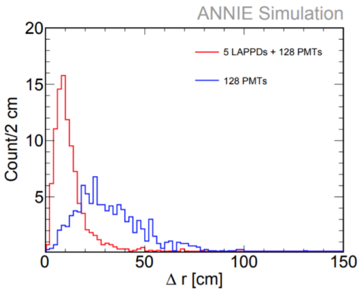


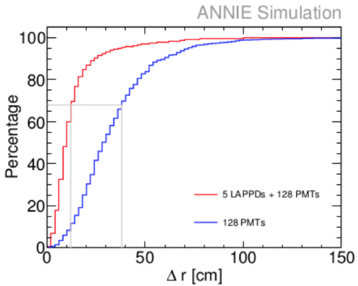


- LAPPDs are 8" $\times$ 8" MCP-based imaging photodetectors, with target specifications of:
  - $\sim$ 50 picosecond single-PE time resolution
  - $<$1 cm spatial resolution
  - $>$ 20% QE
  - High gain and low dark noise rate
- Opportunities to work on new detector technology

ANNIE vertex resolution improvement with LAPPDs

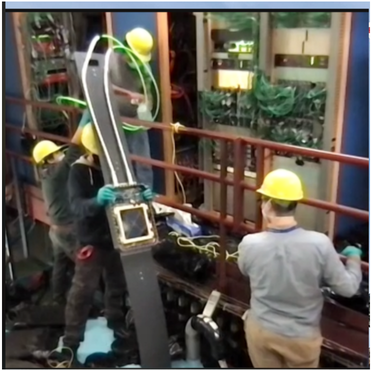
- Large improvement in the in the vertex resolution of reconstructed event.





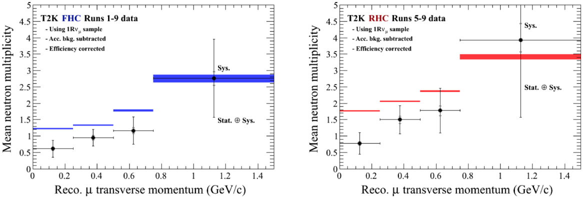
- 128 PMT-only (20% coverage) : 38 cm
- 5LAPPDs+128PMTs: 12cm(more than a factor of 3!)

LAPPD Deployment



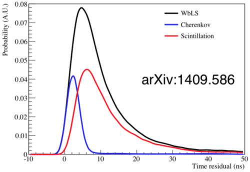
- LAPPD system has been fully tested and validated (tremendous amount of work during the pandemic)
- Successfully deployed the first LAPPD in the ANNIE tank.
- **Exciting results are coming soon!!! stay tuned.**

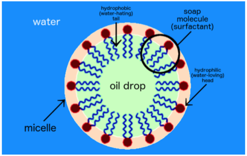
Previous Neutron Multiplicity Measurement



- T2K has measured the mean neutron multiplicity as a function of reconstructed muon transverse momentum
- ANNIE will be able to do a more precise measurements

Phase III Water based Liquid Scintillator





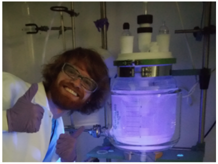
micelle structure

- 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)

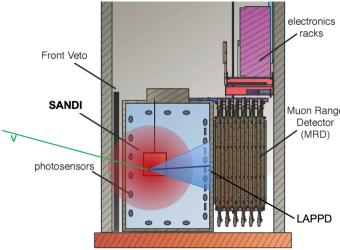
Testing Water based Liquid Scintillator

- Transparent WbLS permits hybrid detection of scintillation and (unabsorbed) Cherenkov signals
- Enhanced neutrino energy reconstruction: WbLS adds scintillation signal for sub-Cherenkov recoil protons etc.
- Enhanced neutron signals: improved light output (3×), detection efficiency (~90%) and spatial reconstruction (40→20 cm)
- Built acrylic vessel (~3'×3') with 365 kg of Gd-WbLS to be inserted in the ANNIE water tank
- Gd-loaded WbLS (0.5% organic fraction) to be produced at BNL (M. Yeh)
- Potential two-week test run in summer 2022.

WbLS test at Davis



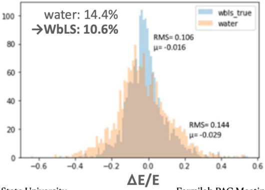
SANDI vessel at Davis



WbLS adds scintillation from hadronic recoil to the muon Cherenkov signal

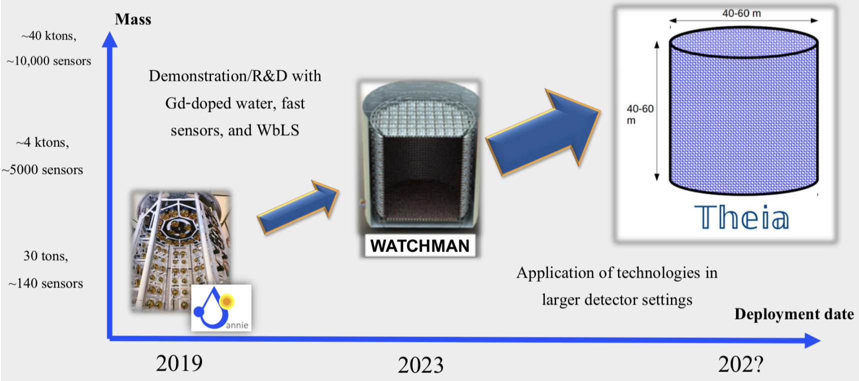
improvement expected for **NEUTRINO energy resolution**

NEW!



Beyond ANNIE Phase II

- Long-term physics activities with water based neutrino detectors.
- Ideal opportunity for a long-term collaboration in addition to DUNE.



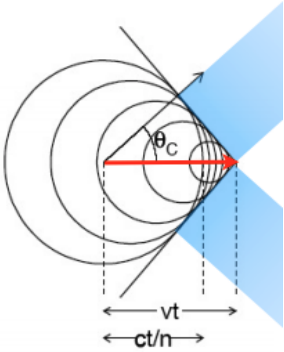
Conclusions

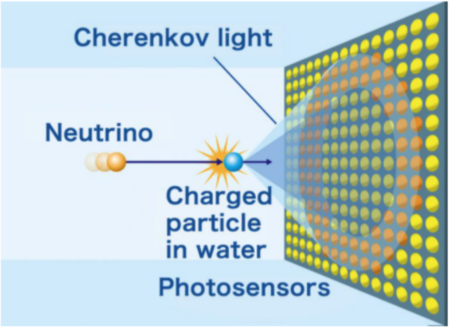
- ANNIE will measure neutron multiplicity, which will provide input to test models that descibes multi-nucleon final states
- Phase I measurement proves the off beam background is low $\sim$ good enough for physics measurement
- Phase II physics data taking is going on
- ANNIE is the first neutrino detector that uses LAPPDs to detect accelerator neutrinos.
- Data analysis is on going, exciting results will be coming soon .

Thank you

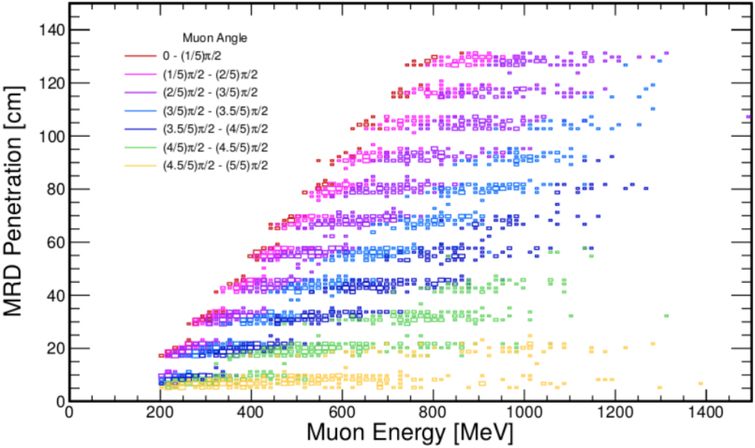
Backup Slides

Detection of Cherenkov Photons



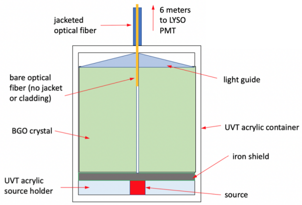


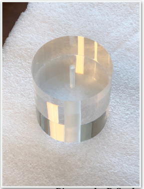
Muons at MRD



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
0
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