The ANNIE Experiment: First Neutrinos on LAPPDs

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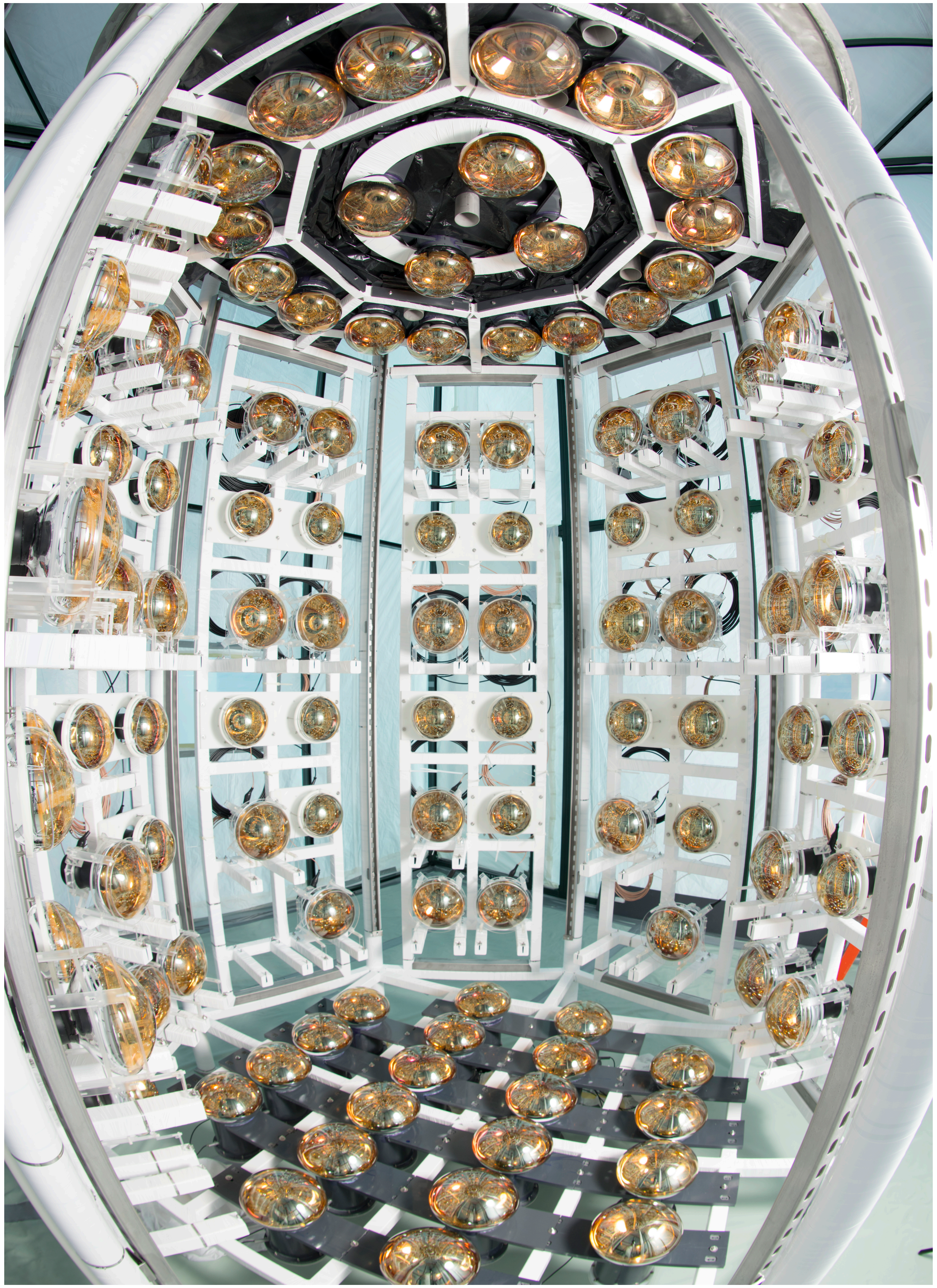


55th Annual Fermilab Users' Meeting - June 16, 2022

The Accelerator Neutrino Neutron Interaction Experiment (ANNIE)

- ANNIE is a neutrino experiment deployed on the Fermilab Booster Neutrino Beam.
  - Study neutrino-nucleus interactions, specifically the neutron yield.
- It is also an R&D platform for new neutrino detection technologies/ techniques:
  - Specifically fast photosensors (LAPPDs) and new detection media (Gd-loaded water and water-based liquid scintillator).

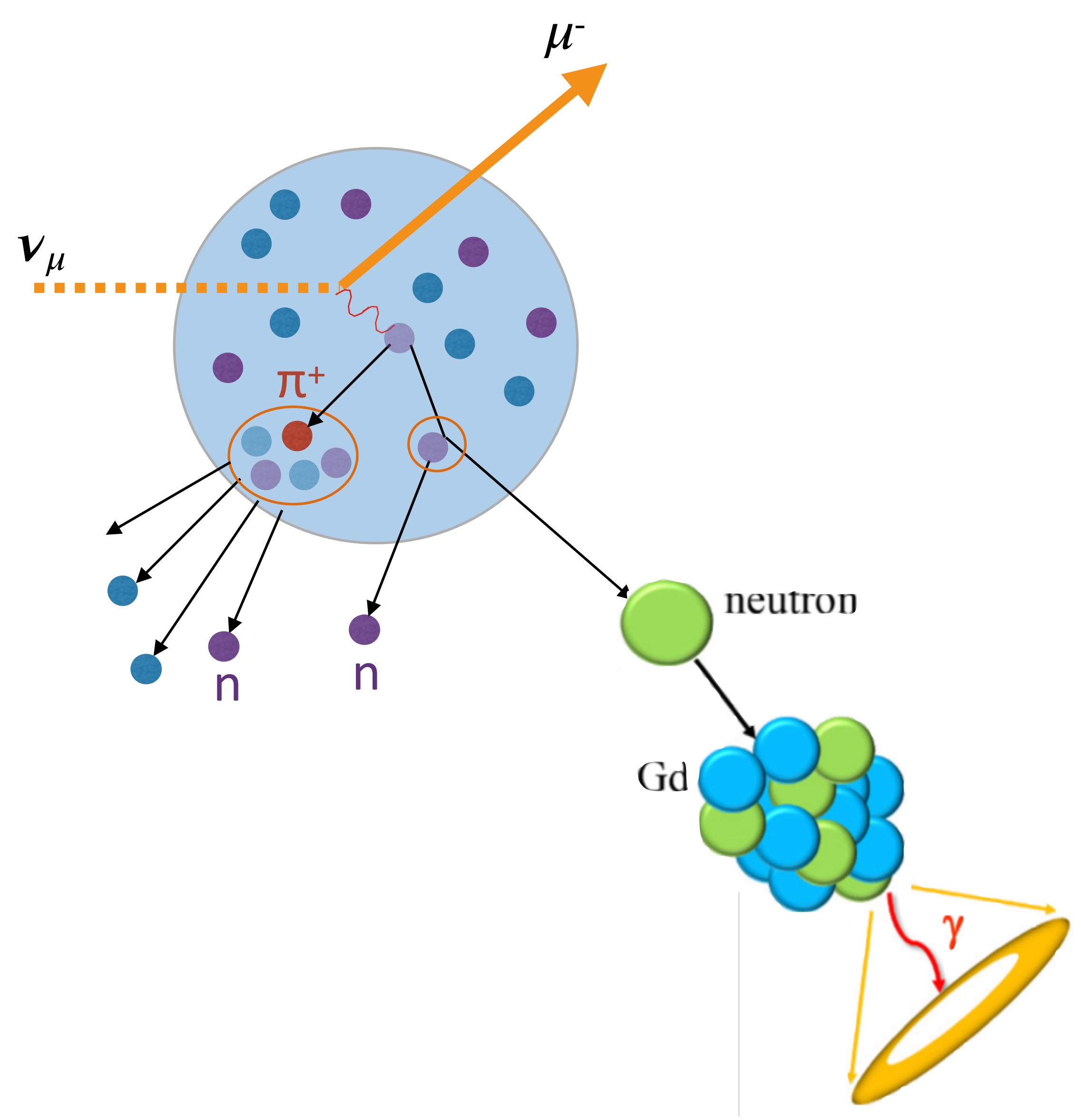
The ANNIE detector is commissioned and taking beam neutrino data!
The first LAPPD has already been deployed !

The ANNIE Collaboration

- ANNIE is an international collaboration of 45 collaborators from 16 (8 non-US) institutions from 5 countries.

ANNIE Physics

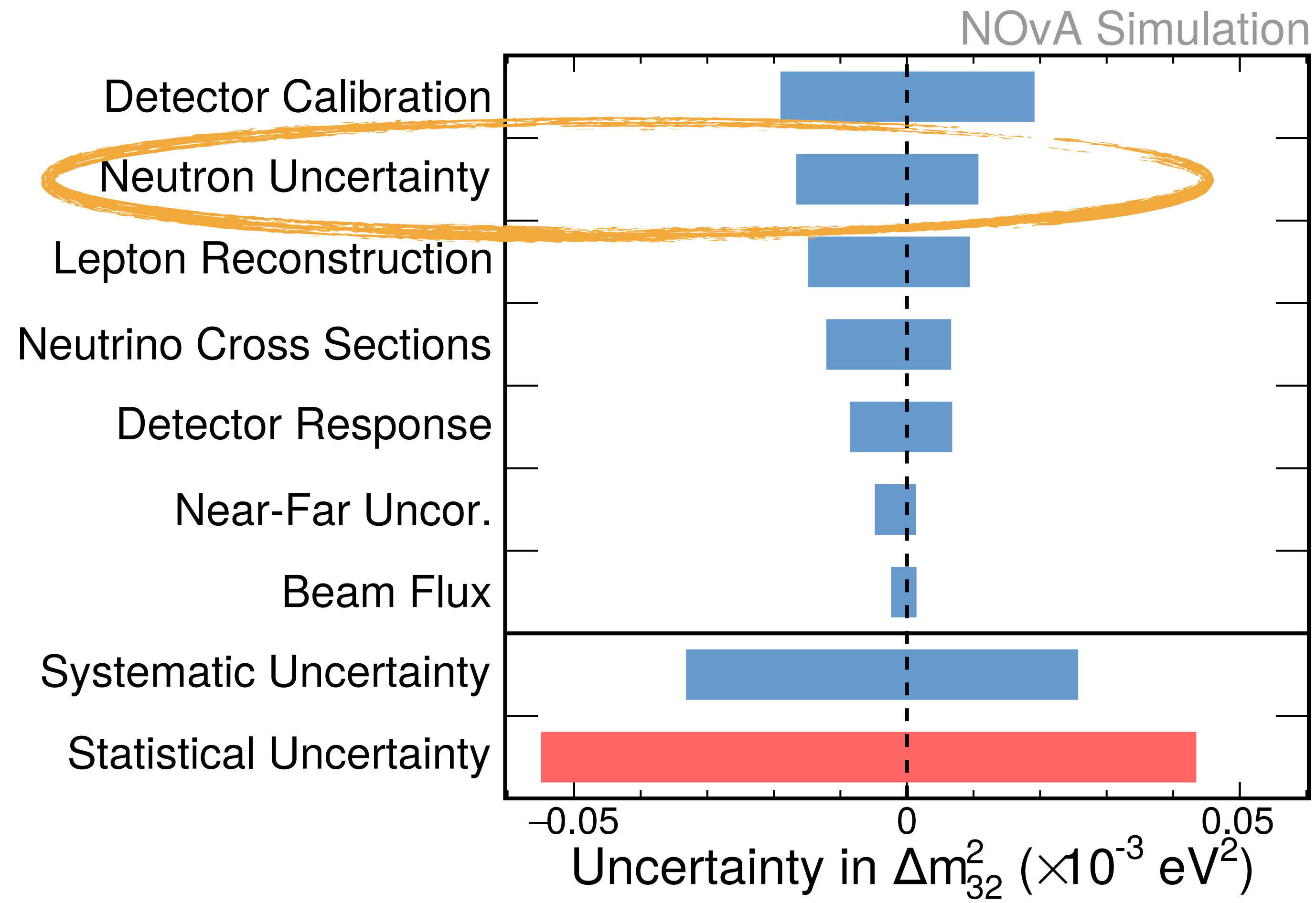
- Neutrons are a major component of the nuclear recoil system and a source of missing energy in neutrino reconstruction/detection.
- ANNIE measures the multiplicity of final state neutrons as a function of the outgoing lepton momentum and direction.
- Neutron detection efficiency (and time to capture) is enhanced by addition of gadolinium to the water.



Gd enhances neutron capture efficiency from 10 to 70%.
Resulting gamma from 2.2 to 8 MeV.
It shortens capture time by an order of magnitude to ~30 μsec.

ANNIE Physics

- Neutrino experiments, in particular long-baseline experiments, must precisely measure neutrino energies.
    - Energy reconstruction is essential for measurements such as Δm^2 .
    - Final state interactions and other intra-nuclear processes impact neutron yield and therefore energy reconstruction.



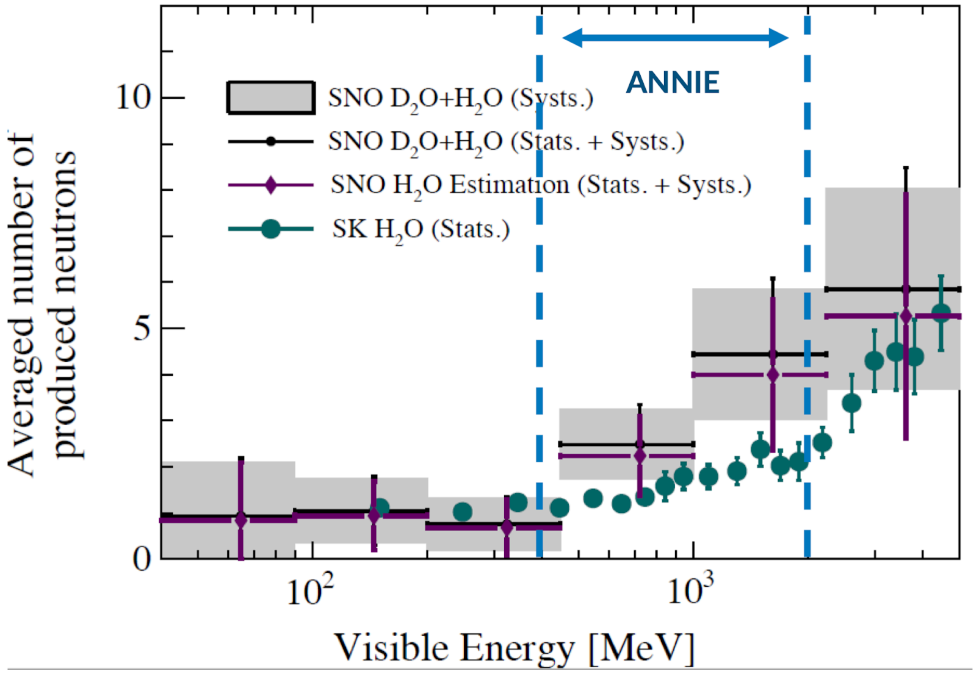
- Nearby SBND LAr-detector provides opportunity for combined water/Ar cross section analysis.
    - Important to understand future long-baseline neutrino oscillation data.

Neutrons are a significant systematic uncertainty in long-baseline experiments.

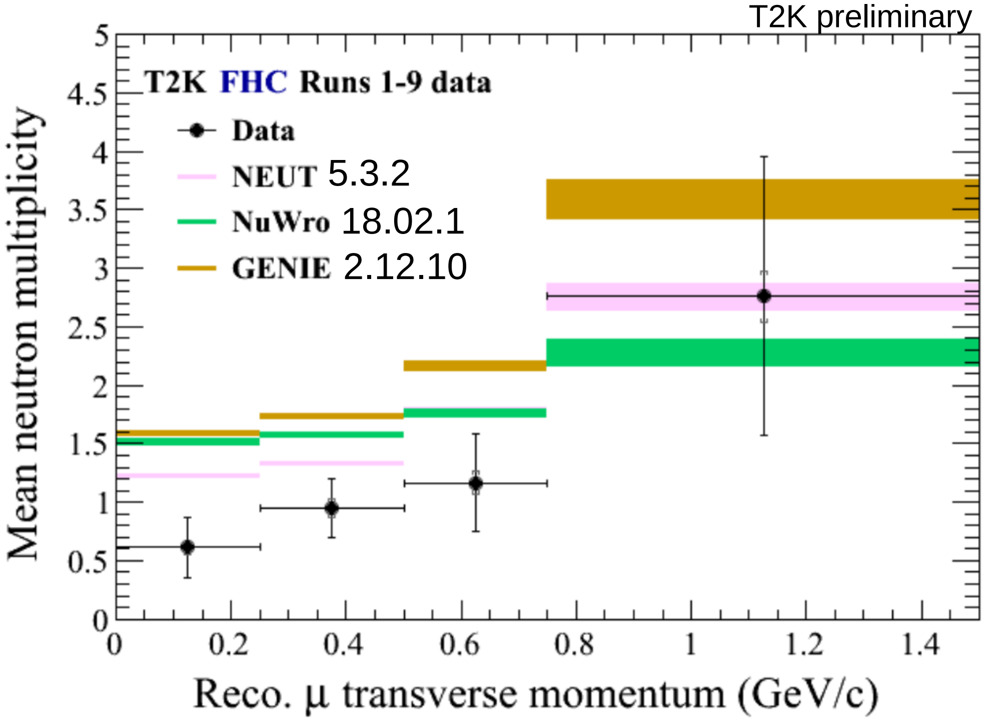
Non-ANNIE Measurements

- SNO and Super-K have measured neutron production from CCQE of atmospheric neutrinos over wide energy range.
- ANNIE lives in a neutrino beam: measure neutron production as function of **momentum transfer,** not visible muon energy.
- T2K has measured neutron multiplicity in similar energy range.
  → **larger statistics and independent measurement in ANNIE.**

neutron production rate as function of **visible energy** in SNO/SK

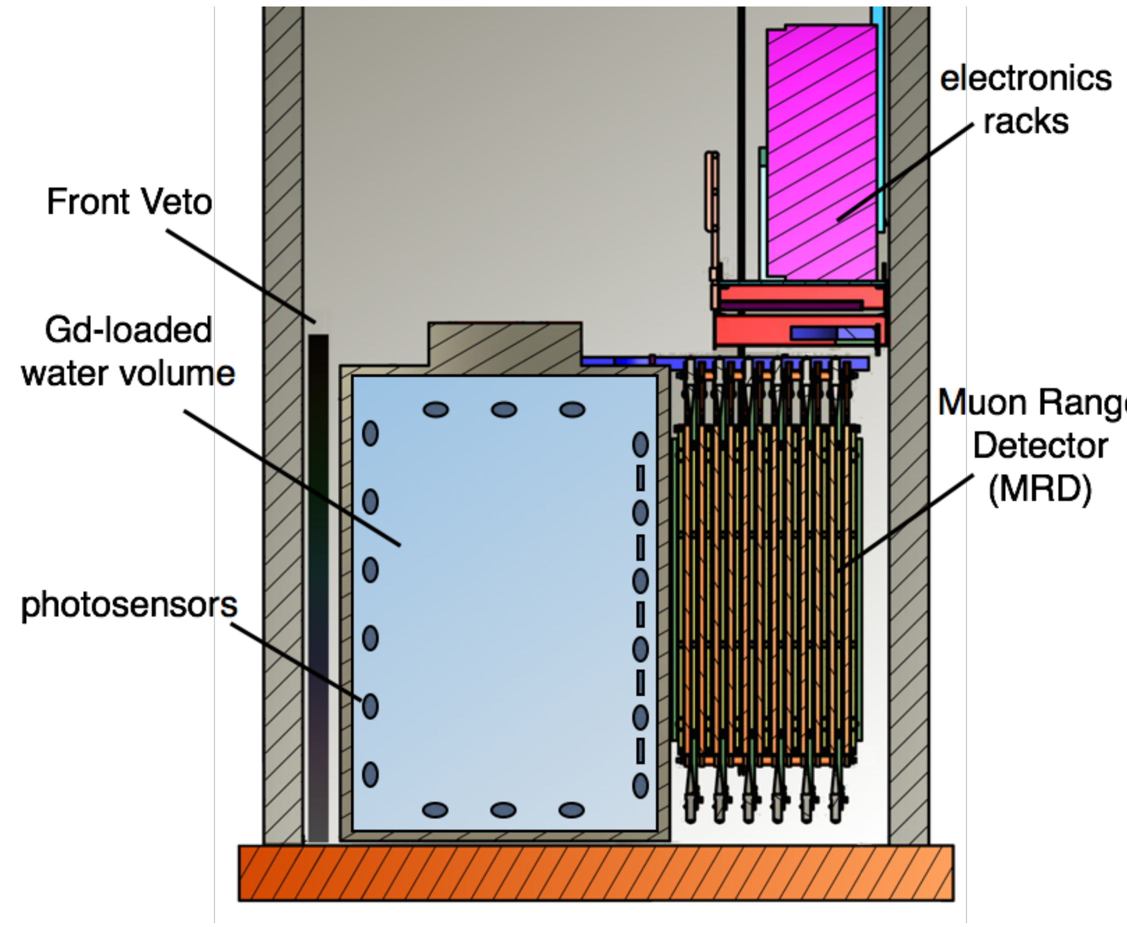


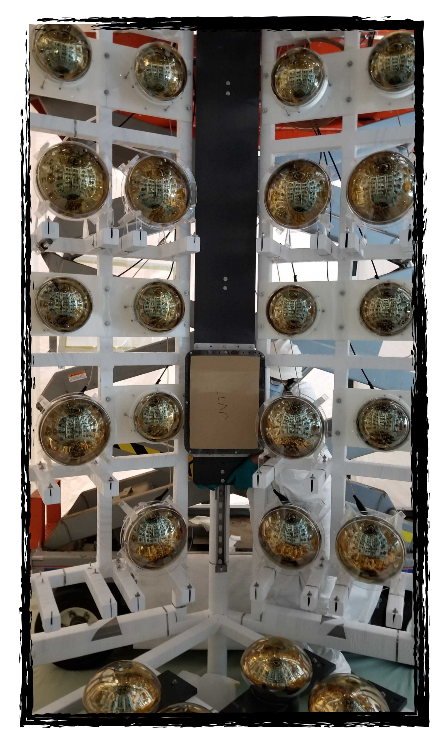
ν-mode



The ANNIE Detector

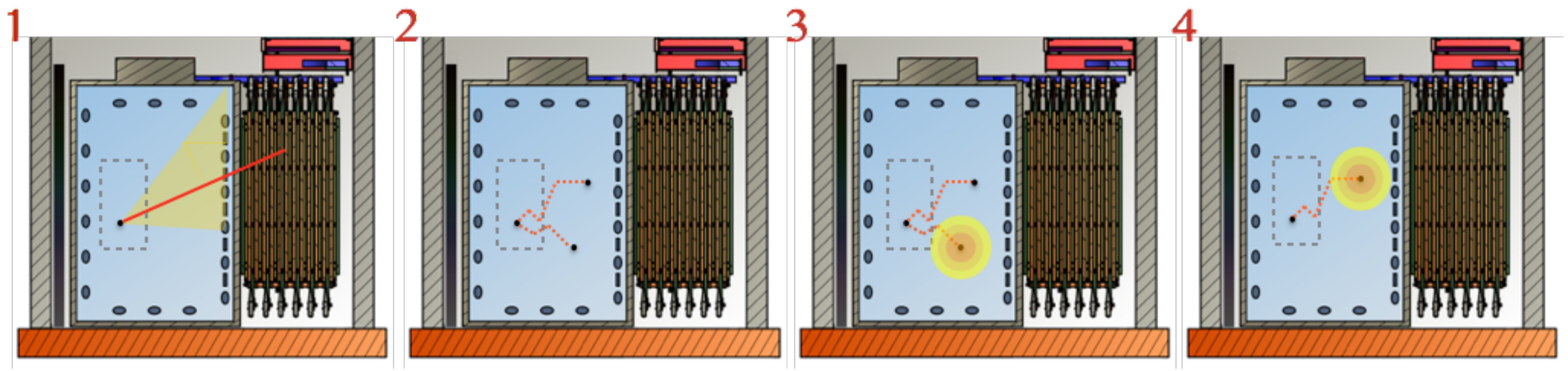
- Steel tank holding 26 tons of **Gd-loaded water**
- **132 PMTs** (8"-11")
- Initially 5+ **LAPPDs** (20 LAPPDs or more possible)
- **Front muon Veto (FV):** 2 overlapping layers of scintillator paddles
- **Muon Range Detector (MRD):** 11 X-Y alternating scintillator layers with 5cm iron absorbers





LAPPDs are inserted on slide rails between PMTs

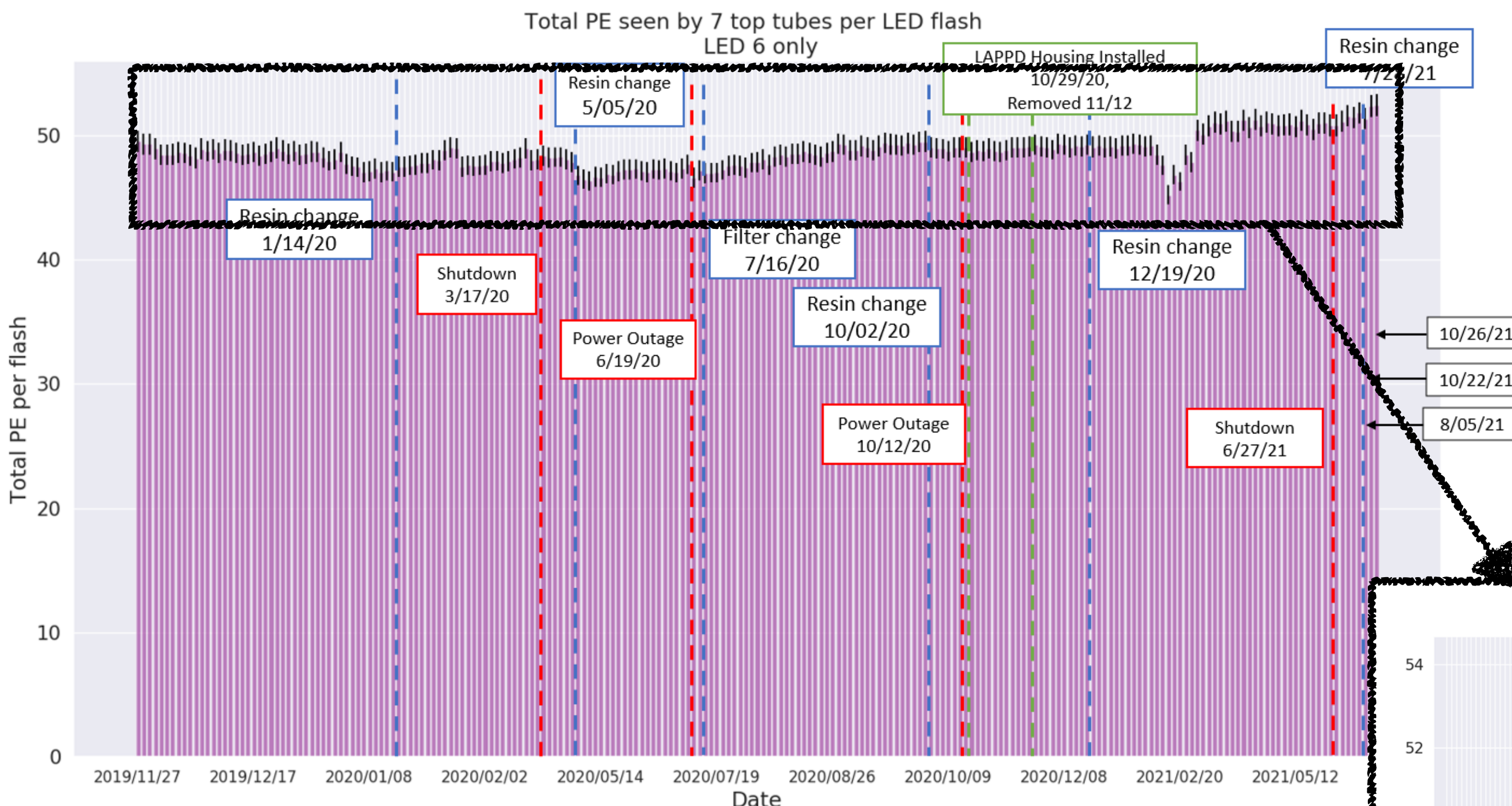
Neutrino Interactions in ANNIE

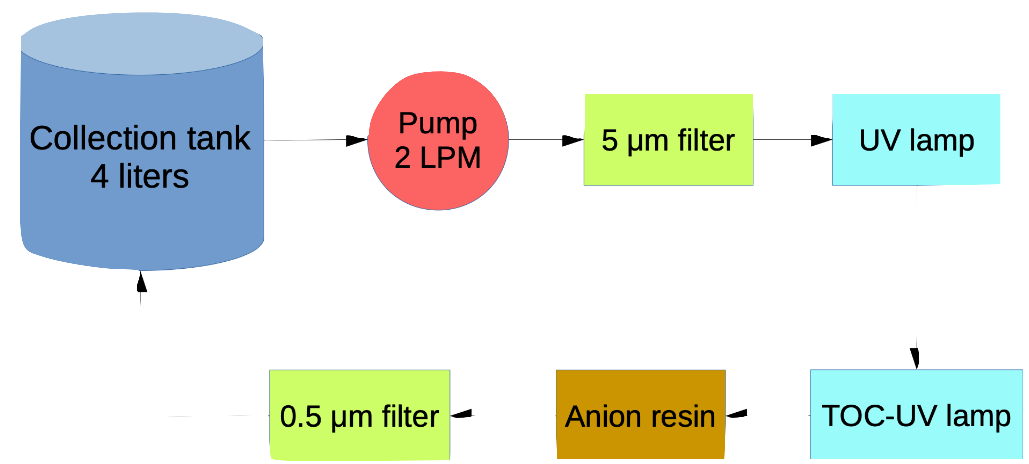


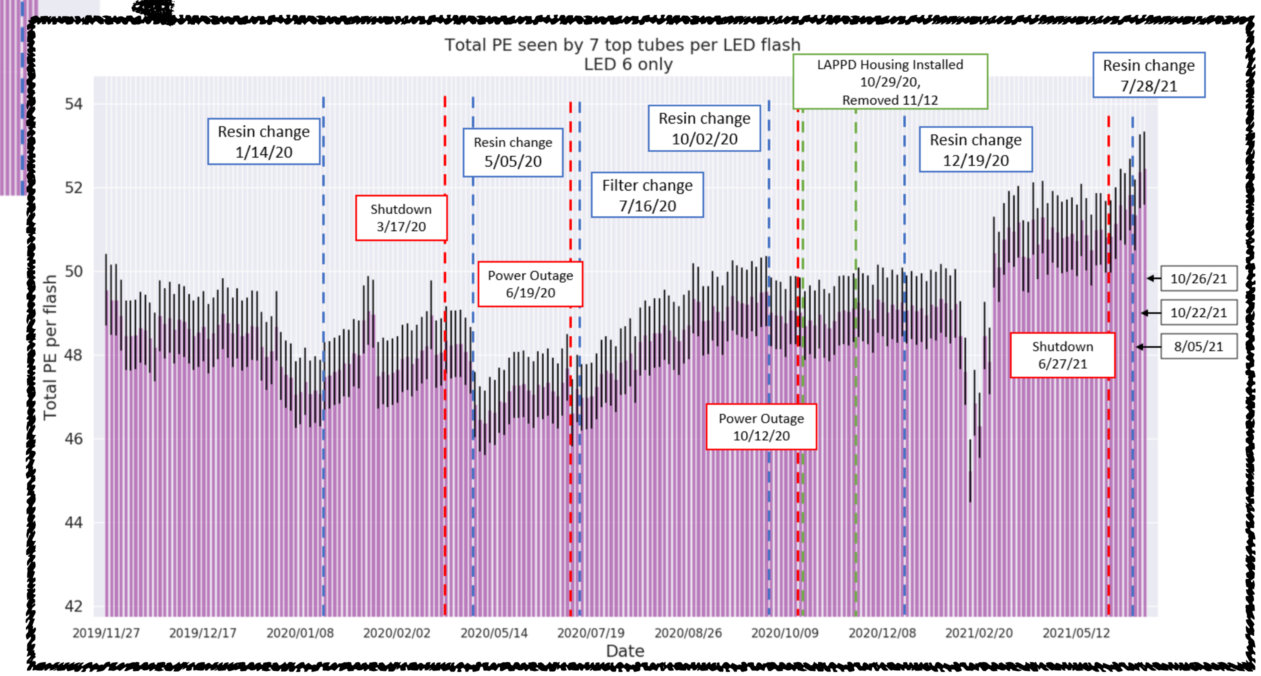
1. Neutrino charged current interaction in the fiducial volume produces a muon.
    - Vertex is reconstructed by using light from LAPPDs and muon momentum reconstructed with MRD.
2. Neutrons travel, scatter and thermalize.

3.- 4. Thermalized neutrons are captured on the Gd producing flashes of light detected by the standard PMTs.

Enabling Technology: Gd-loaded Water



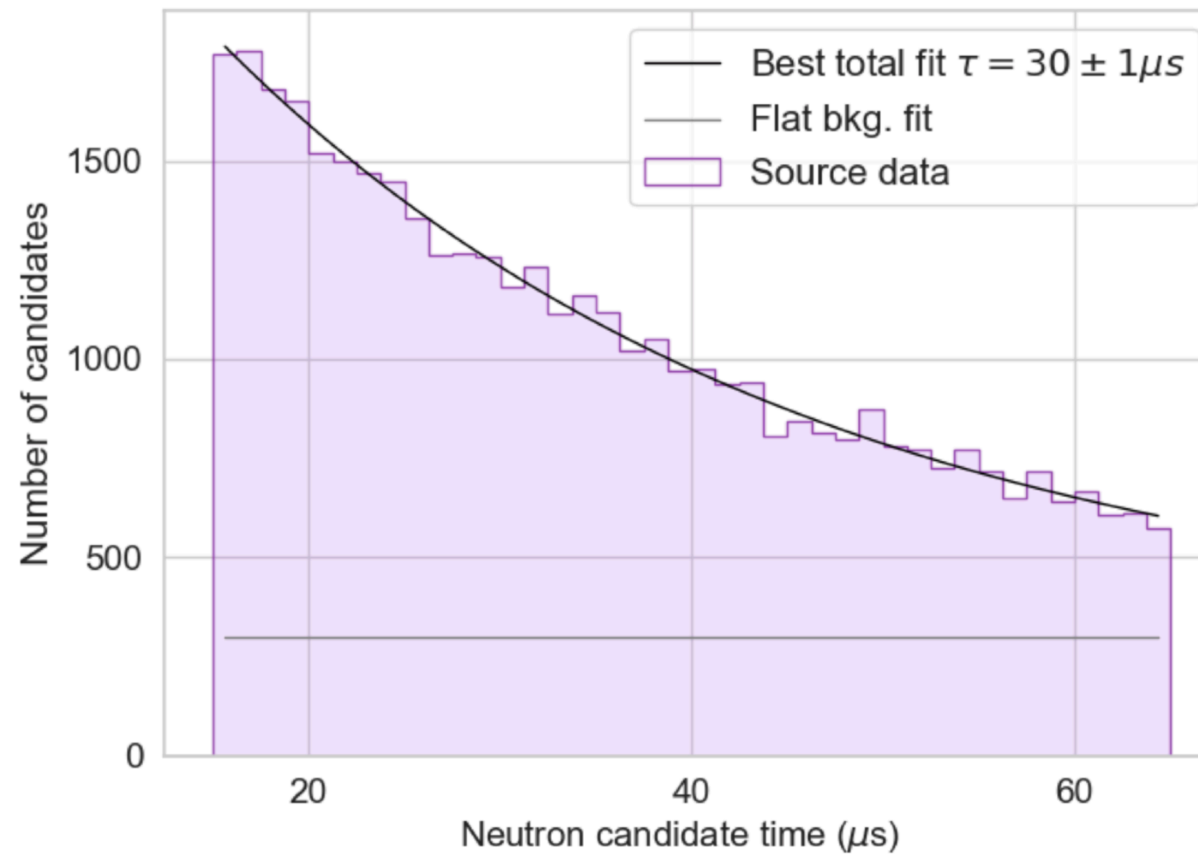


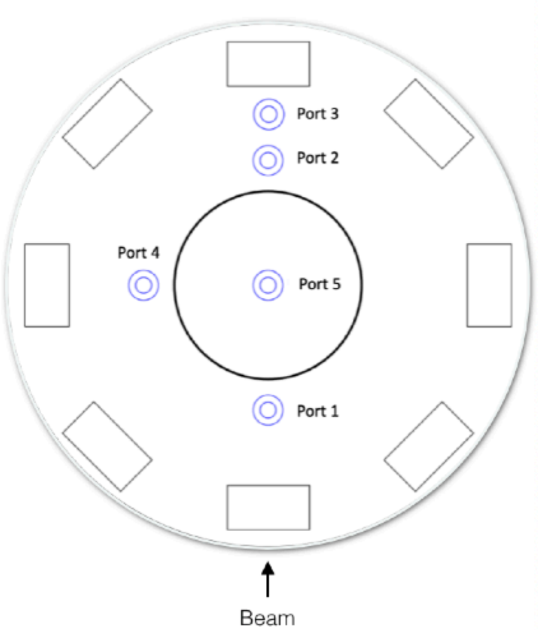


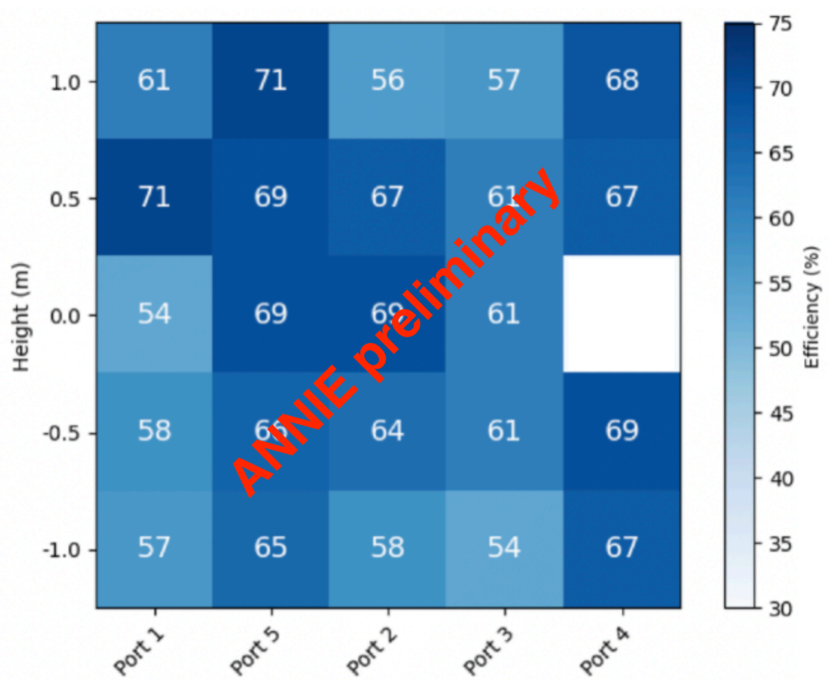
- ANNIE is the most gadiated neutrino detector in the World.
- ANNIE monitors water transparency by measuring intensity of LED flashes with PMTs across the water volume.
- By circulating the water, **custom-designed ANNIE's purification system** has kept the water transparency at the initial high levels for almost 2 years now.

ANNIE Neutron Capture Calibration

- In order to achieve ANNIE's main goals, we must understand the neutron capture efficiency.
- Deployment of a tagged AmBe neutron source inside the water volume.
- Neutron capture time matches expectation for a Gd concentration 0.1% by mass.





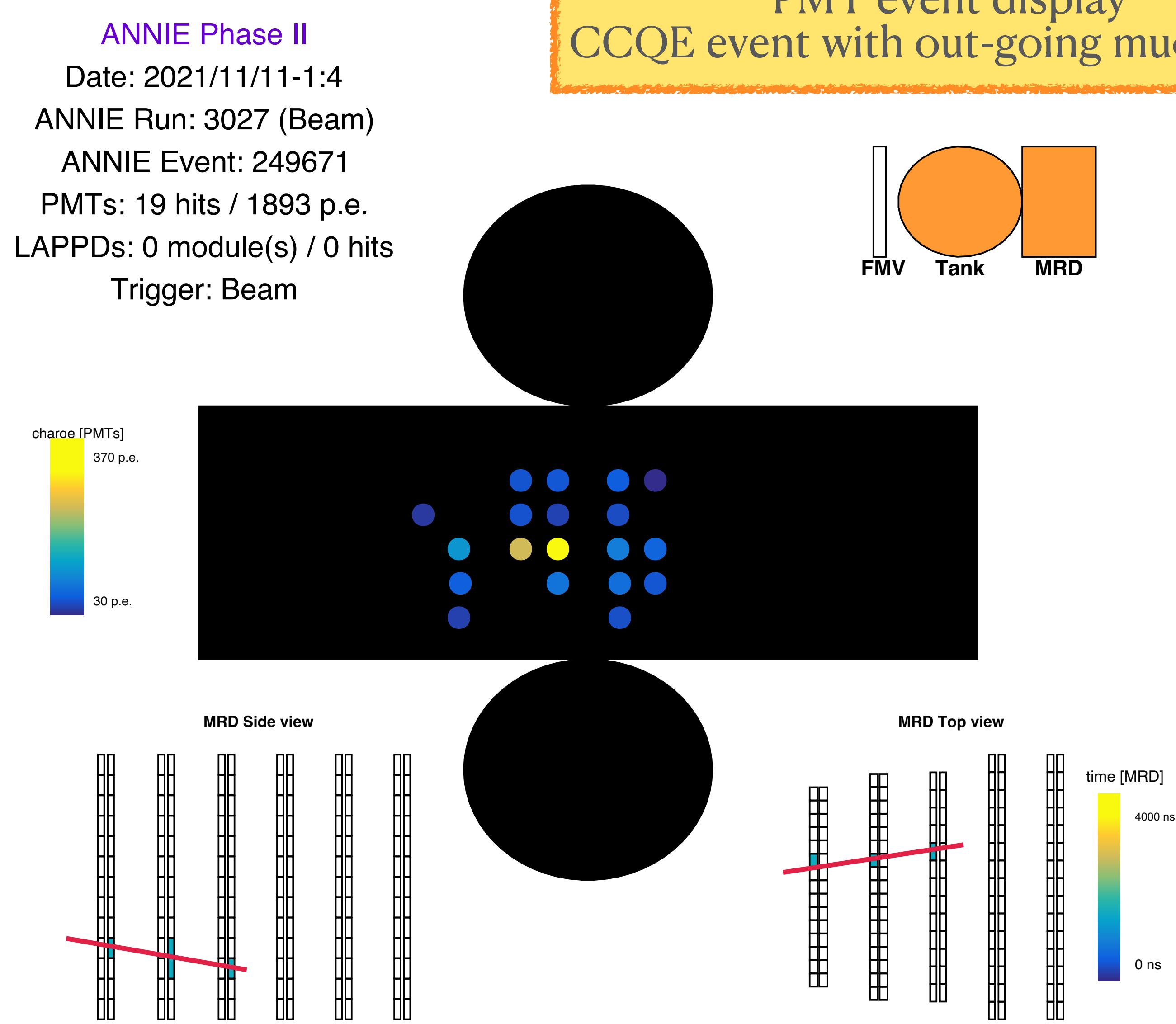


- Position dependent neutron capture efficiency has been measured to be consistent with expectations: ~55-70%.

ANNIE Neutrino Beam Data

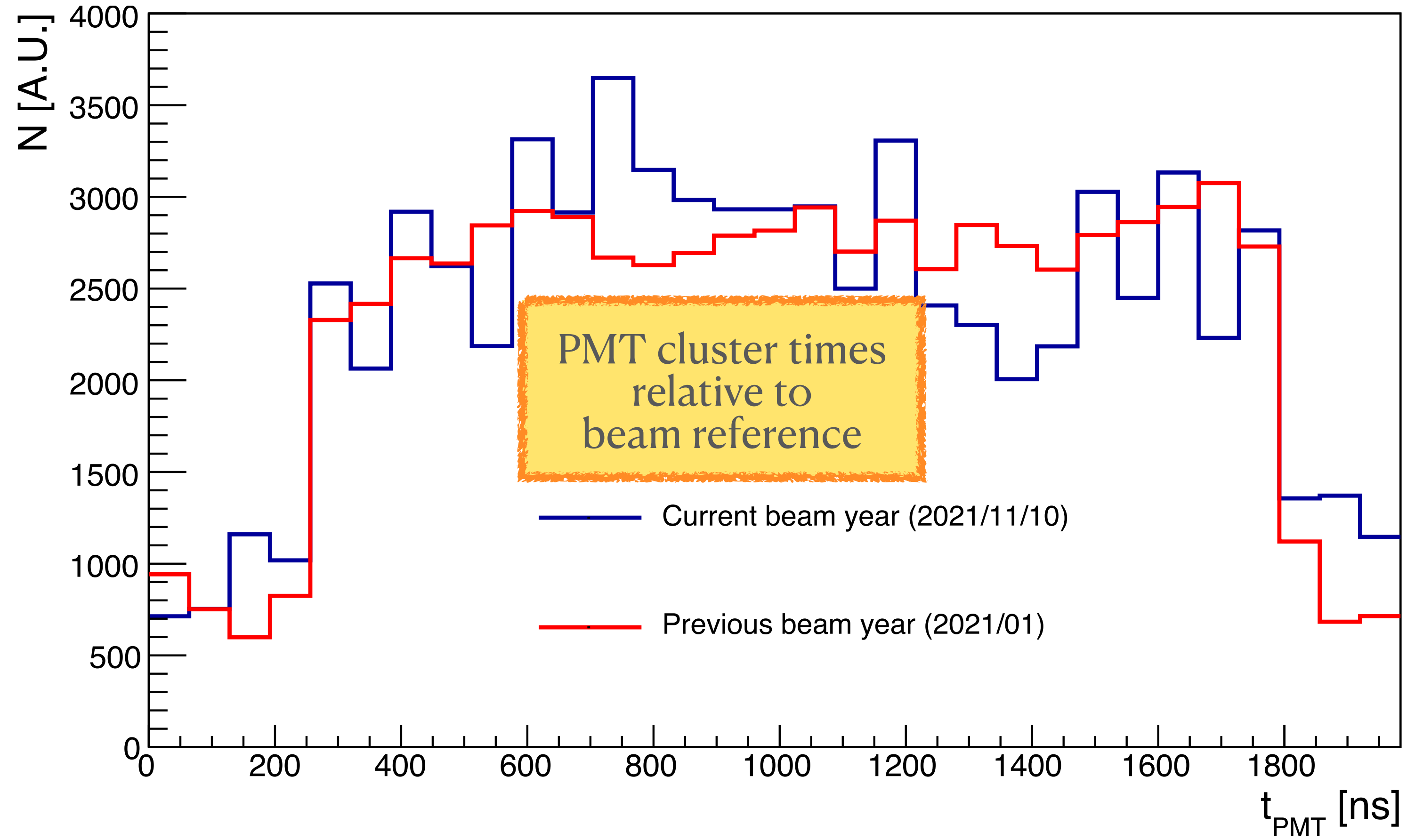
- All “conventional” ANNIE systems up to specs and running on high duty factors. Beam data taking in the Booster beam since January 2021.
- Charge Current (CC) quasi-elastic (QE) neutrino interactions are the golden signal for the determination of neutron multiplicity.
- Candidates are identified by a Cherenkov disk in the tank, a coincident track in the MRD and no signal in the FMV.

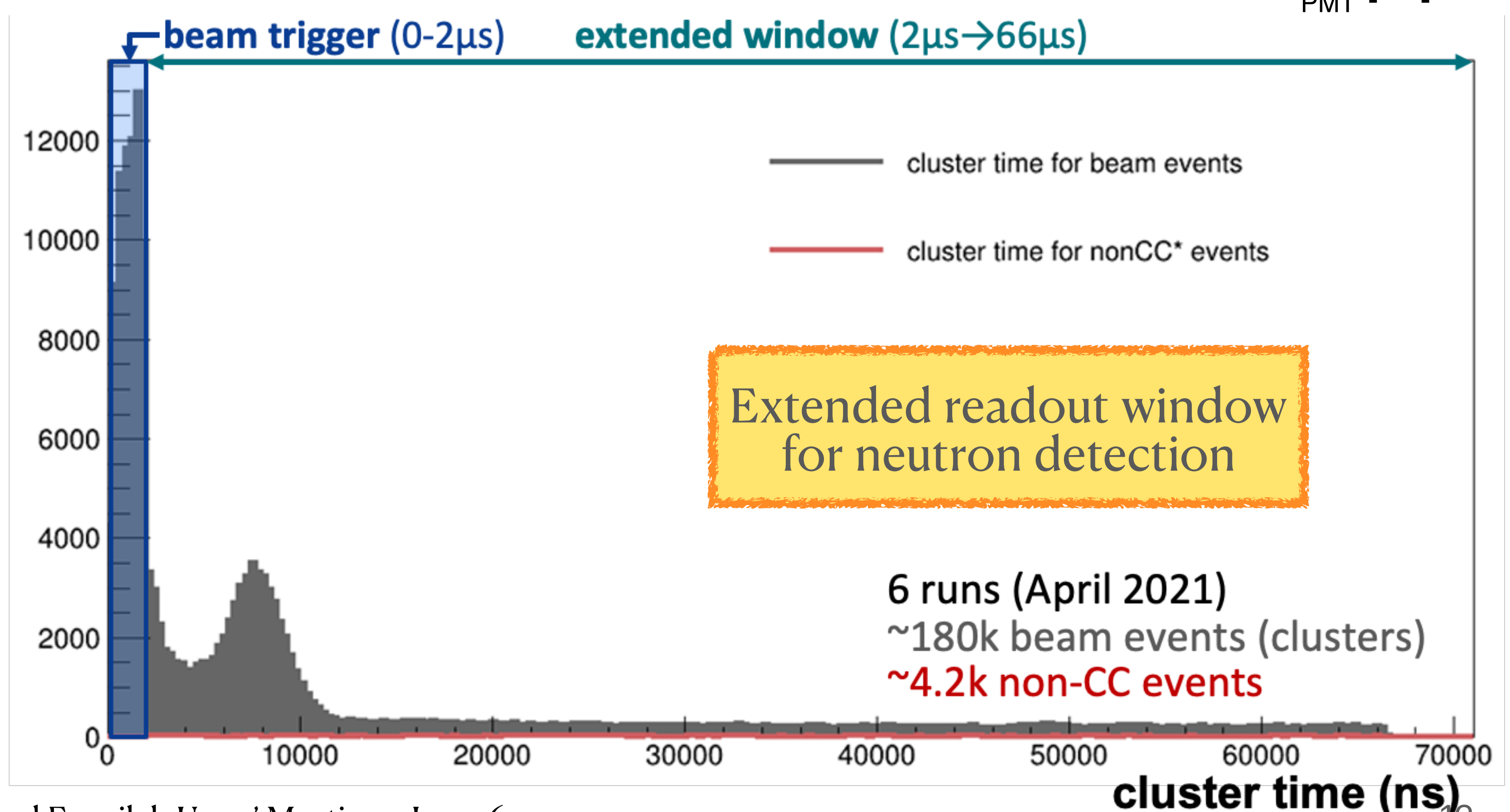
PMT event display
CCQE event with out-going muon track



ANNIE Neutrino Beam Data

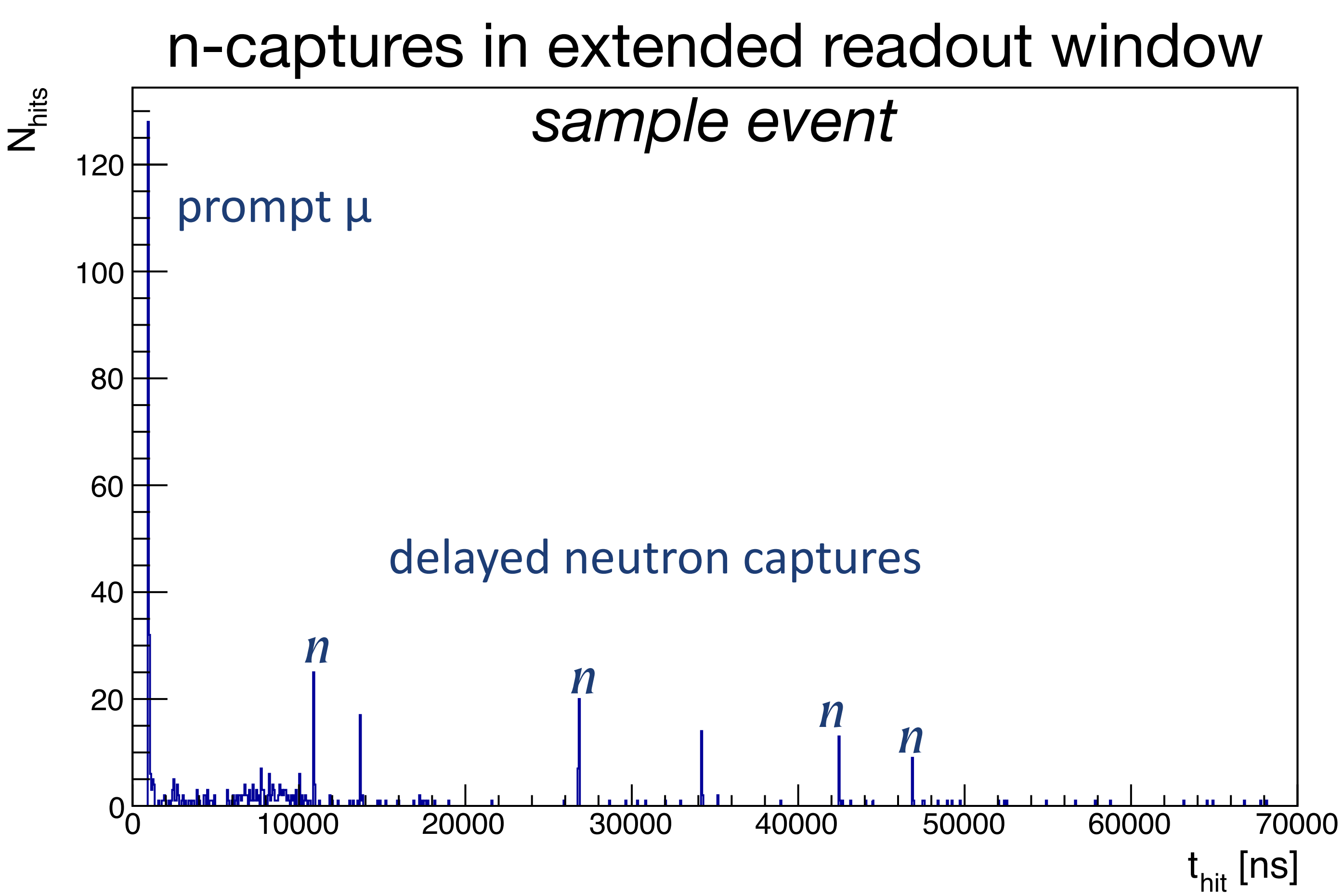
- Selecting PMT cluster times relative to the beam shows an excess in-time with the expected timing of the BNB.
- For beam triggers (<2 µsec) an extended window (2-66 µsec) is recorded to enable neutron detection.

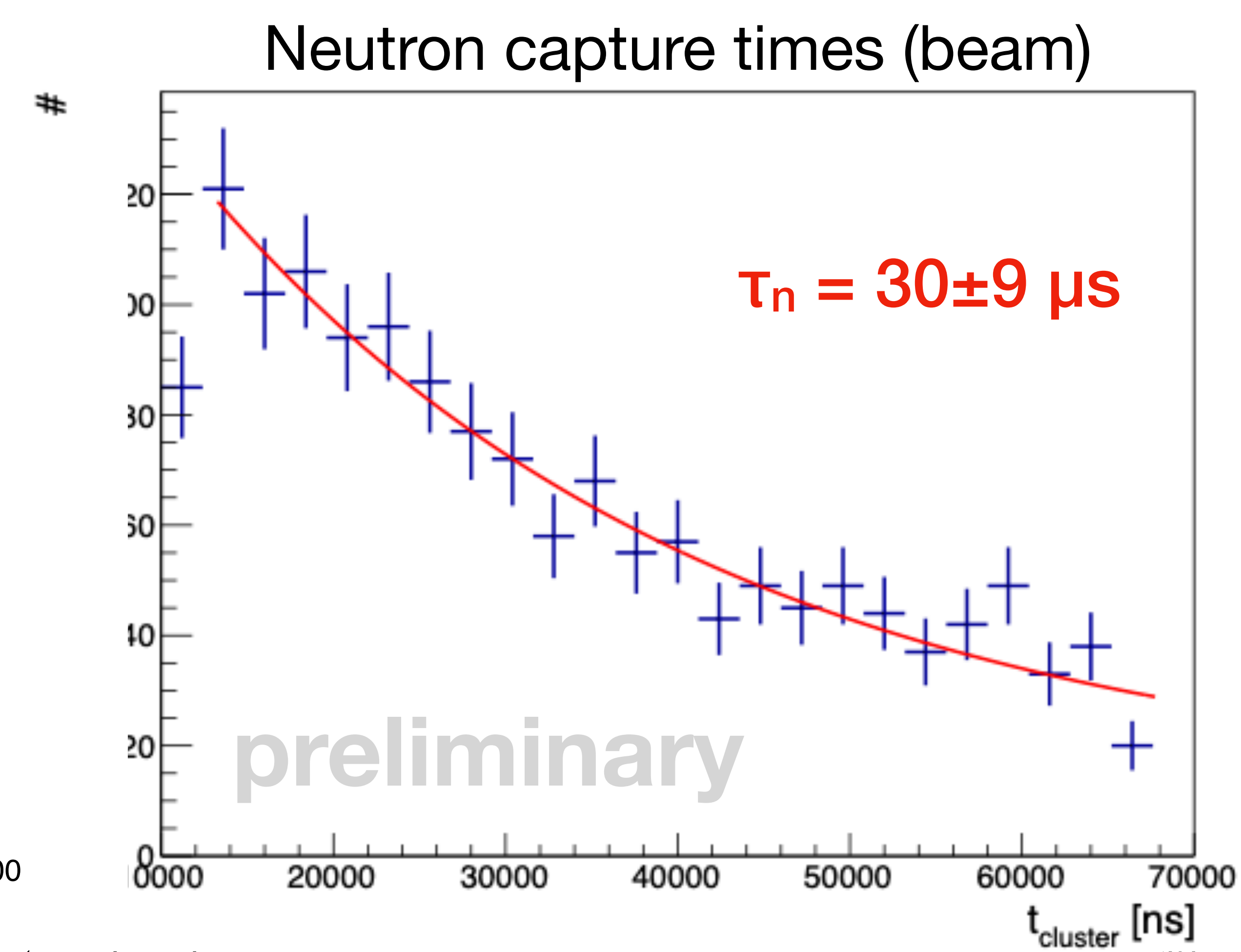




Neutrons in ANNIE Neutrino Beam Data

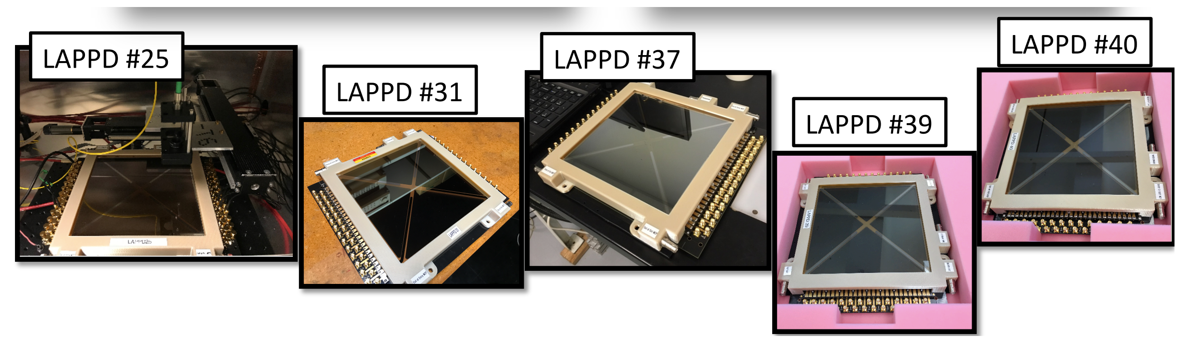
- Beam triggers with a prompt event featuring large PMT signals (≥5 p.e.) are followed by an extended acquisition window of ~70 μs.
  - Allows acquisition of subsequent neutron captures without trigger threshold.
- Selected neutron candidates feature the expected capture time profile at nominal Gd concentration.

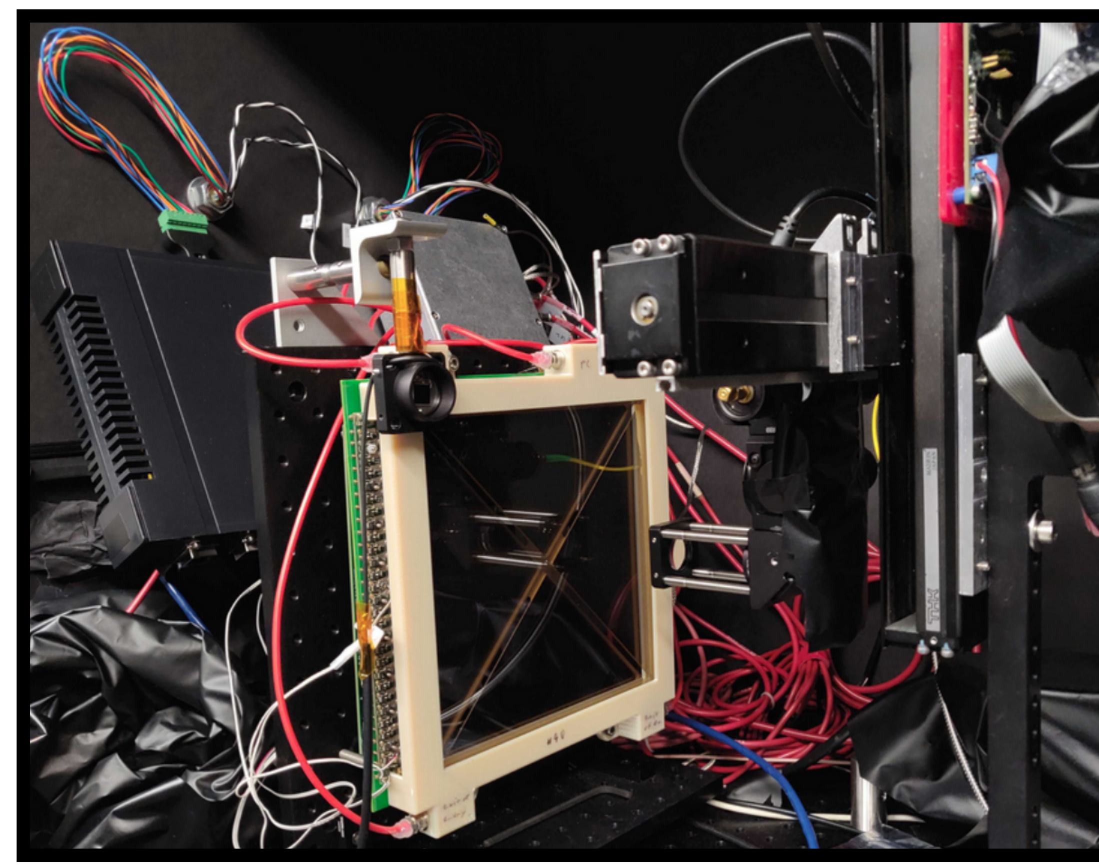




Enabling Technology: LAPPDs

- Large Area Picosecond Photo-Detectors (LAPPDs) are 20 x 20 cm tiles based on microchannel plates (MCPs) with resistive and emissive coating.
- The LAPPD is readout through 28 anode data strips.
- Fast photodetector capabilities (~<100 psec time resolution) and excellent position resolution (mm-cm scale).
- ANNIE has obtained 5 LAPPDs to be deployed in the tank.
  - A 6th LAPPD purchased by Tubingen will become available this year.

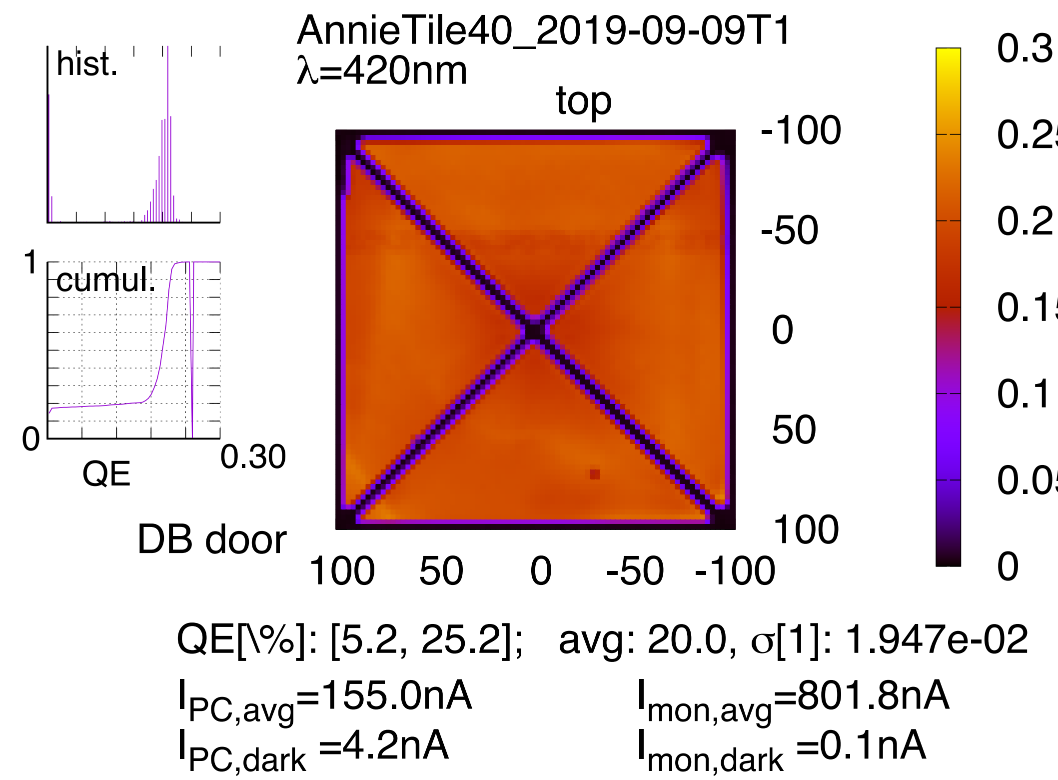


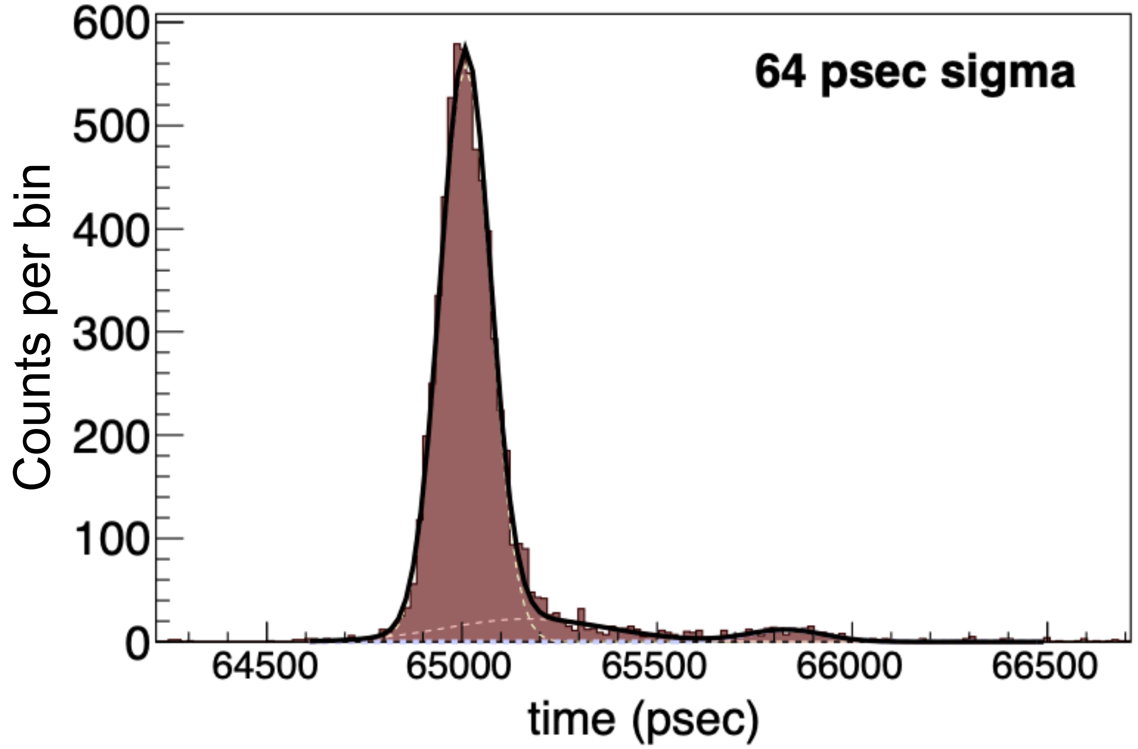


We have taken LAPPDs from prototypes in test stands to a deployable technology.

Enabling Technology: LAPPDs

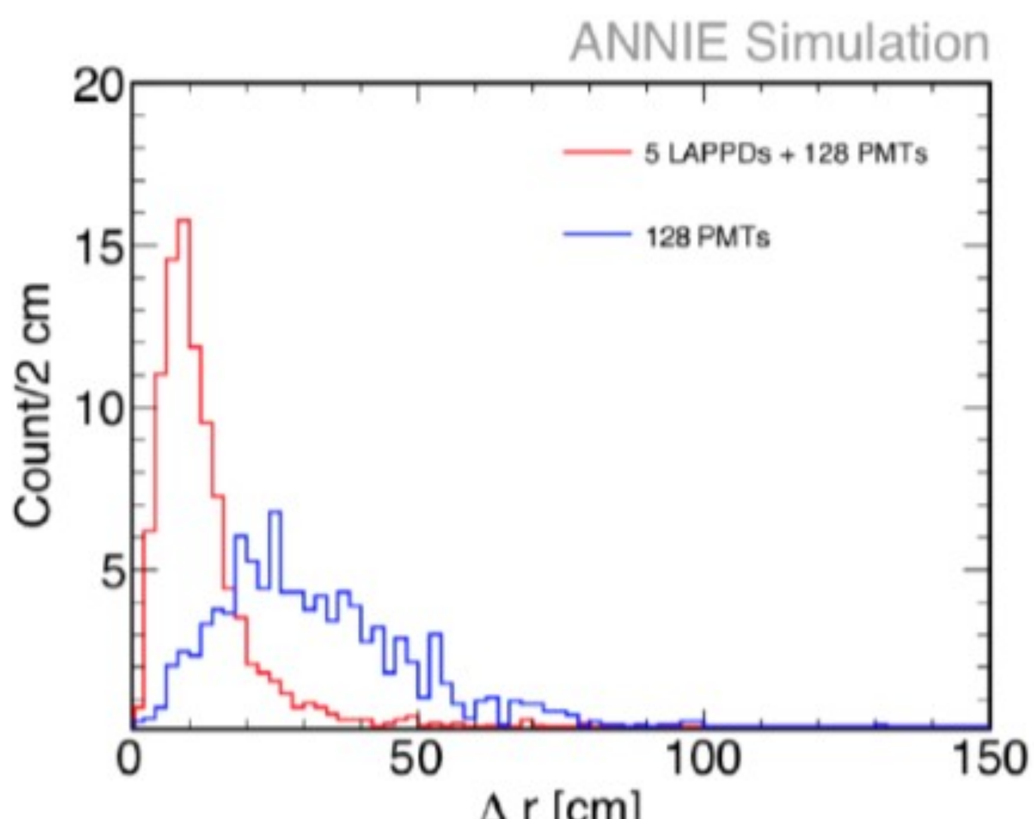
- Characterization and systematic tests of LAPPDs are done at a dedicated facility at Fermilab (including quantum efficiency, gain and timing calibration automated scans).
  - They meet the ANNIE requirements: QE~20%, gains >10^6, time res < 100 ps.
- The first LAPPD (#40) has been fully characterized and has been deployed.

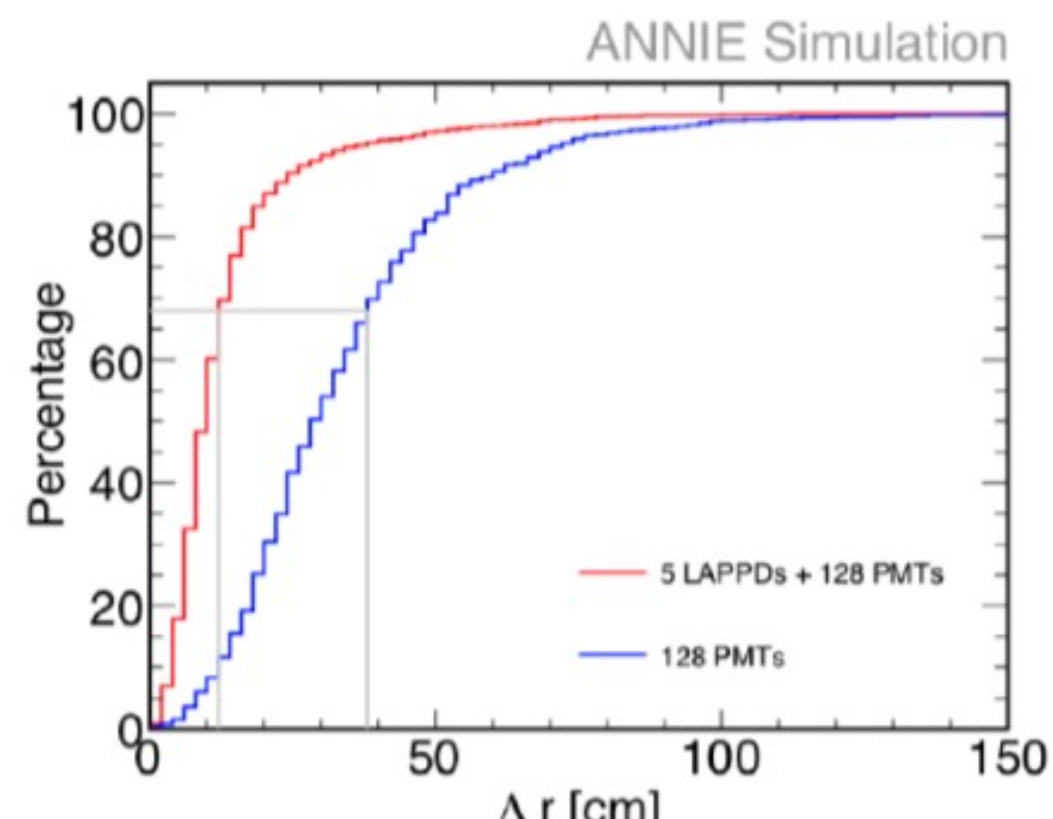




Enabling Technology: LAPPDs

- High time and spatial resolutions from the LAPPDs impact neutrino vertex resolution as well as tracking angular resolution.
- By adding 5 LAPPDs to the existing PMTs the accuracy of the vertex reconstruction is improved by a factor of >2 allowing for more precise reconstruction of the muon and thus neutrino energy.
    - Similarly the angular resolution (not shown) by a factor of 2.





Vertex Radial Displacement: Δr

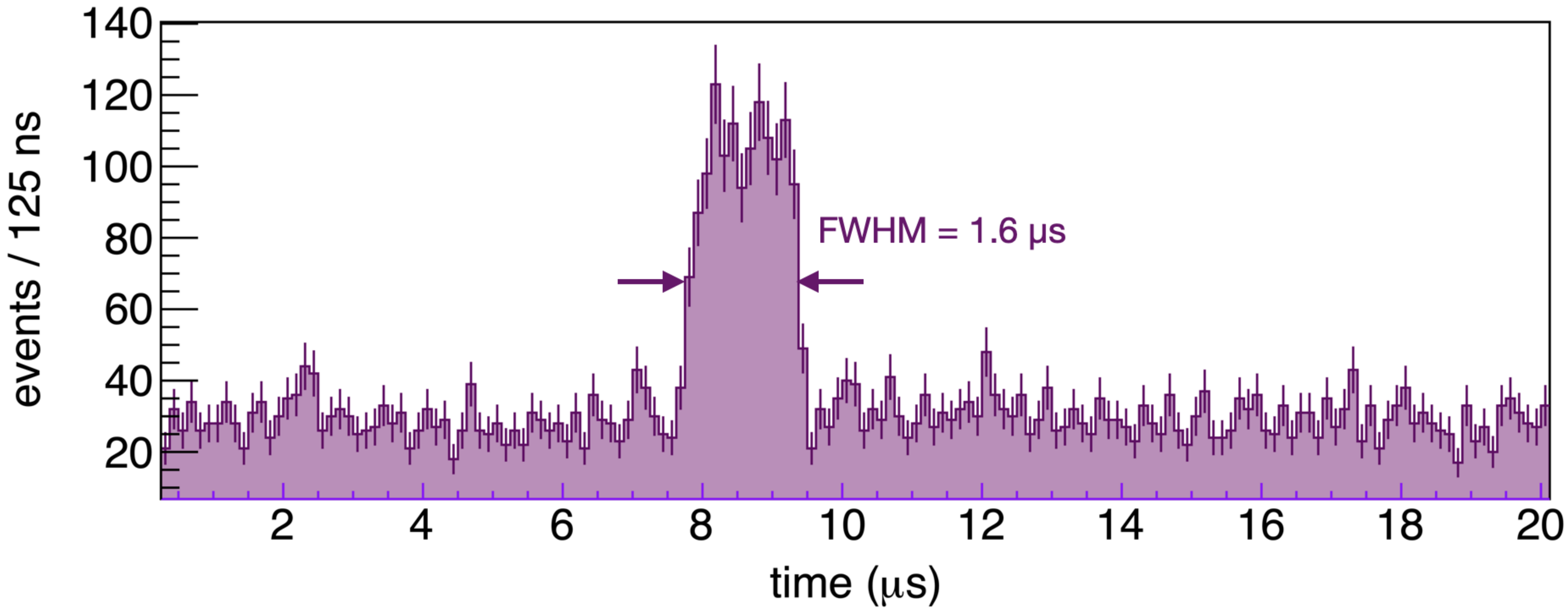
Enabling Technology: LAPPDs

- First LAPPD was deployed March 29 of 2022.
  - Operating stably under water with consistent slow controls monitoring: humidity, temperature and voltage are within specifications.
- The LAPPD was deployed in a specially designed waterproof housing with the electronics package.
- Two waterproof cables carry the power and data.
- Position of the LAPPD on the mounting board is determined to sub-cm level.

First LAPPD deployed in a HEP experiment!

ANNIE First LAPPD Neutrinos

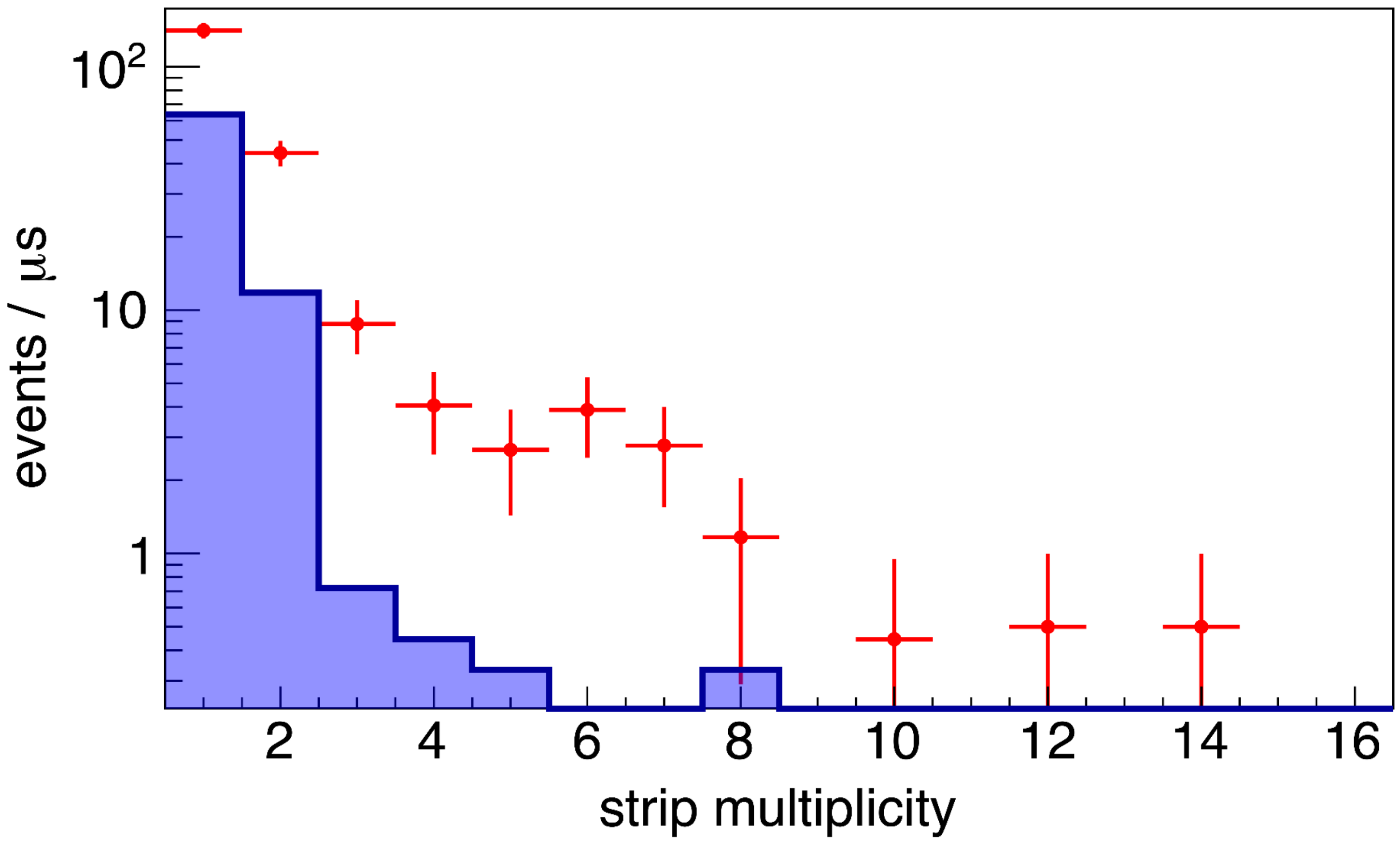
- The excess above background are LAPPD-triggered events in-time with the BNB. The excess has a width of 1.6 μsec.
- Background can be further reduced using simple cuts and information from other detector systems.



World's first: neutrinos observed with LAPPD!

ANNIE First LAPPD Neutrinos

- The distribution of events with different strip multiplicities (the number of LAPPD strips in an event with pulses above threshold) shows an excess at higher multiplicities for in-time data (in red) vs off-beam (in blue).
- The excess are expected to be neutrino events.

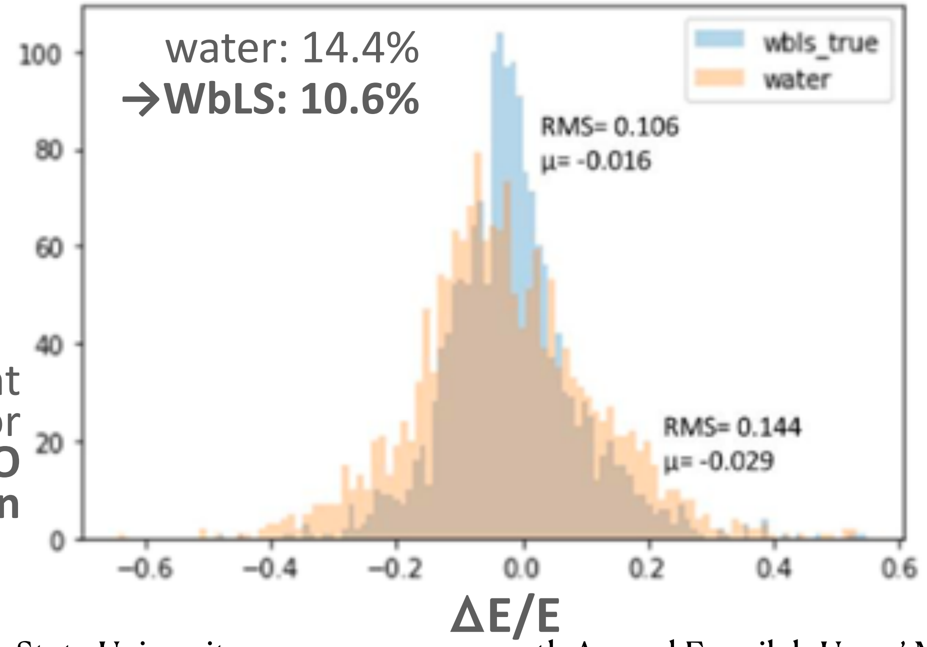


World's first: neutrinos observed with LAPPD!

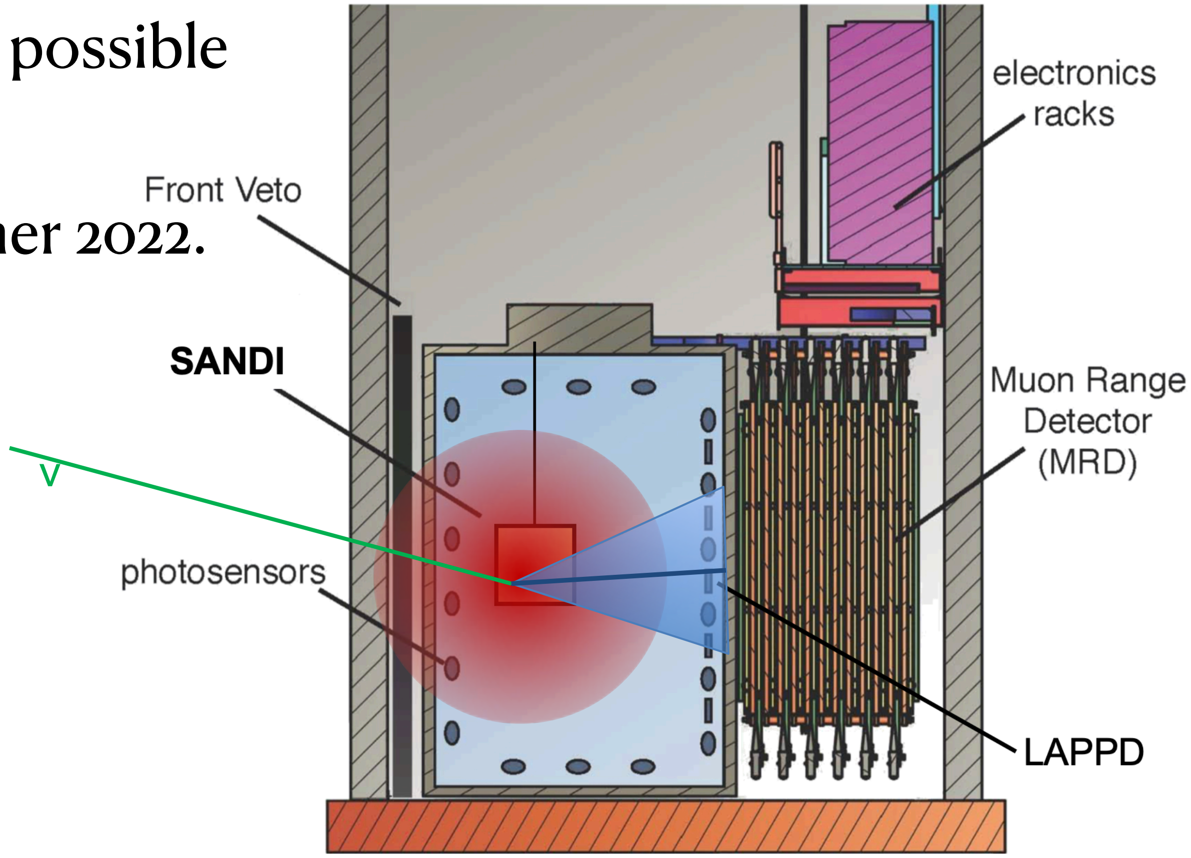
Testing water-based scintillator (WbLS)

- 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') to hold WbLS in ANNIE.
- WbLS to be produced at BNL (M. Yeh). Studying possible Gd-loading.
- Aiming for two-week test run at the end of summer 2022.

SANDI vessel at Davis



improvement expected for **NEUTRINO energy resolution**



WbLS adds scintillation from hadronic recoil to the muon Cherenkov signal

ANNIE Summary

- The ANNIE collaboration has constructed, assembled and installed the detector which is taking neutrino beam data.
- The Gd-loading of the detector has been a success. First neutron source calibration run has been accomplished.
- Significant development has been done to enable the World's first multi-LAPPD deployment.
- Preparations to deploy WbLS in progress.
- ANNIE observes neutrons (from AmBe calibration and beam!) and neutrinos on LAPPDs!

Exciting times for ANNIE, new collaborators are welcome!

Backup

Further physics goals

Diffuse Supernova Neutrino Background (DSNB)

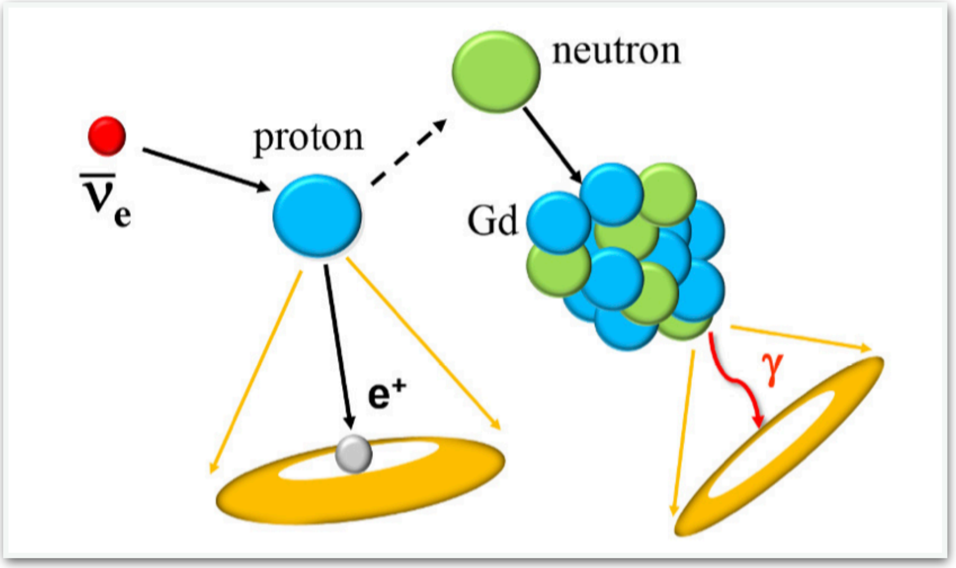
- Main motivation for adding Gd to SK
  → enhanced signature for Inverse Beta Decays
- Dominant residual background in SK-Gd due to NC reactions of atmospheric neutrinos

→ ANNIE can provide precision data on the relevant GeV neutrino cross-sections

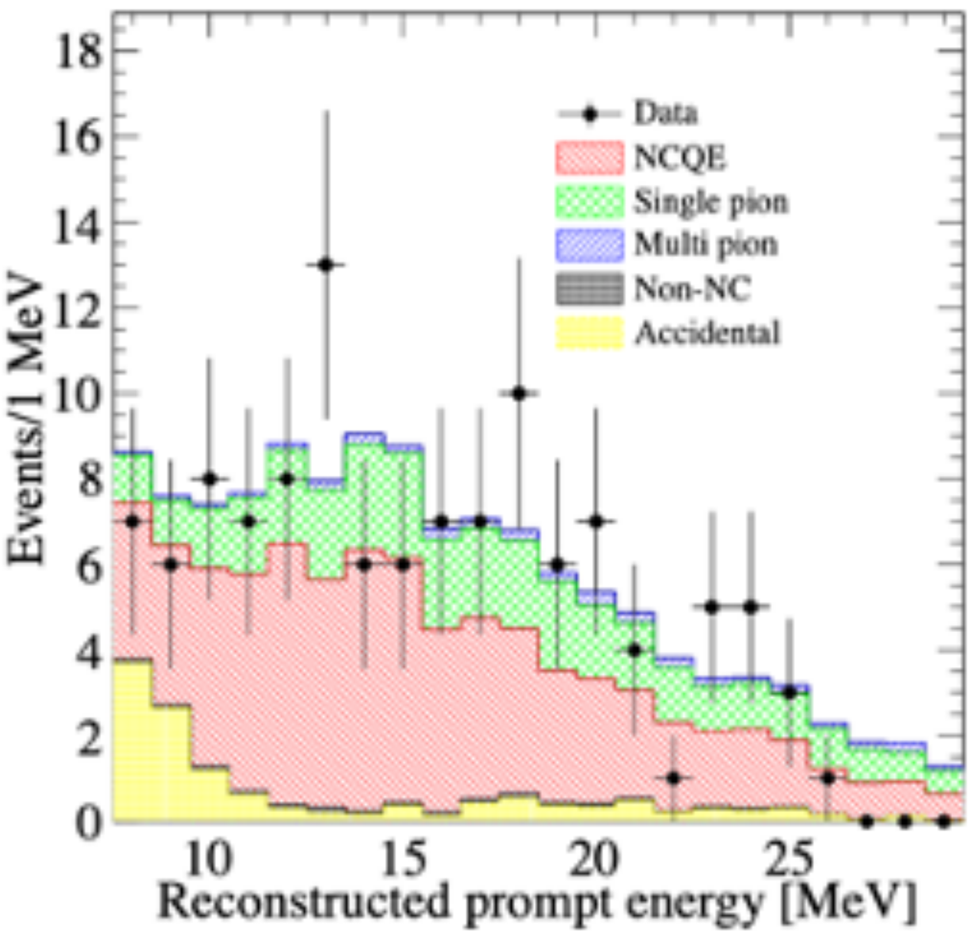
Proton Decay

- Atmospheric neutrinos are dominant background for proton decay searches
- Neutrons can be used to discriminate proton decay signals from backgrounds

→ Precision data from ANNIE

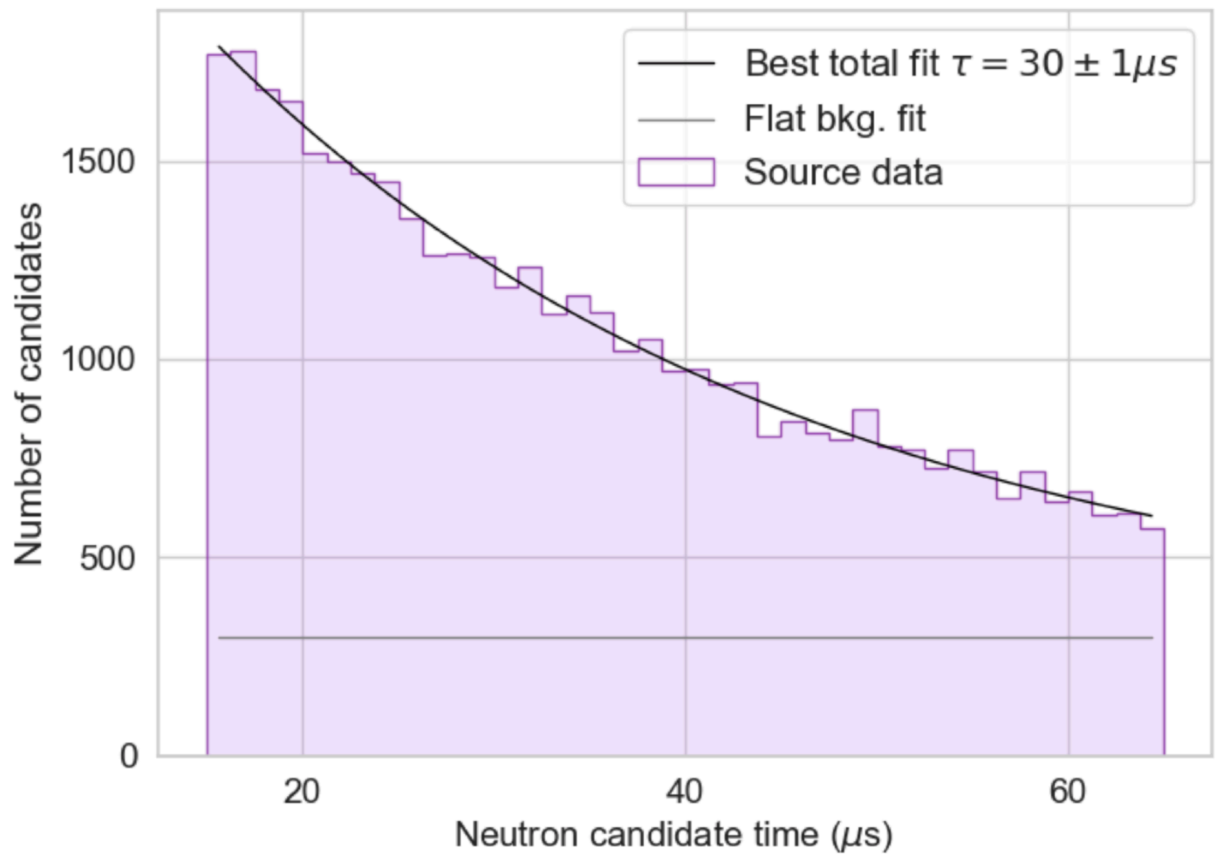


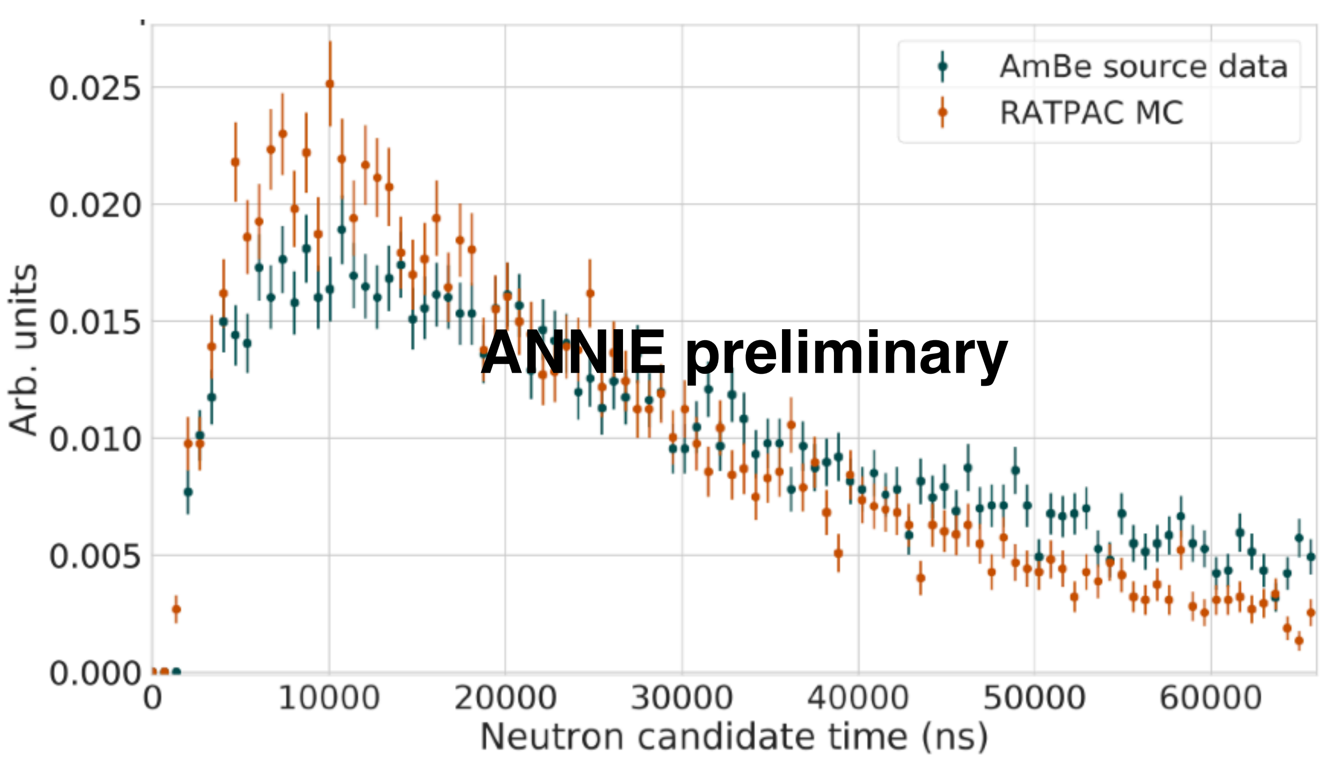
SK-IV measurement of NC atmospheric events (2019)



ANNIE Neutron Capture Calibration

- Deployment of a tagged AmBe neutron source inside the water volume.
- Data/MC comparison for neutron candidate time for a central deployment.





- Neutron capture time matches expectation for a Gd concentration 0.1% by mass.

ANNIE Neutron Capture Calibration

- Modeling the neutron multiplicities to extract the true detection efficiency:

Position dependent multiplicity

Uncorrelated background

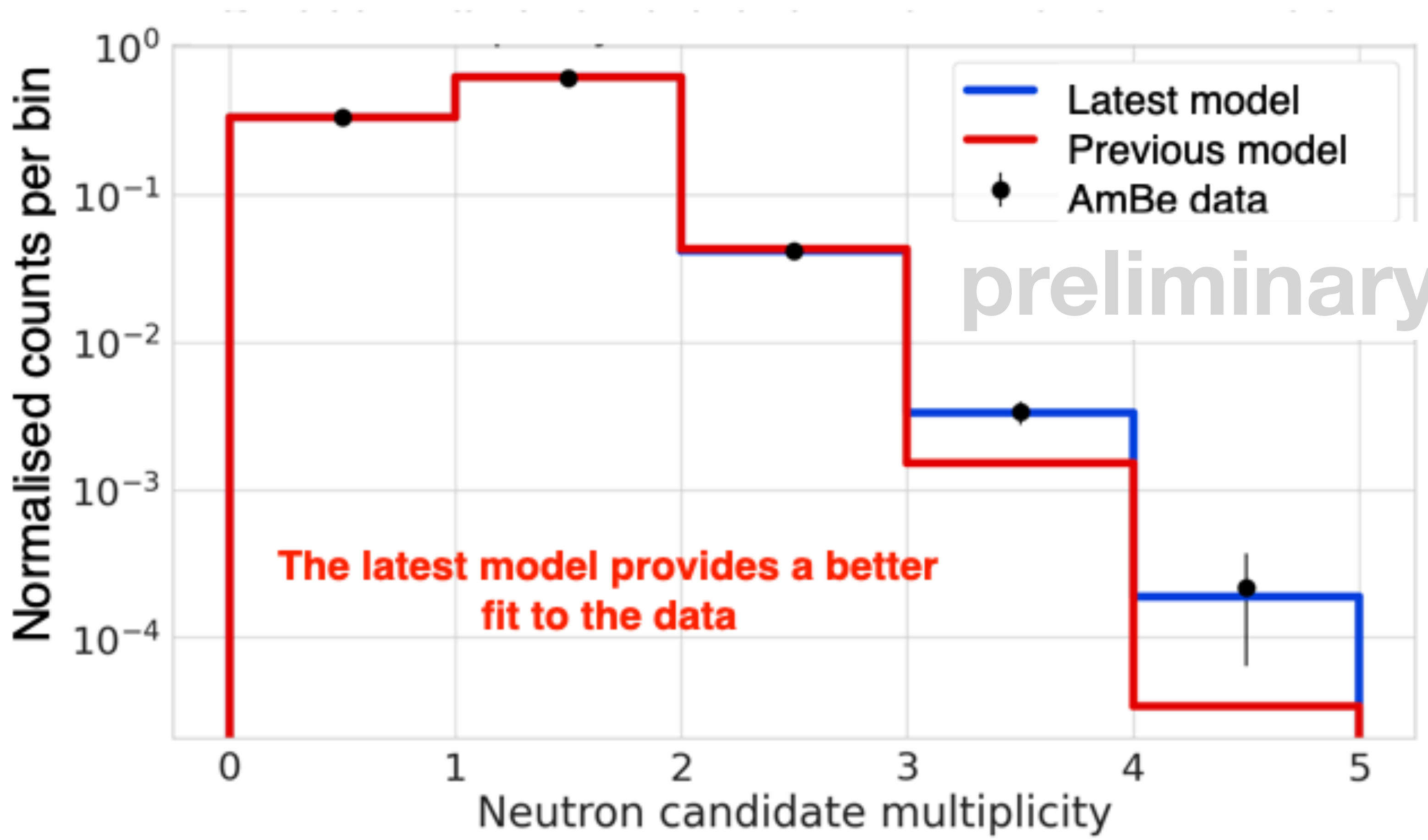
Uncorrelated neutron-gamma pairs from AmBe source

$$M(x) = B(n;\epsilon_n) + \frac{\lambda_b^x e^{-\lambda_b}}{x!} + \frac{\lambda_{un}^x e^{-\lambda_{un}}}{x!} + \left(\frac{\lambda_\gamma^x e^{-\lambda_\gamma}}{x!} + M_{\gamma n}(n_\gamma)\right)$$

Bernoulli distribution for a given neutron detection efficiency

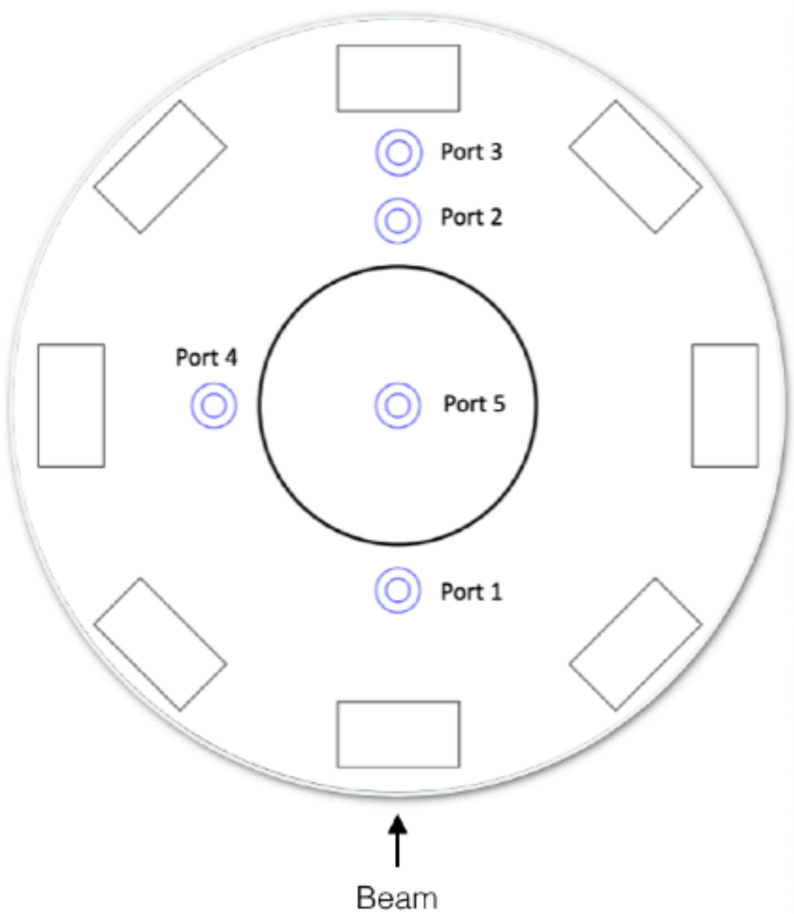
Uncorrelated neutrons from AmBe source

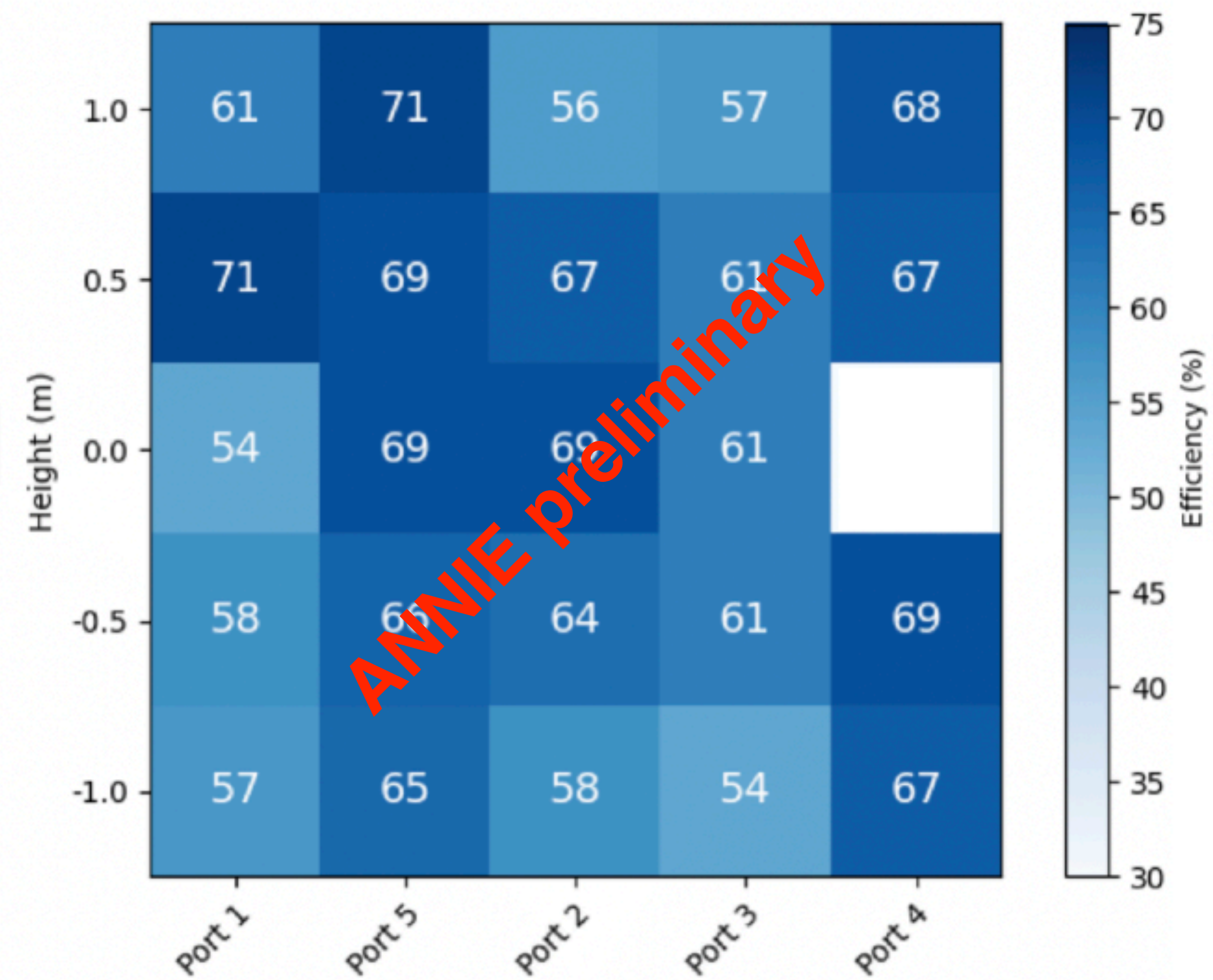
AmBe neutron multiplicity



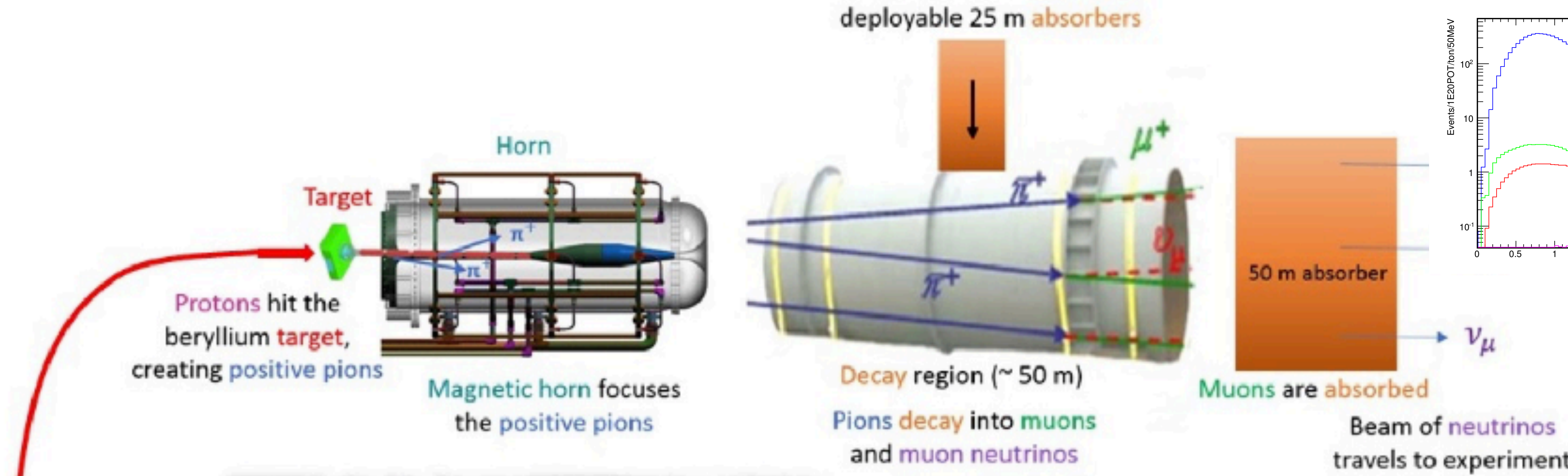
ANNIE Neutron Capture Calibration

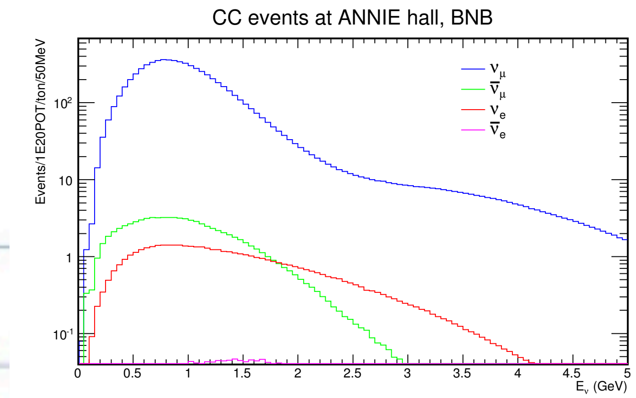
- For each of 25 source positions a best fit of signal and background data was performed to determined detection efficiency.
- Position dependent neutron capture efficiency has been measured to be consistent with expectations: ~55-70%.

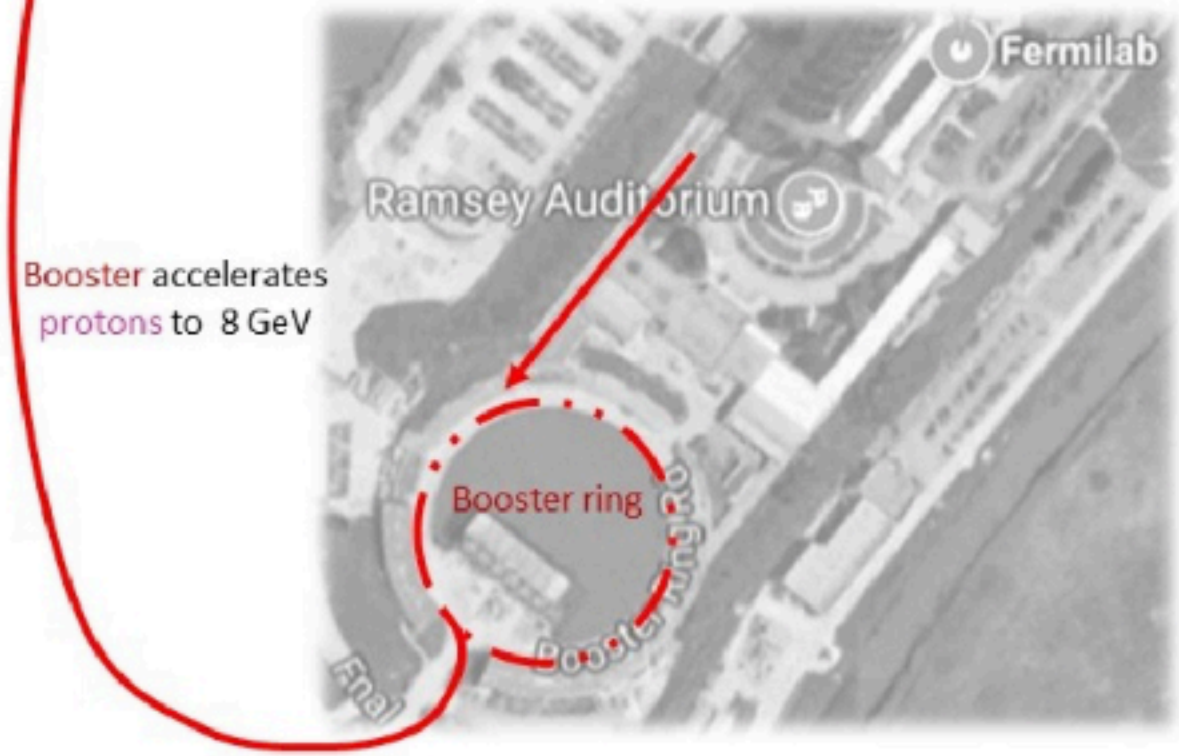




The Booster Neutrino Beam





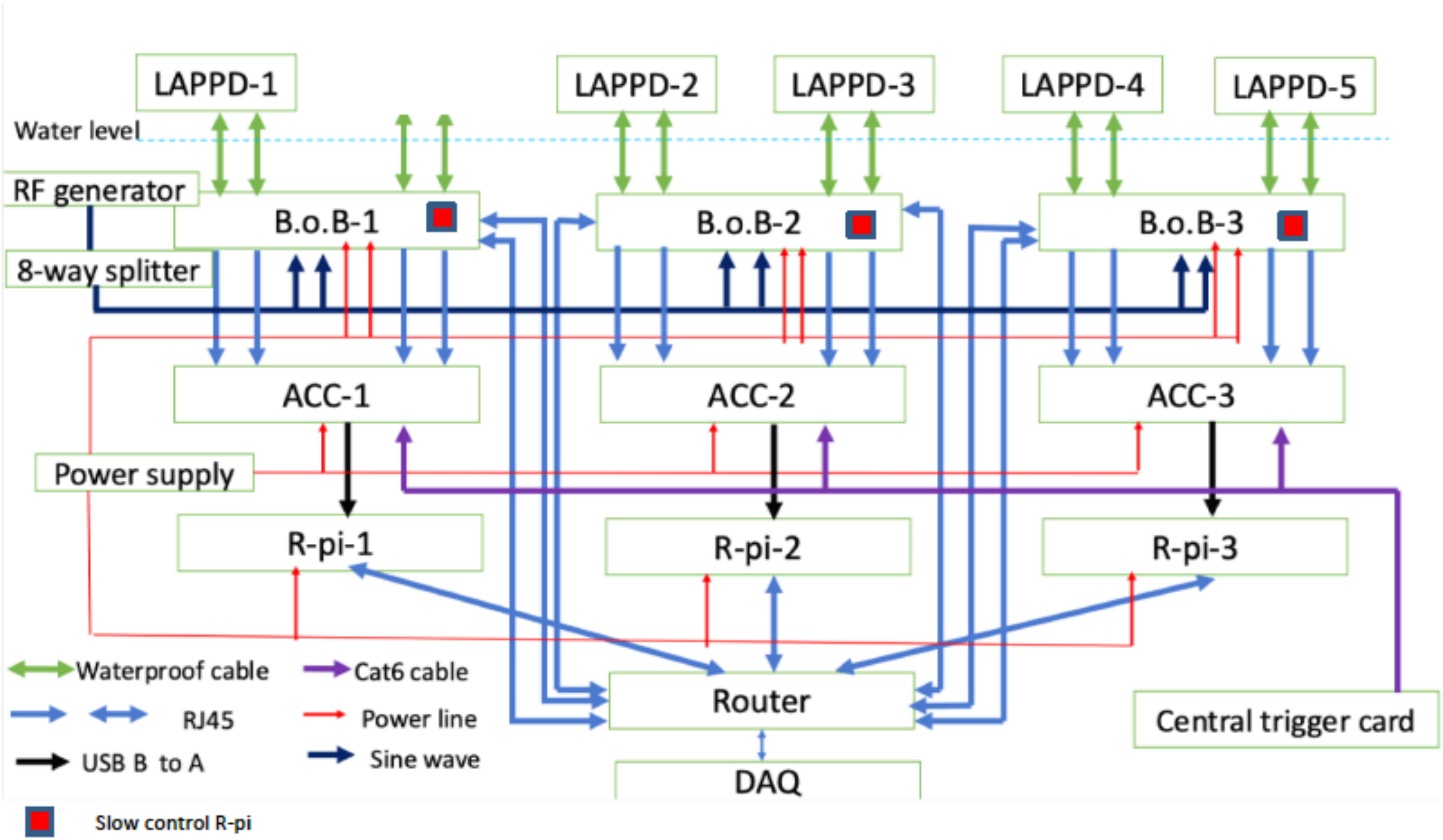


- The Booster Neutrino Beam produces a beam that is 93% pure muon neutrinos and has a spectrum that peaks at about 700 MeV.
- We estimate on the order of 11,000 charged current muon neutrino interactions per ton per year.

LAPPD System

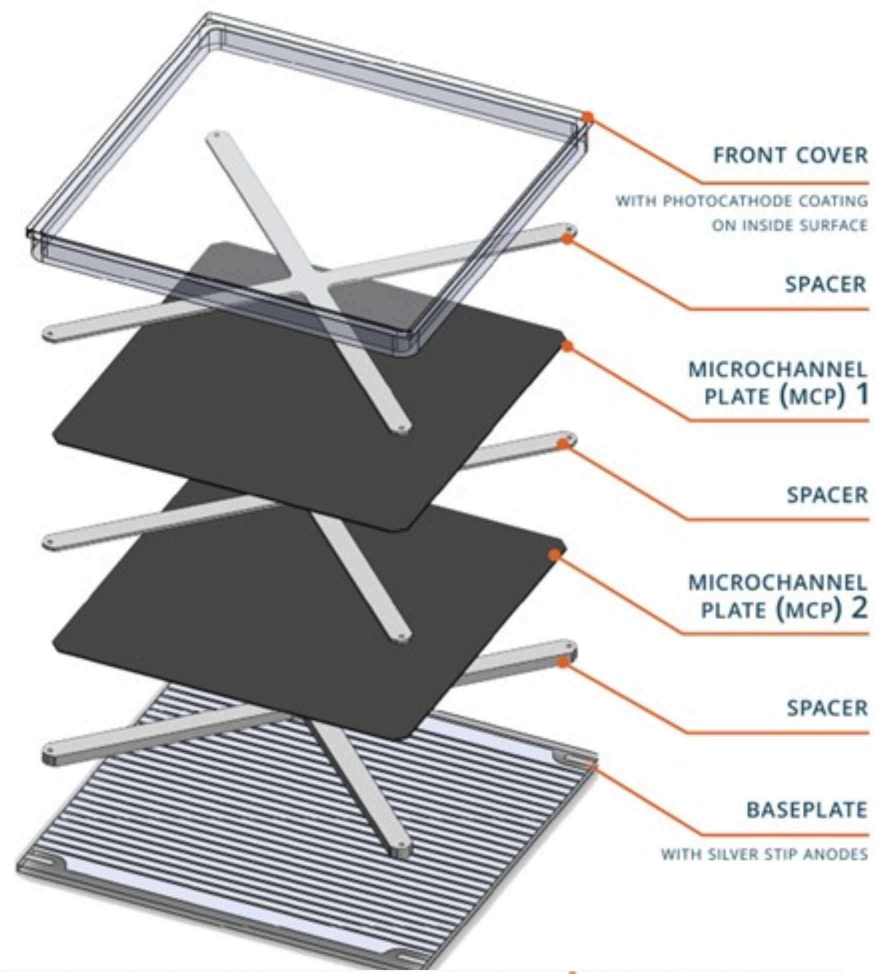
Overview, Surface Electronics

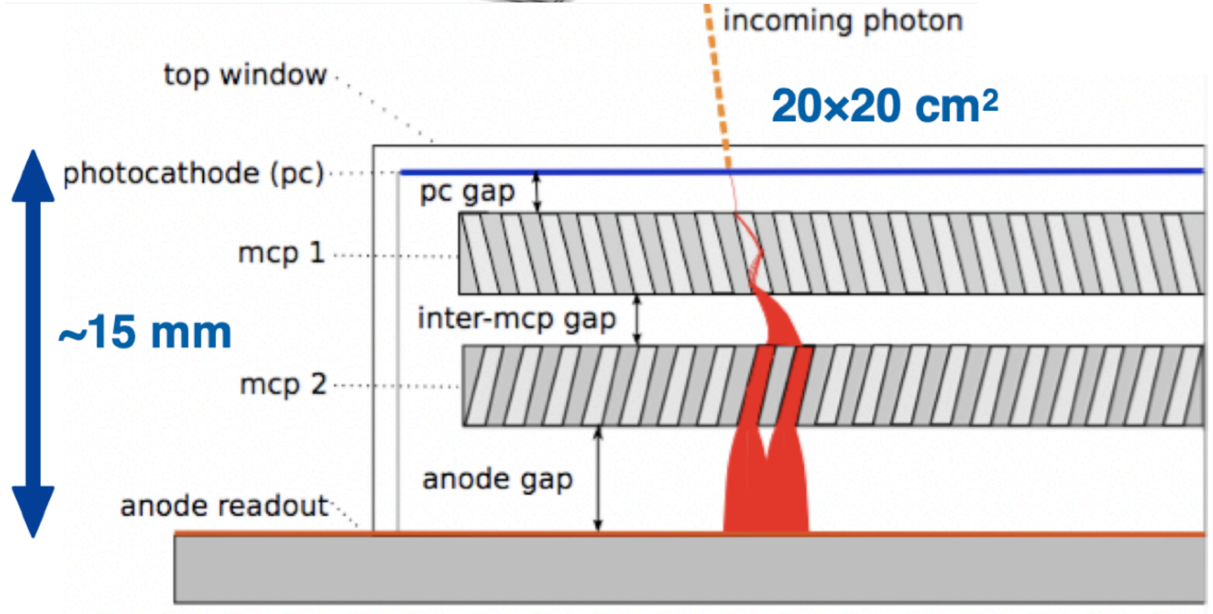
Surface Electronics



Enabling Technology: LAPPDs

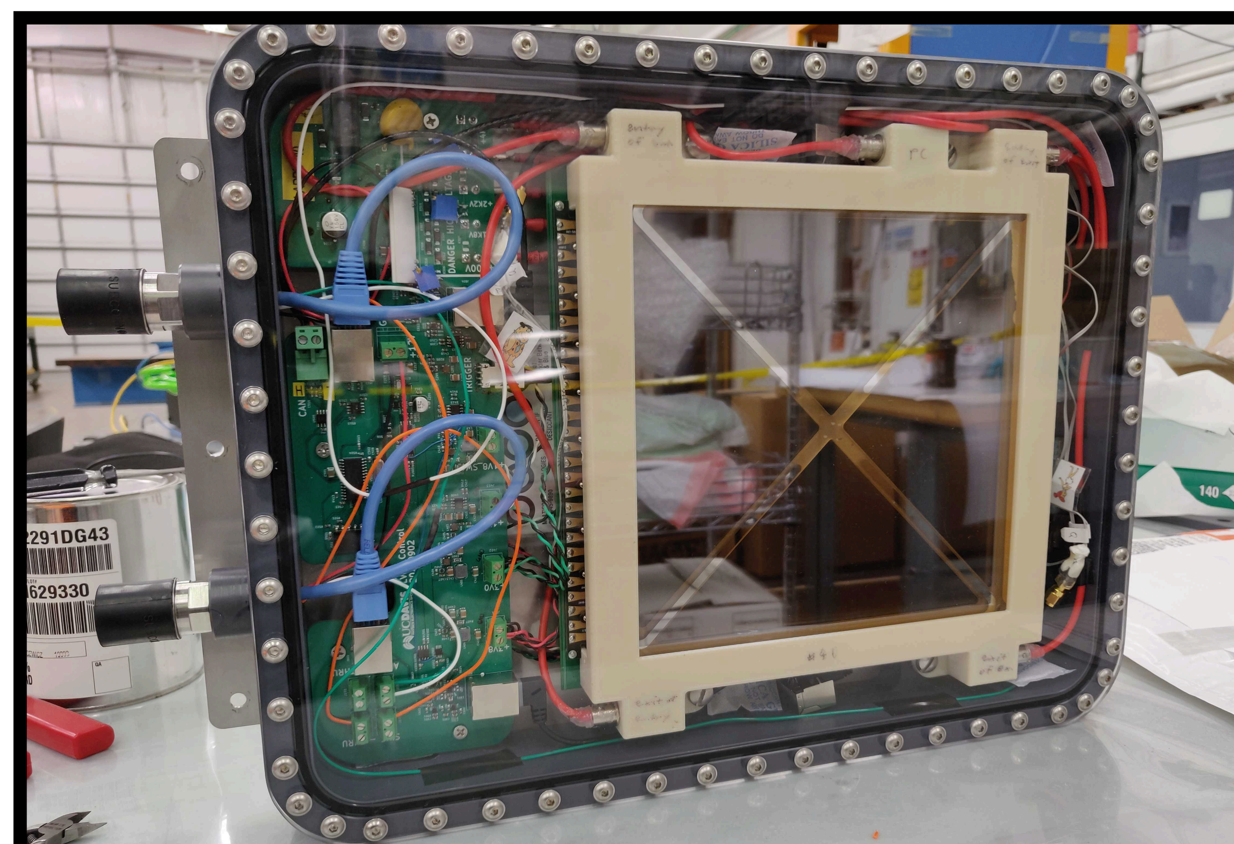
- LAPPDs were developed by a consortium of universities, national laboratories and industry.
- Key innovation is a glass substrate with layers of conductor/resistive materials made with atomic layer deposition techniques.
- Photoelectrons are multiplied by two layers of MCPs. The electron cascades then hit one or more strip anodes.
- Reading out the signal at both ends of the strip the time differential can be used to determine position in that dimension. The second dimension is given the position of the strip.

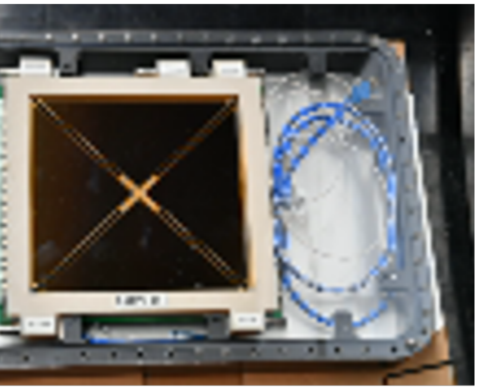




Enabling Technology: LAPPDs

- We have designed waterproof housing, trigger and readout compatible with the timing capabilities and requirements, and the slow controls for monitoring and HV/LV delivery.
- The LAPPD package and associated electronics are composed of:
  - a waterproof housing with acrylic window, steel backplane and PVC sidewalks
  - a board (Analog Pickup Board) that mounts to the back of the LAPPD and brings signals to the two readout mezzanine cards
  - two readout cards (ACDC cards) per LAPPD which use five PSEC4 chips per ACDC. Each PSEC4 chip can record up to 30 channels with a sampling of 10 Gsps at 12 bit.
  - a board for voltage control and sensor readout (LVHV card)
  - active and passive temperature and humidity sensors
  - and externally an ANNIE-central-card (ACC) that collects data from up to 4 LAPPDs and handles the sync and trigger of the system.

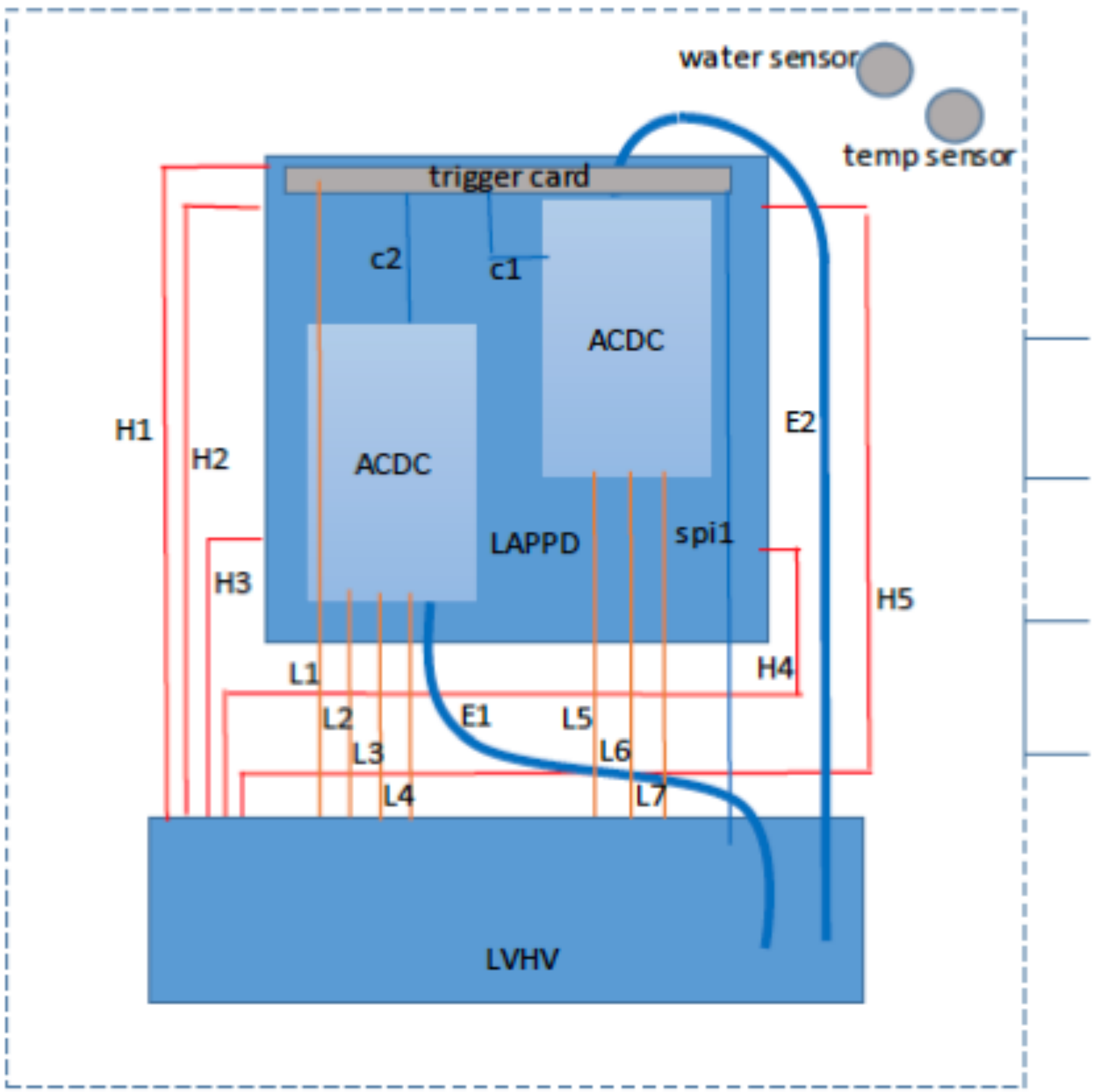


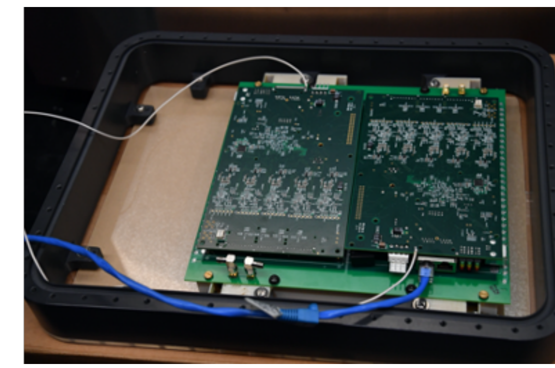


LAPPD Deployment Package

LAPPD, Readout, Slow Controls, Monitoring

Waterproof housing

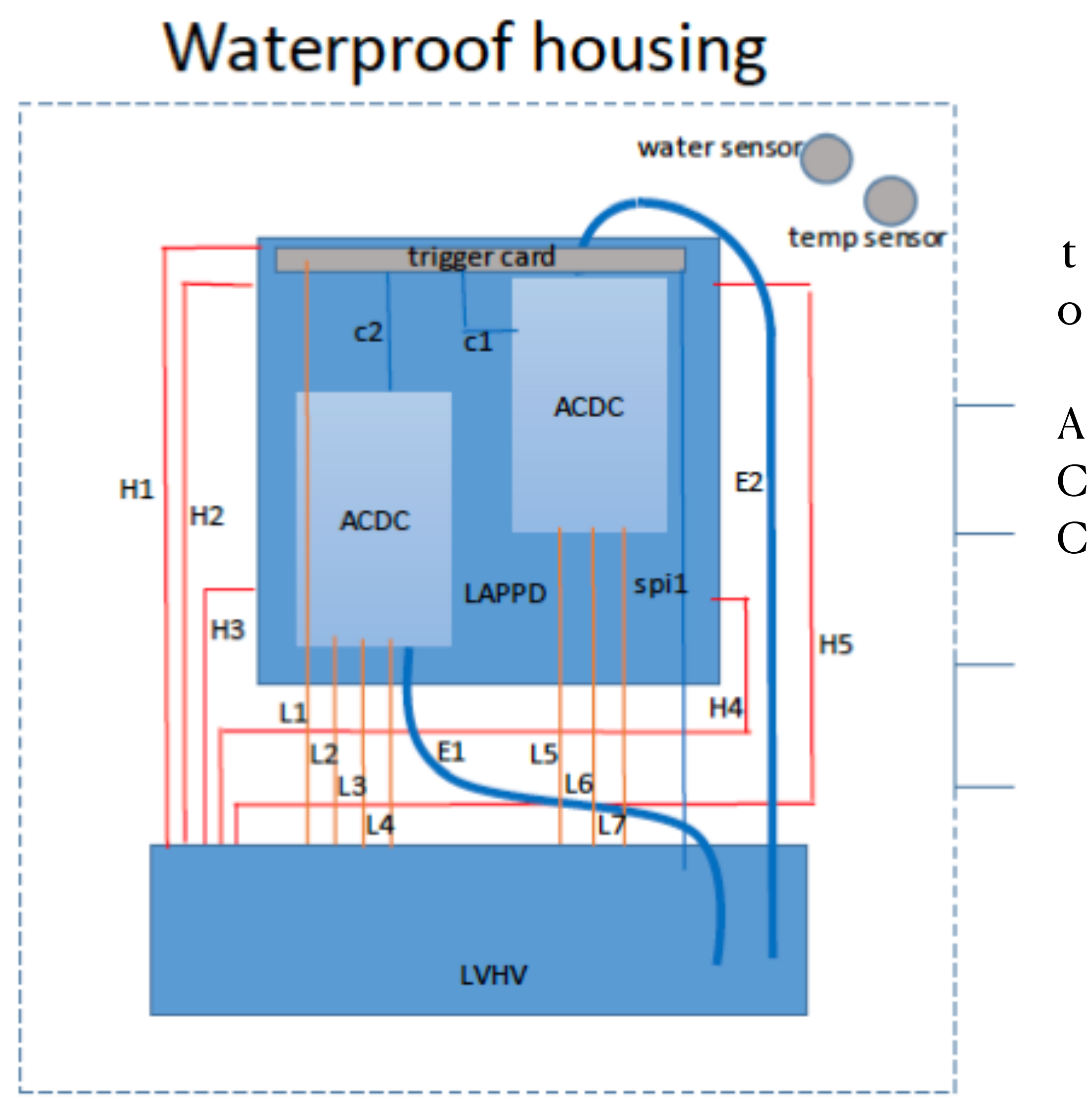




- ACDC: signal digitization
- LVHV:
  - power, slow controls
  - AC-coupled communications pas-through
- Trigger card:
  - passive signal bridge from striplines to ACDC
  - Replaces onboard ACDC trigger.

LAPPD PSEC Electronics

- The implementation and commissioning of PSEC electronics for ANNIE presented several technical challenges.
- **Power distribution Revision:** In-situ modifications to the PSEC sampling board (ACDC) and the addition of a power distribution board (LVHV) which operate close to the LAPPD were required to reduce power draw and heating relative to original design. We are currently testing the second iteration of the LVHV board.
- **ACC/ACDC Firmware Revision:** The firmware for both the ACDC and the control board that operates outside the tank (ACC) were completely rewritten to introduce new features and increase operation speeds to meet ANNIE specifications.
- **Channel Self-trigger:** The current version of PSEC electronics being used for ANNIE has issues with the channel level self-trigger. A prototype board providing an alternate trigger has been designed and tested.

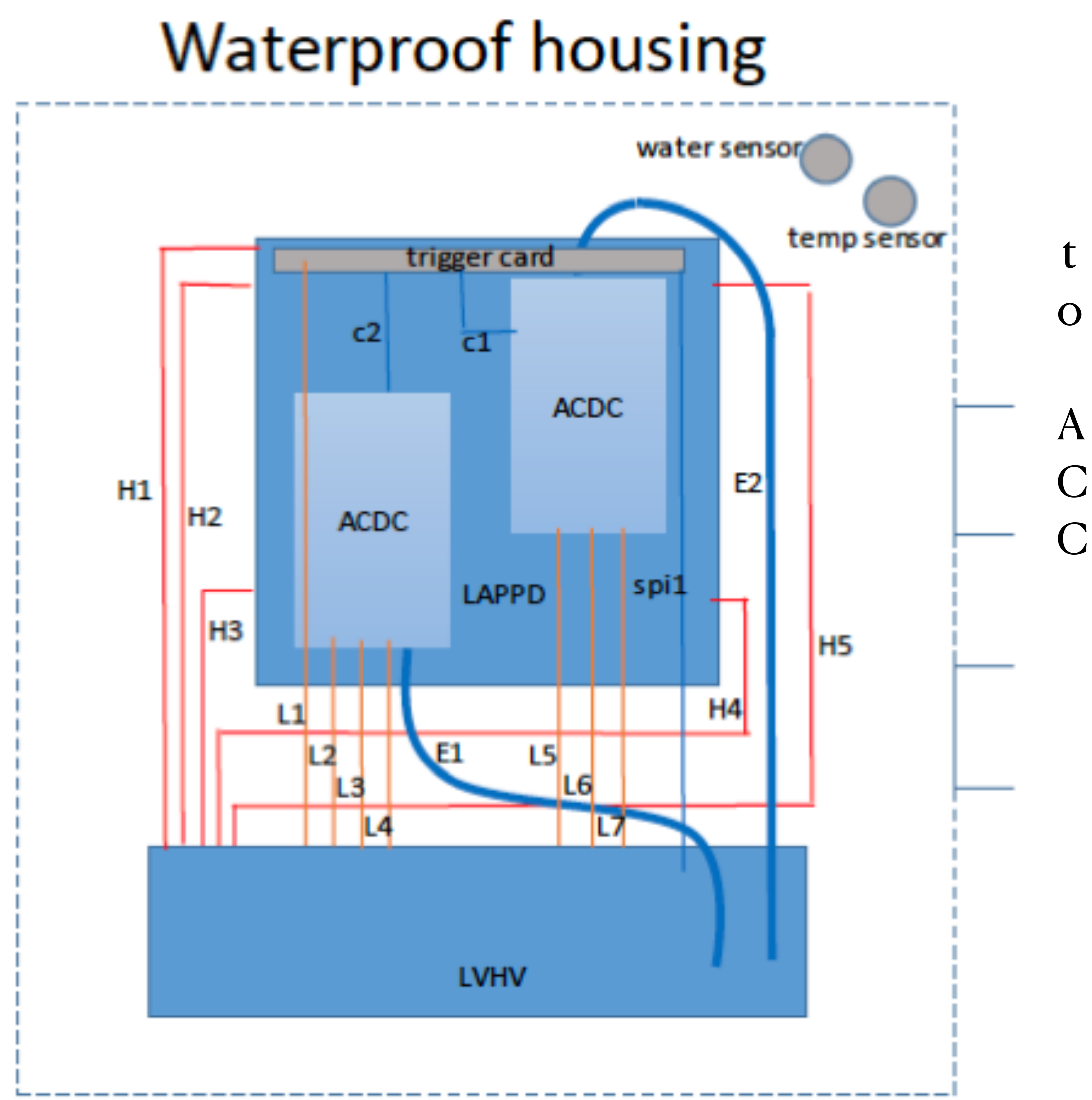


New triggers boards have been delivered and successful demonstration of LAPPD self-triggered readout with new Trigger Board

Redesigned LVHV boards have been delivered and are currently being integrated

LAPPD PSEC Electronics

- The PSEC electronics were designed with a DC-coupled LVDS connection.
- Previous tests of ACC/ACDC communications over a the length of the waterproof cable were successful.
- However when power was added over the cable a number grounding and noise issues were made evident.
- A review of power, grounding, and communication lines in the electronics system was carried out and resulted in the redesign of the LVHV board with:
  - Better filtering on the power and ground lines
  - A new interface that enables AC coupling (instead of DC coupling) of the communication lines
  - Corresponding additional revisions to the ACC/ACDC firmware (completed)

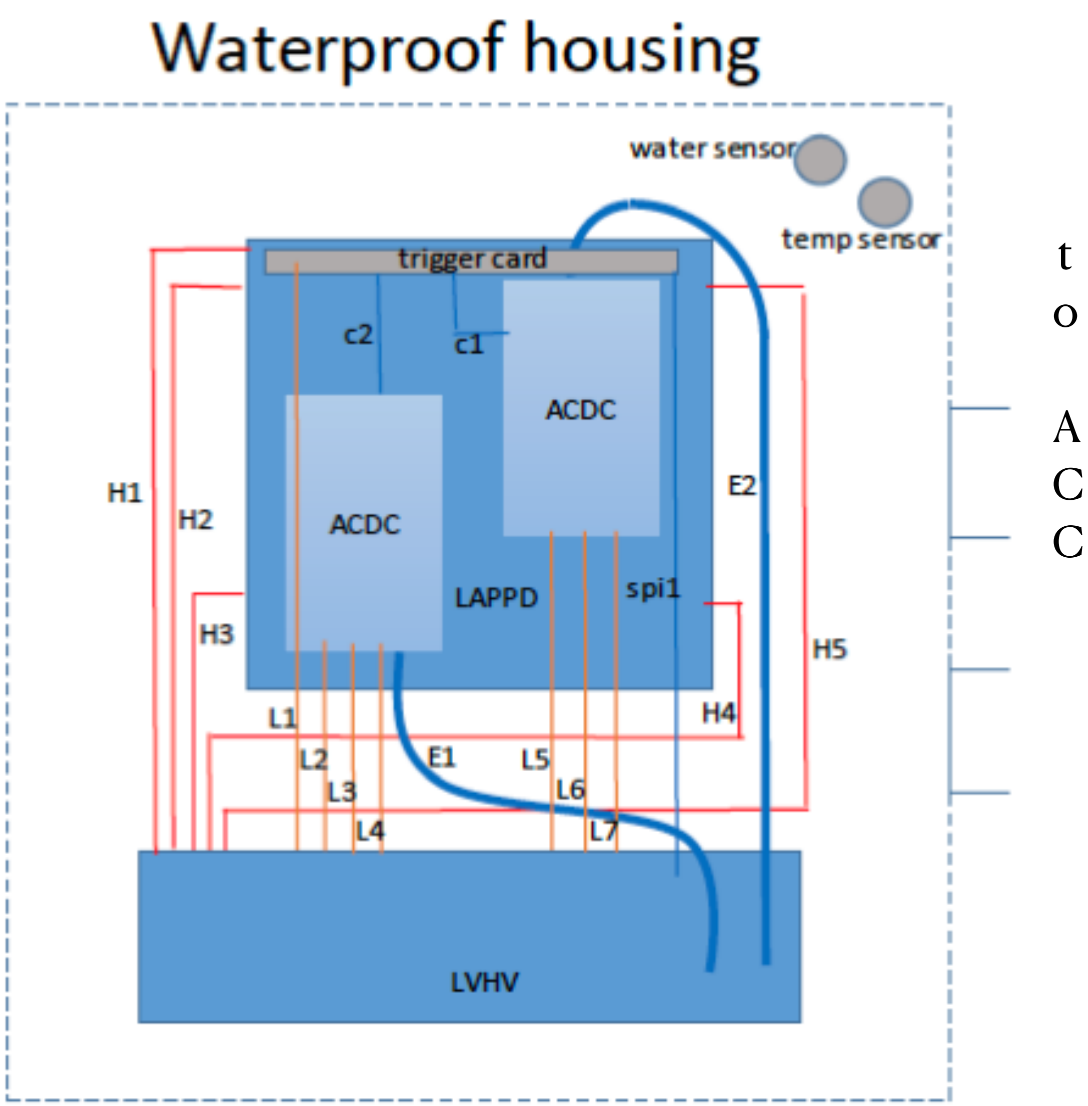


New triggers boards have been delivered and successful demonstration of LAPPD self-triggered readout with new Trigger Board

Redesigned LVHV boards have been delivered and are currently being integrated

LAPPD PSEC Electronics

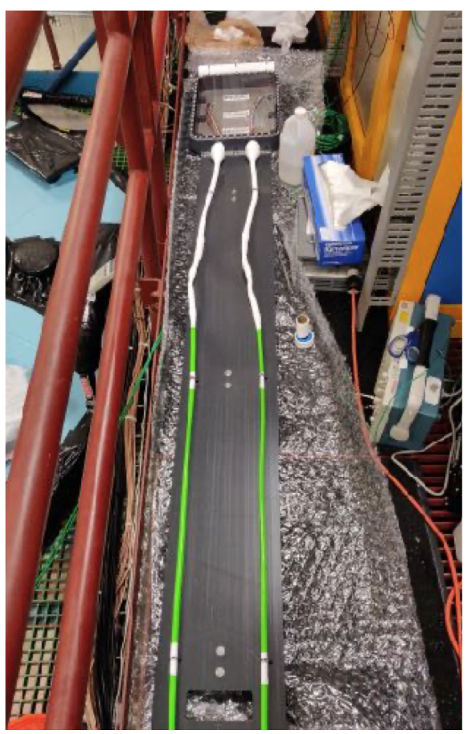
- The implementation and commissioning of PSEC electronics for ANNIE presented several technical challenges.
- **Power distribution Revision:** In-situ modifications to the ACDC and the addition of LVHV board were required.
- **ACC/ACDC Firmware Revision:** The firmware for the ACDC and ACC were completely rewritten.
- **Channel Self-trigger:** A trigger board was designed and tested.
- **Redesign of the LVHV:** with an interface that enabled AC coupling for tank to surface communication.

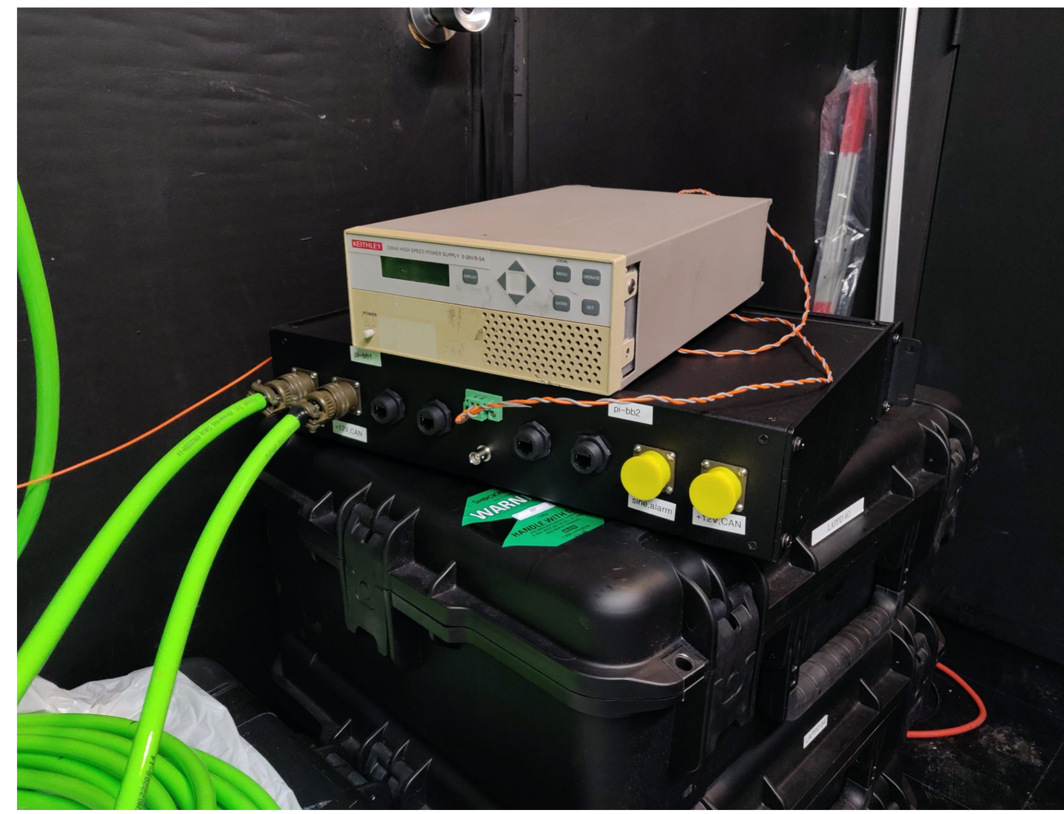


Currently undergoing full system integration test in Lab 6

LAPPD Housings and Interface Electronics

- Successful test deployment of housing in Spring 2021. All housings are in hand.
- Break out Boxes (BoB) provide slow controls, interface between surface electronics, power and waterproof cable.
- Falmat waterproof Ethernet cables connect BoB to waterproof housing containing LAPPD & readout electronics.
- Fit test of PSEC electronics in housing.

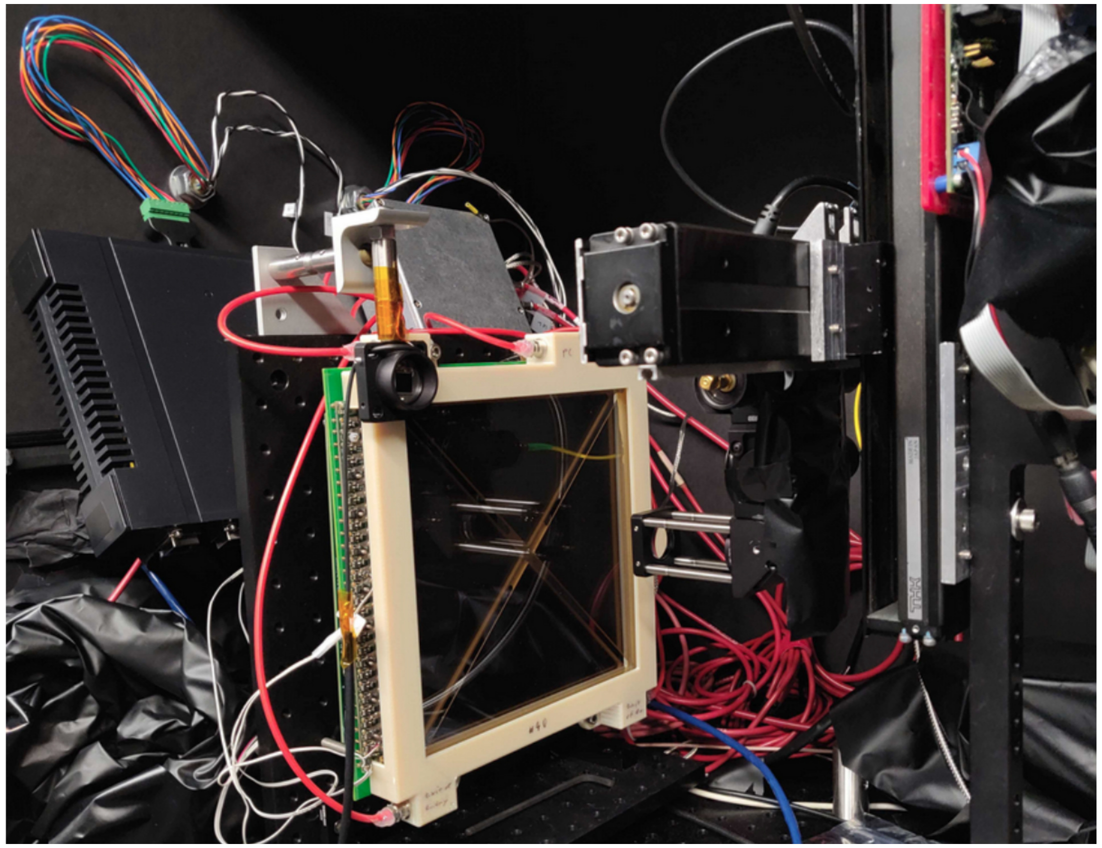


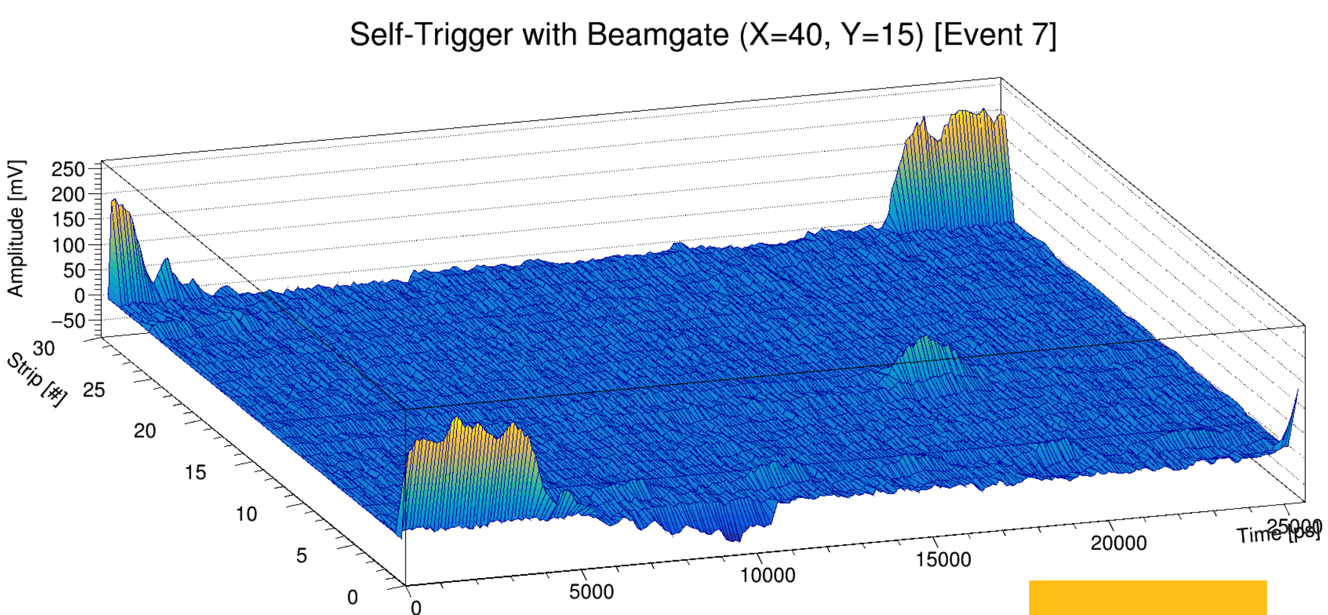


LAPPD surface Breakout Box

LAPPD On-site Integration tests

- Currently undergoing full system integration test in Lab 6, including waterproof cables.
- New trigger boards have been delivered and successful demonstrated LAPPD self-triggered readout.
- Redesigned LVHV boards have been tested, delivered and are currently being integrated .
- Full system integration test in Lab 6, including waterproof cables
  - First test of AC coupled communications. Seeing some communication noise at the moment.

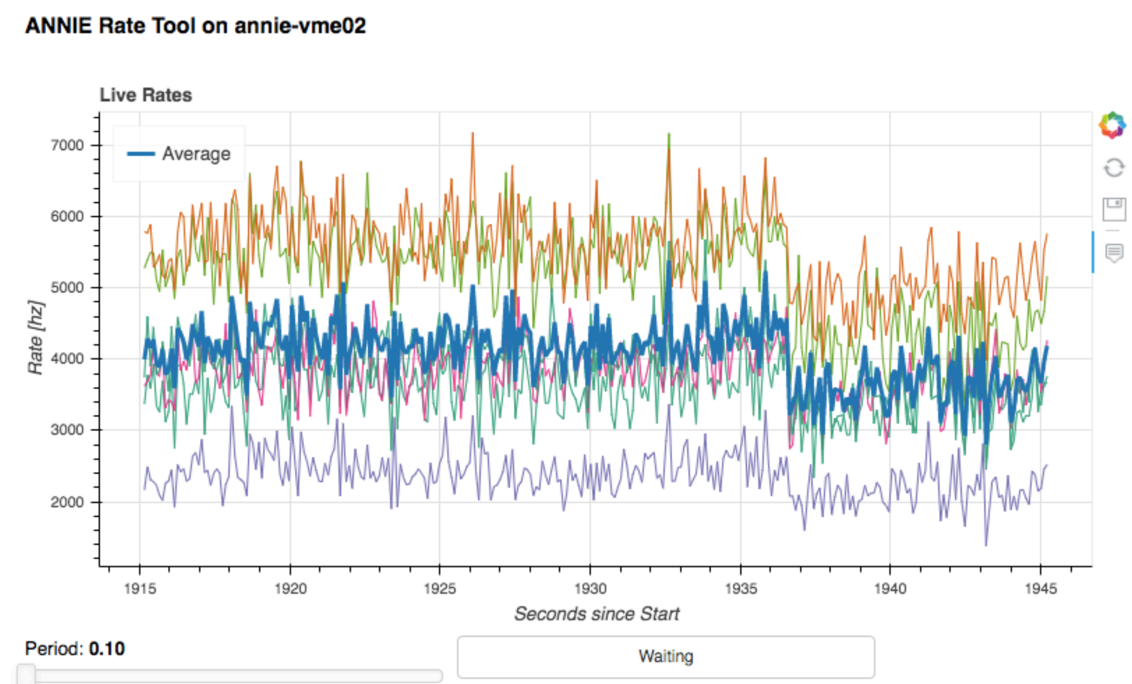




NEW!

ANNIE DAQ & Electronics

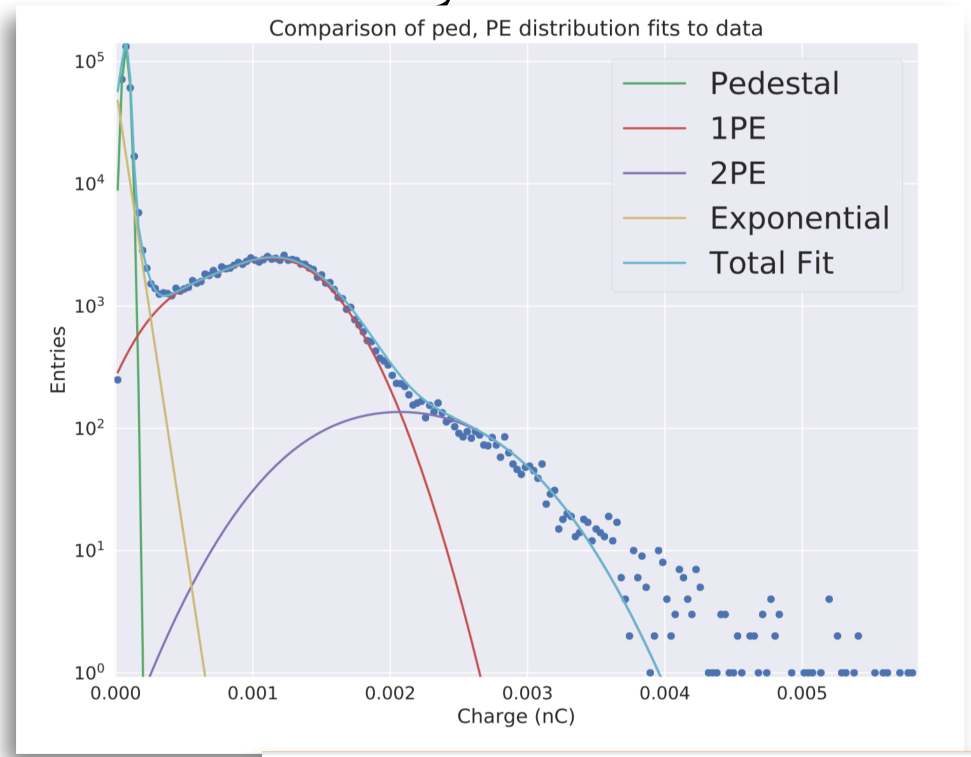
- The ANNIE DAQ consisted of 3 parallel systems:
  - The PMT readout uses flash ADC cards developed by the KoTO collaboration with firmware newly rewritten for ANNIE.
  - The MRD uses the same CAMAC system employed by SciBooNE.
  - Timing and trigger logic are handled by the ANNIE central trigger card.
- The parallel data streams from these systems is managed by the ToolDAQ software framework.
- Operated stably over the last beam period.

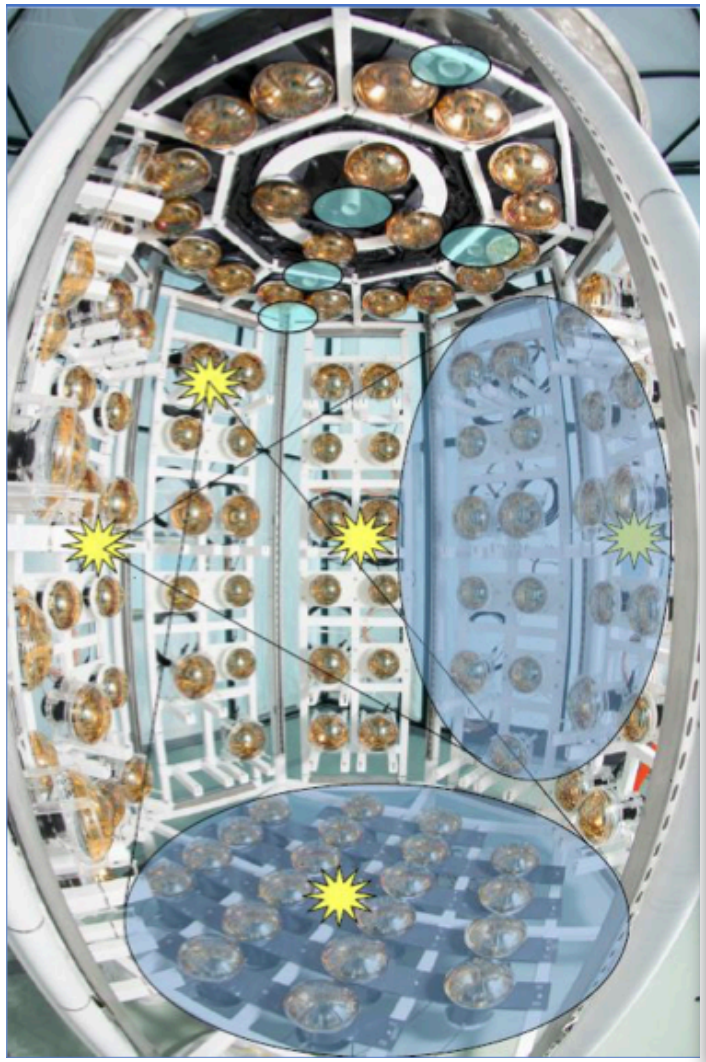


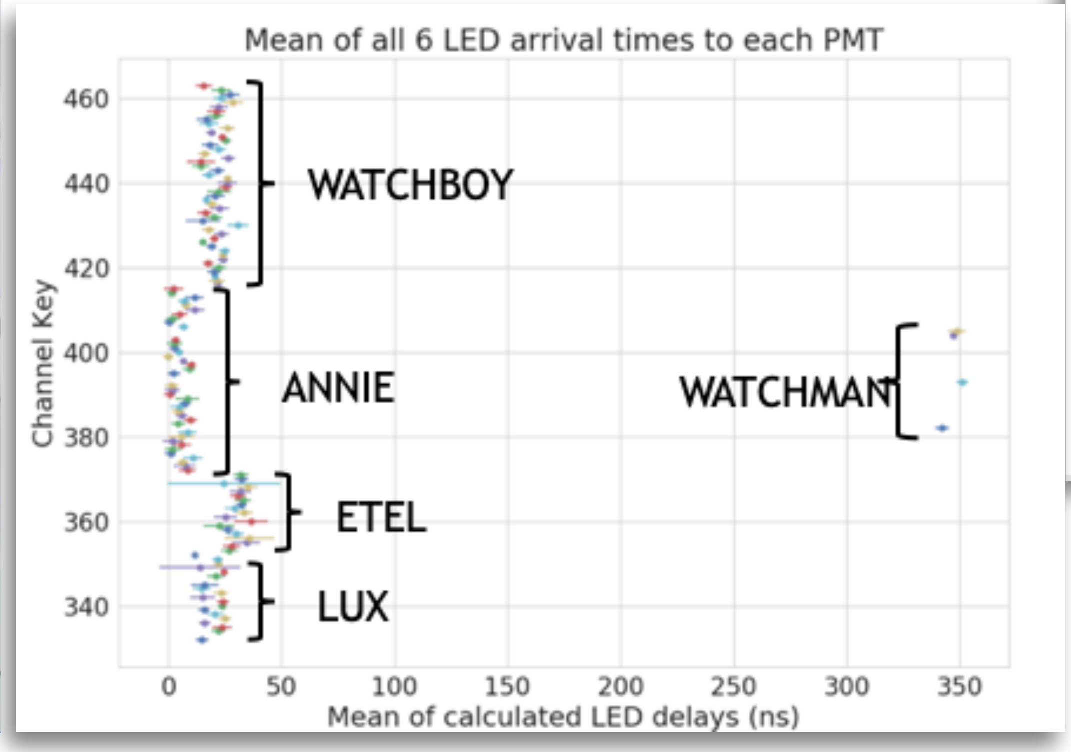
- Most recently updated DAQ to enable LAPPD readout:
  - Upgraded DAQ and trigger system for streaming operation.
  - Added a 4th asynchronous data stream for LAPPDs.
  - Validated and tested new LAPPD DAQ readout with simulated hardware.
  - Added LAPPD monitoring system and laser trigger.

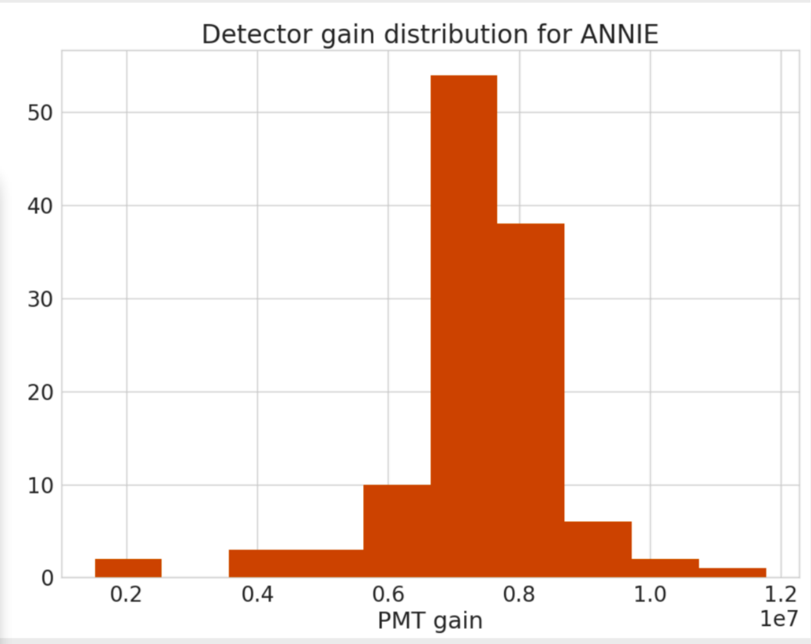
ANNIE PMT Calibration: LED system

- Have extracted single PE gain for each PMT.
- PMT voltages have been set for average gain of 7×10^6.
- Balance of good peak-to-valley ratios (1.5-2 throughout the detector) with reasonable dark rates (<10 kHz for most PMTs) .
- Cable delays have been determined with an uncertainty of 5 ns.



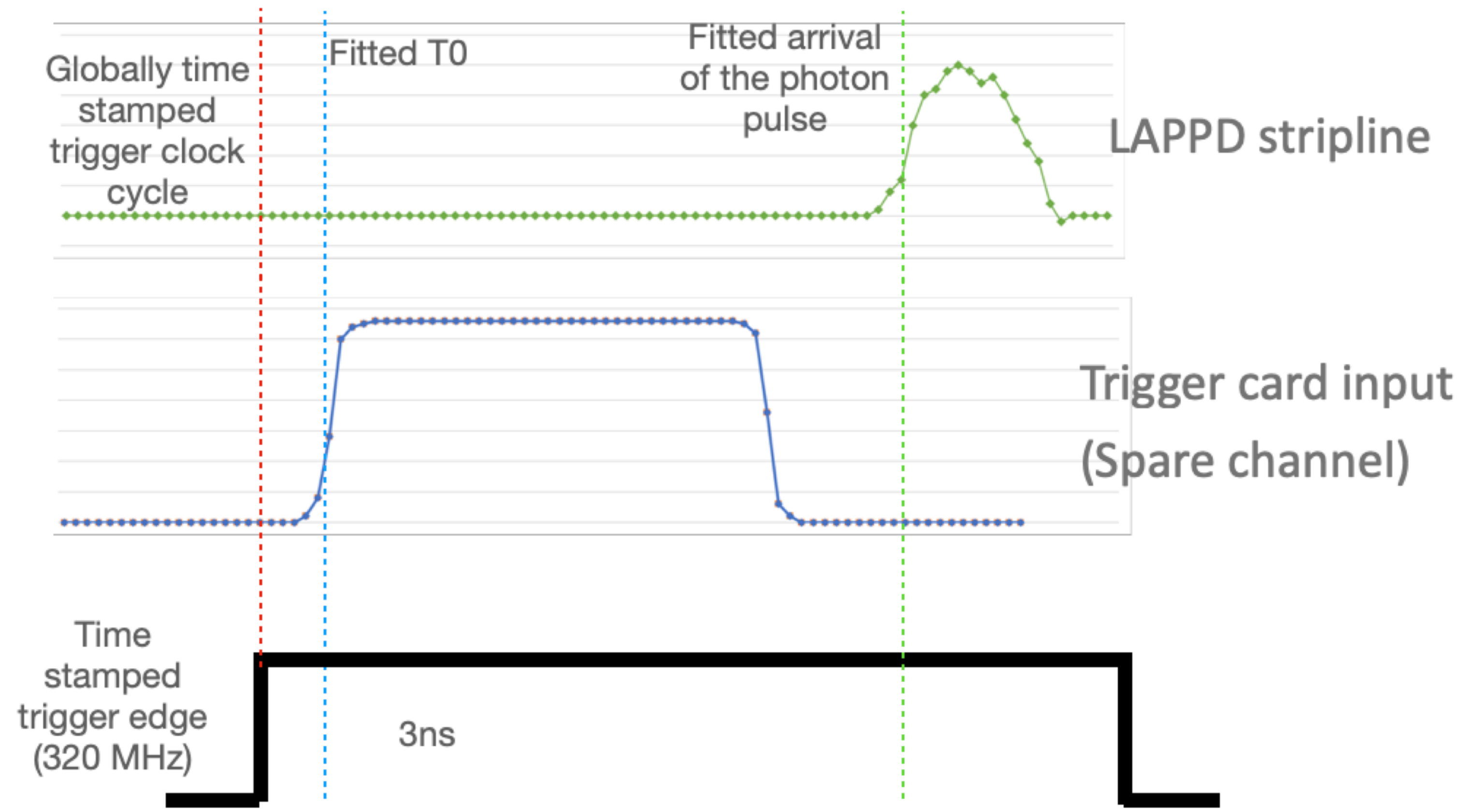






ANNIE LAPPD/PMT Calibration: Timing and Sync

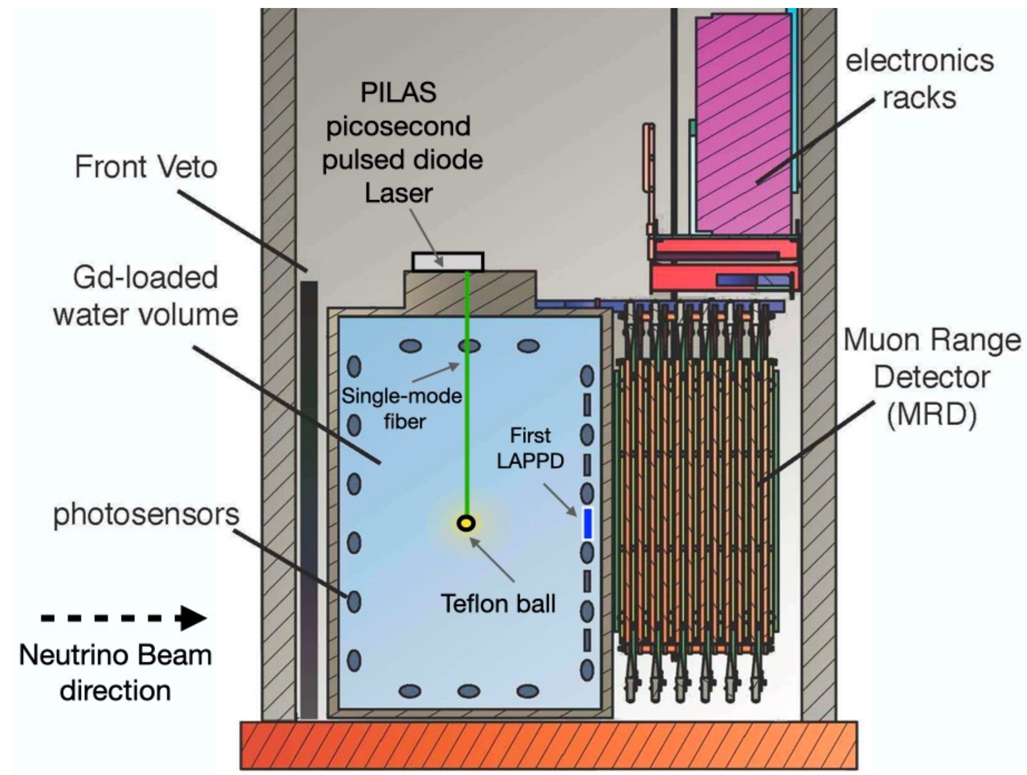
- All systems in the ANNIE detector are driven by a 125 MHz system clock, produced by a GPS-disciplined oscillator in the Central Trigger Card.
- All beam and calibration events initiated by the CTC (including the laser) are time-stamped and recorded by the DAQ.
- The CTC also sends a pulse-per-second (PPS) sync signal every GPS second to use for timing alignment.



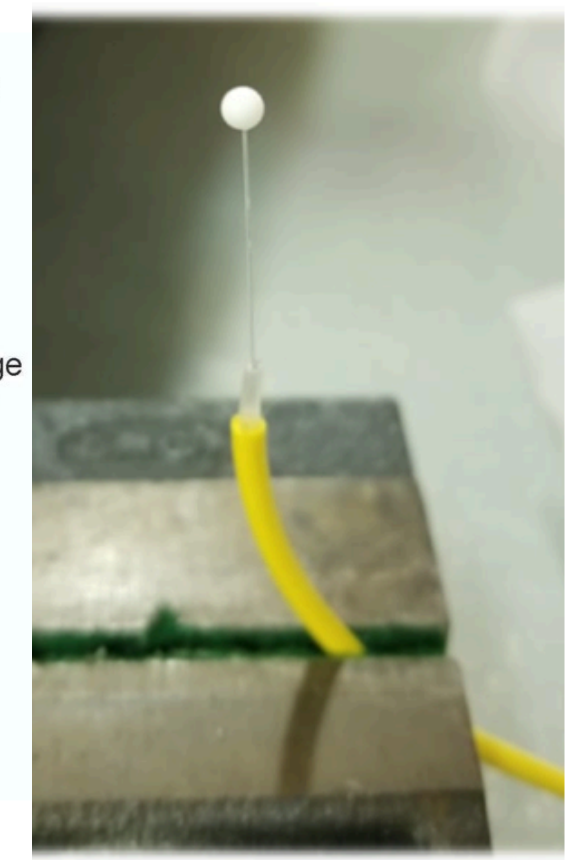
- The internal 40 MHz clocks of the LAPPD readout boards are latched onto the 125 MHz CTC clock with a phase-locked loop.
- The 40 MHZ is multiplied by 8 to provide a 320 MHz counter used to timestamp trigger events with a precision of 3 ns. An analog copy of this signal is used to fit for the exact arrival time of the triggers ith the 3 ns clock cycle.

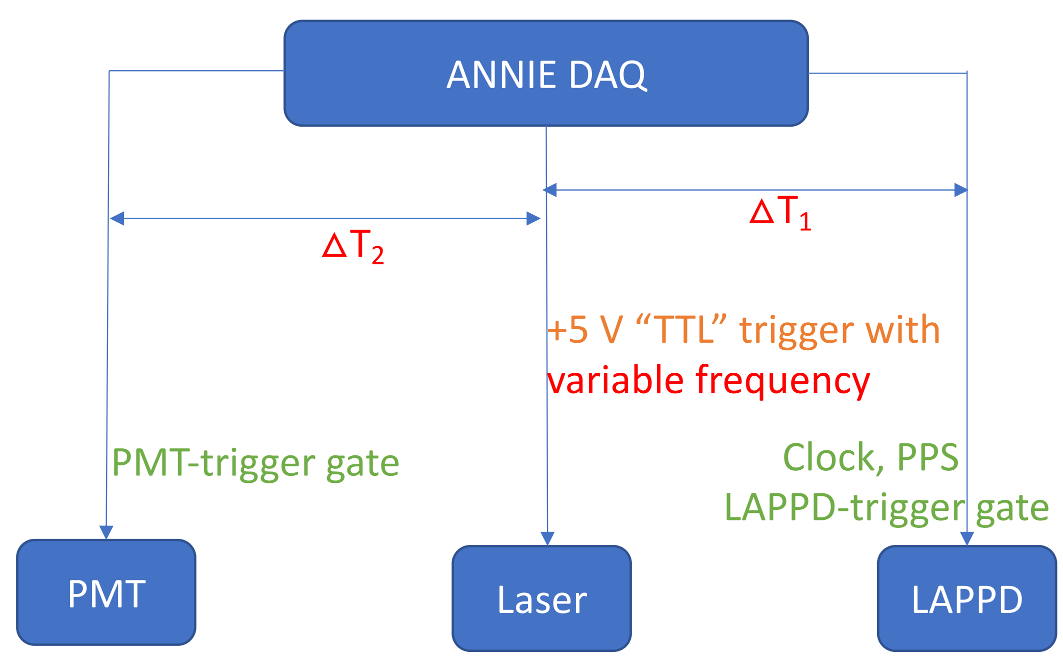
ANNIE LAPPD/PMT Calibration: Laser system

- Sub-ns timing for PMTs and Picosecond timing for LAPPDs requires cross-calibration.
- Laser system with diffuser ball to insert ultra-fast light pulses using 400 nm laser with each pulse train of 30 ps with 3 ps jitter.
- The laser can be triggered by the DAQ which also controls the gate signals for the PMT and LAPPD simultaneously.



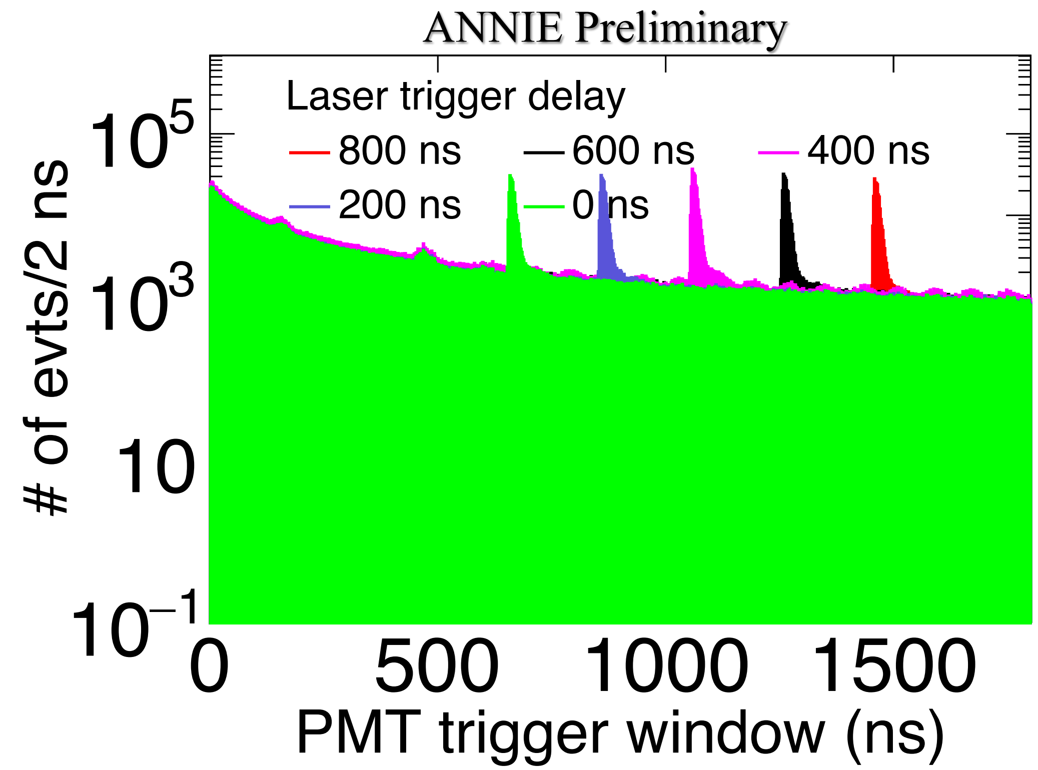
Laser setup in ANNIE Phase II detector

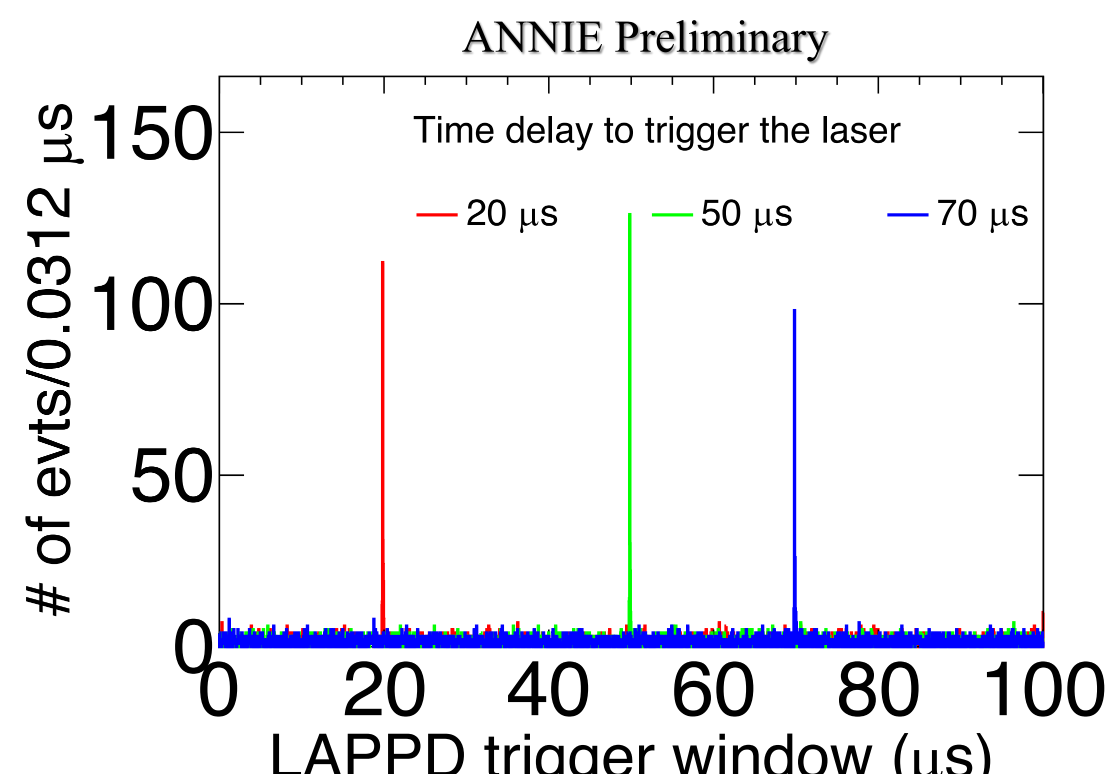




ANNIE LAPPD/PMT Calibration: Laser system

- The arrival time of PMT pulses as a function of time since the beginning of the trigger window initiated by the laser.
- The time-stamps of LAPPD self-trigger events relative to the trigger window initiated by the laser.
- The peaks correspond to laser induced signals above background for different delays.

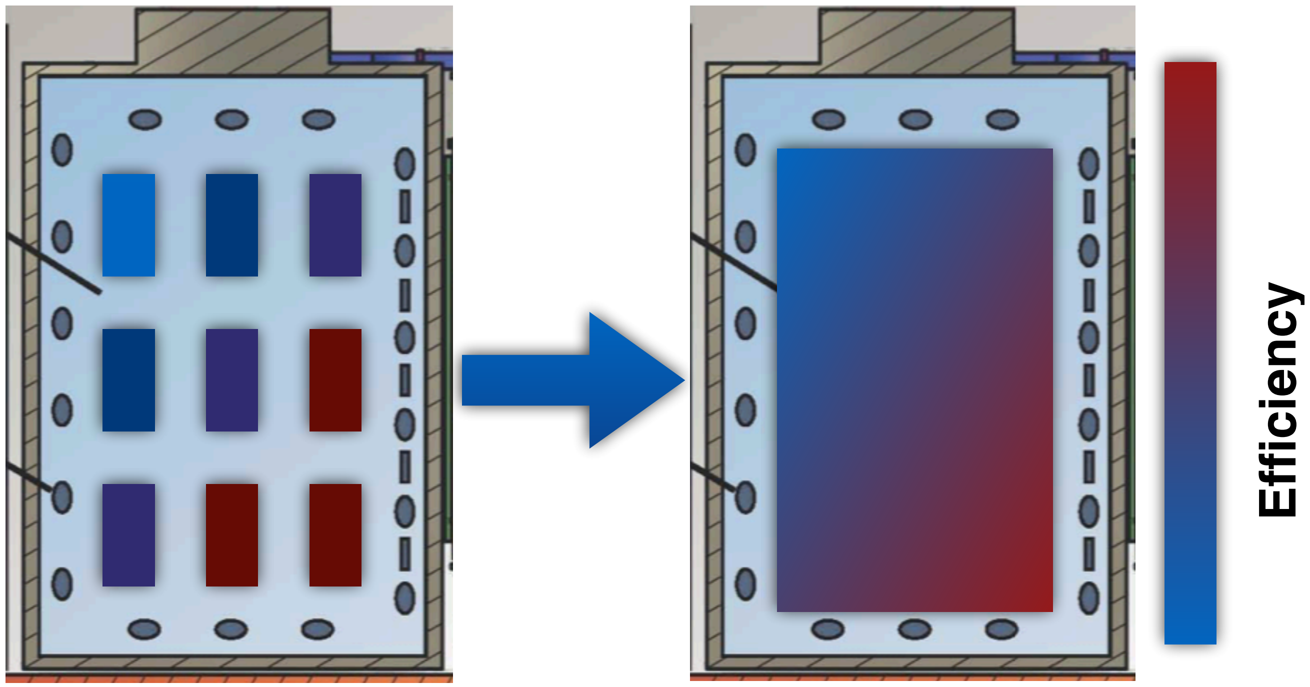




ANNIE Neutron Capture Calibration

- In order to achieve ANNIE's main goals, we must understand the position-dependent neutron capture efficiency.
- This efficiency can be mapped by deploying a neutron source at specific locations within the tank.
- Therefore we need a calibration source that produces a single neutron and that can be tagged.

To measure neutron multiplicities, ANNIE's position-dependent neutron detection efficiency must be well measured.

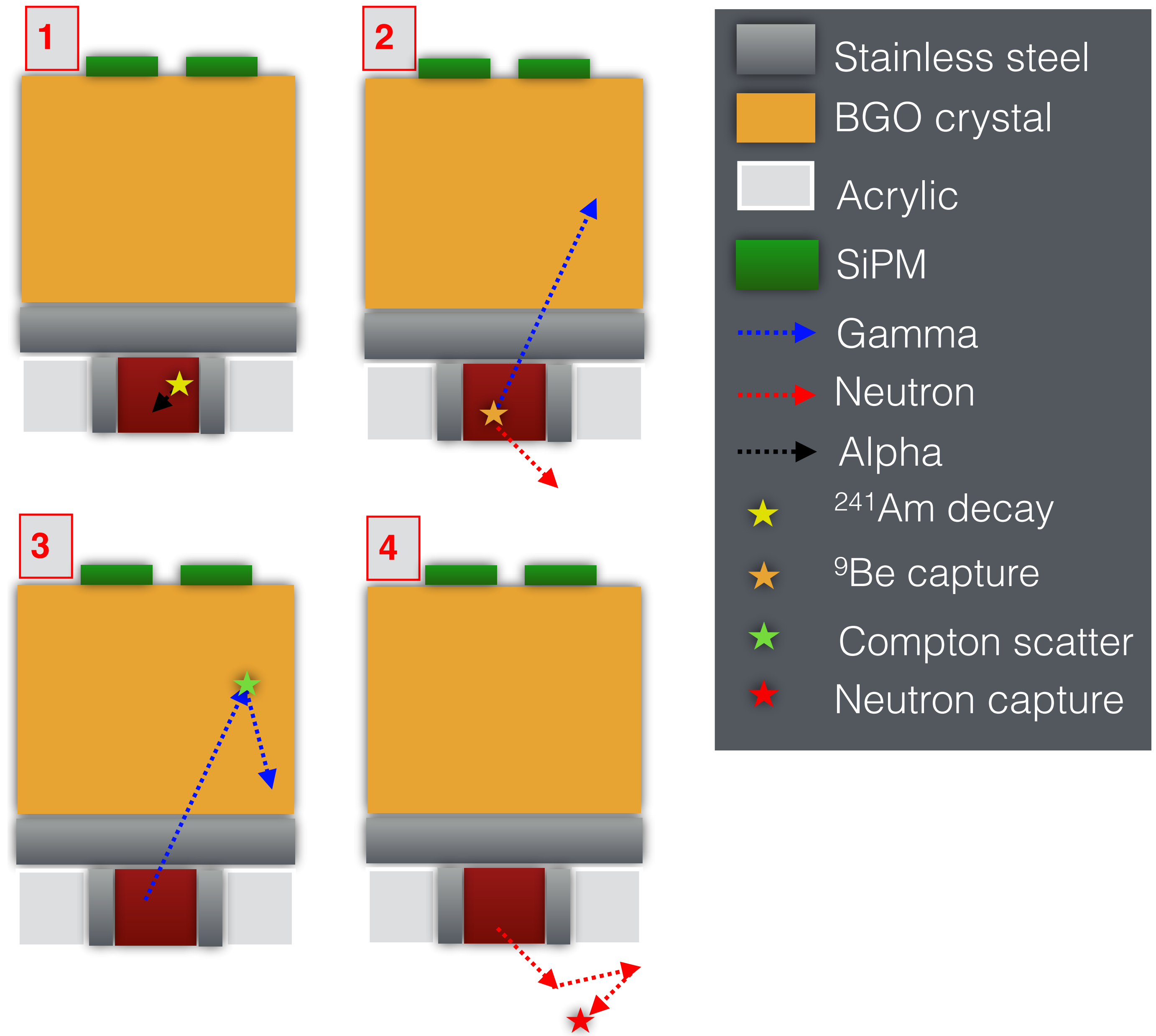


By placing a calibration source throughout the detector....

...the neutron capture detection efficiency will be mapped.

ANNIE Neutron Capture Calibration

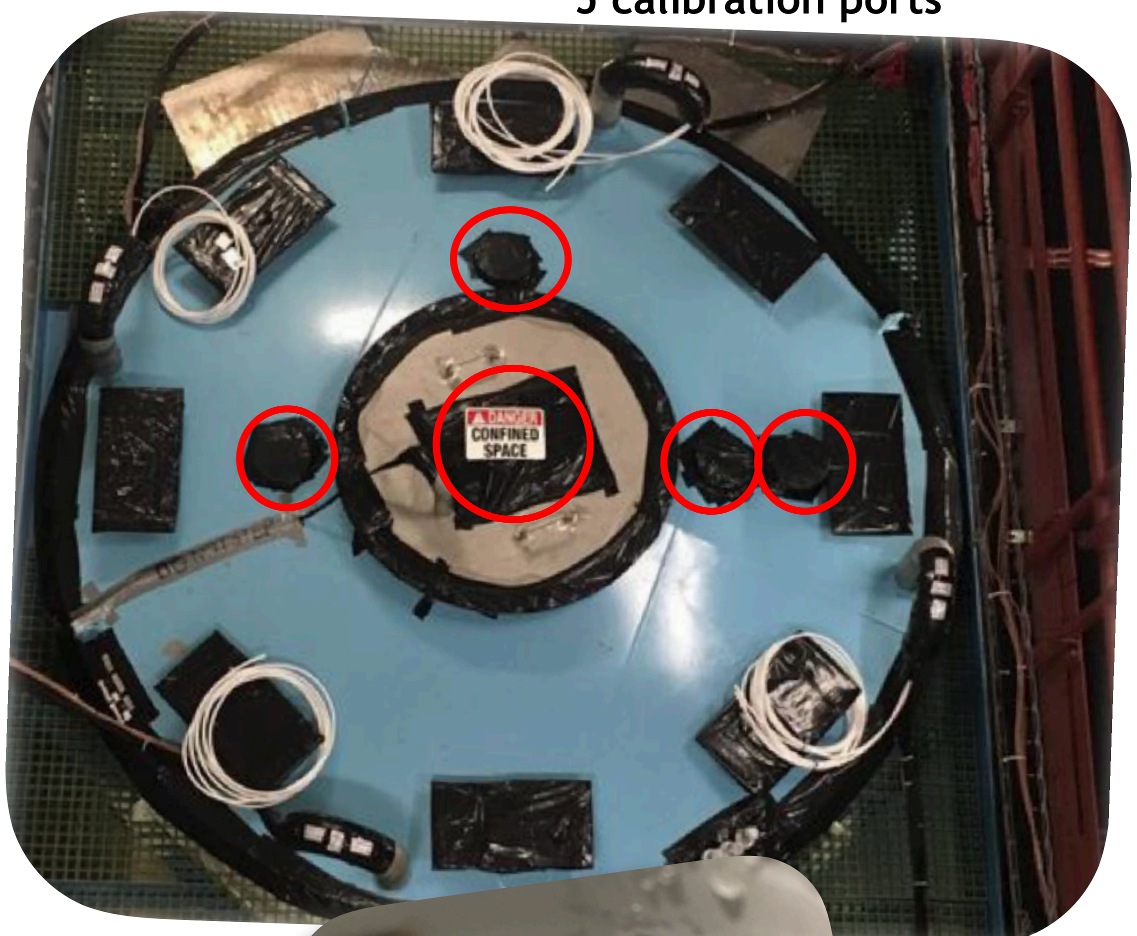
- An AmBe source, a mixture of ^{241}Am and ^{9}Be, produces a neutron and 4.44 MeV gamma.
- Two SiPMs and a bismuth germanium oxide (BGO) crystal are used to detect this gamma.
    - High yield of ~8500 photons per MeV, emitting in range of 375-650 nm (peak at 480 nm). Material density (7.13 g/cm3) increases Compton scatter likelihood.
- The neutron detection efficiency is determined by searching for the 8 MeV gamma cascade produced upon capture in the Gd water.



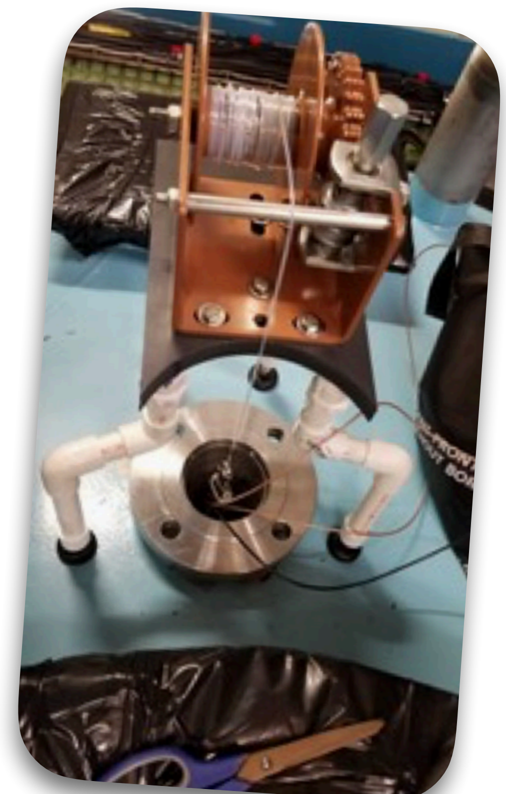
1. ^{241}Am decays to ^{237}Np via alpha emission (half-life = 432.2 yr).
2. ^{9}Be can capture the emitted alpha to produce ^{12}C* and a neutron. ^{12}C* produces a prompt 4.44MeV gamma.
3. 4.44 MeV gamma can Compton scatter in the BGO crystal - this gives us a trigger.
4. Neutron thermalises in ANNIE and is captured on Gd.

ANNIE Neutron Capture Calibration

5 calibration ports

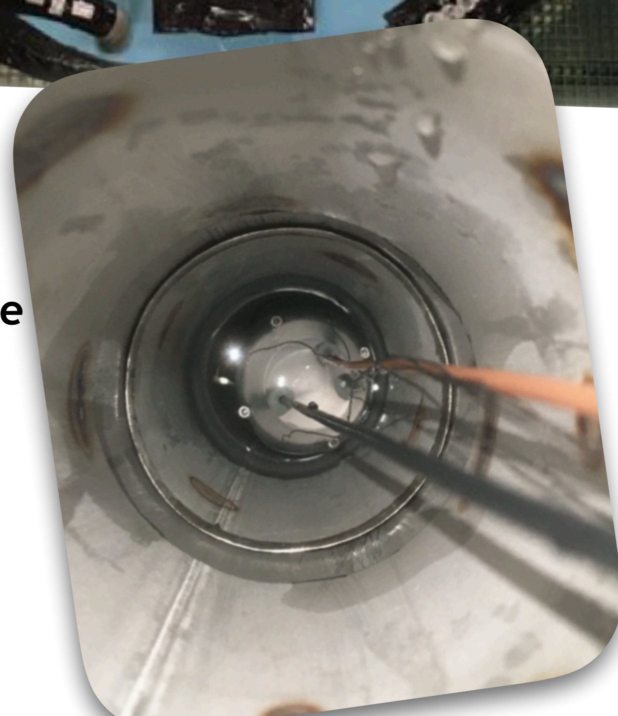


Deployment winch

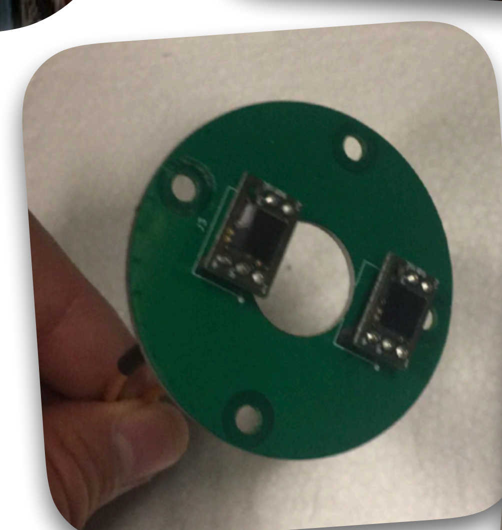


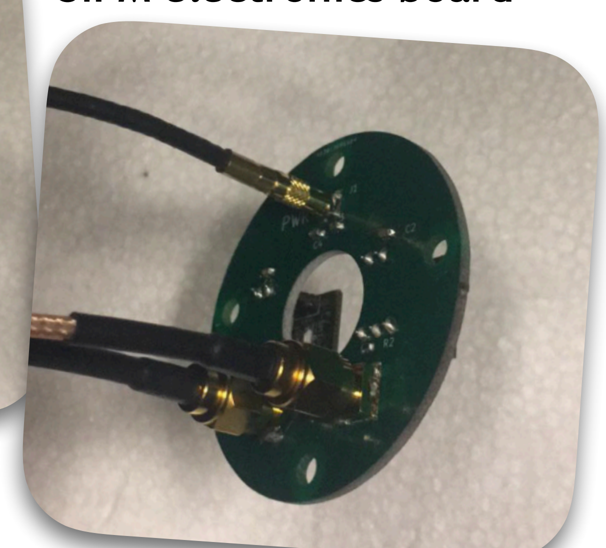
UVT acrylic container

Submerging the
AmBe source
container



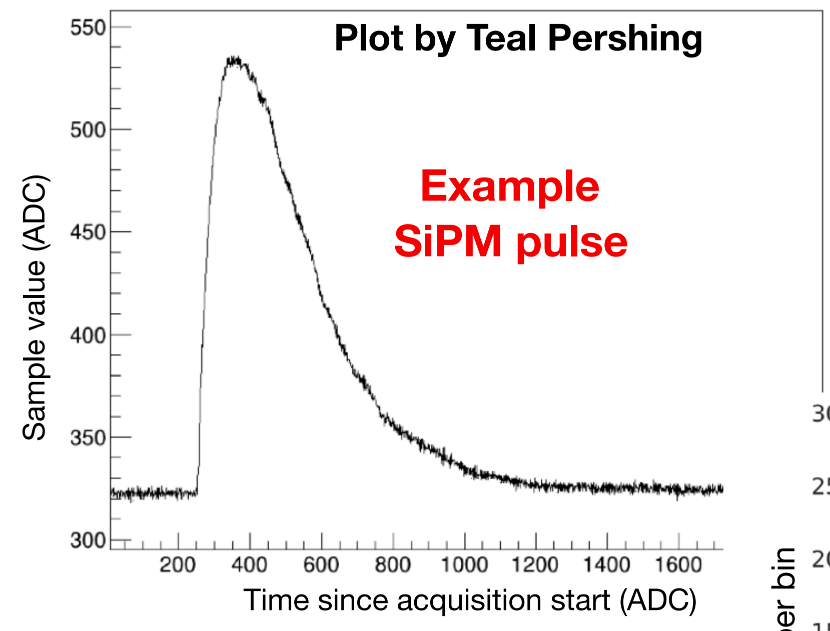
SiPM electronics board

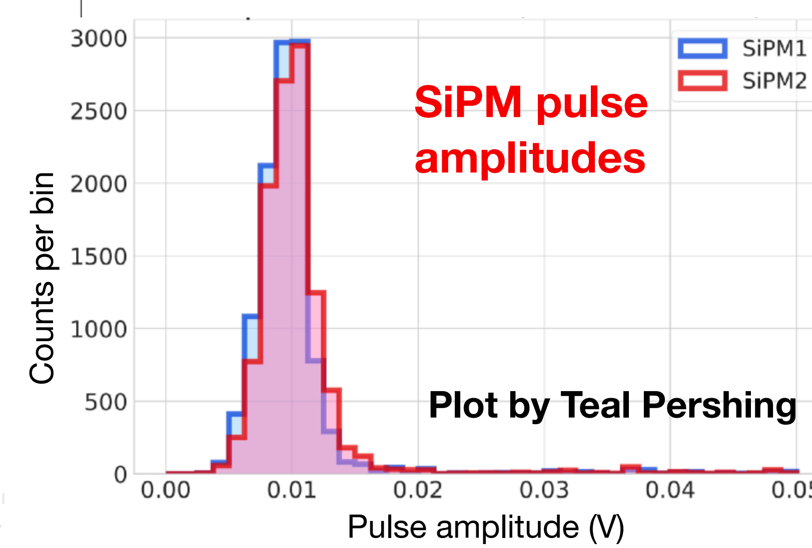


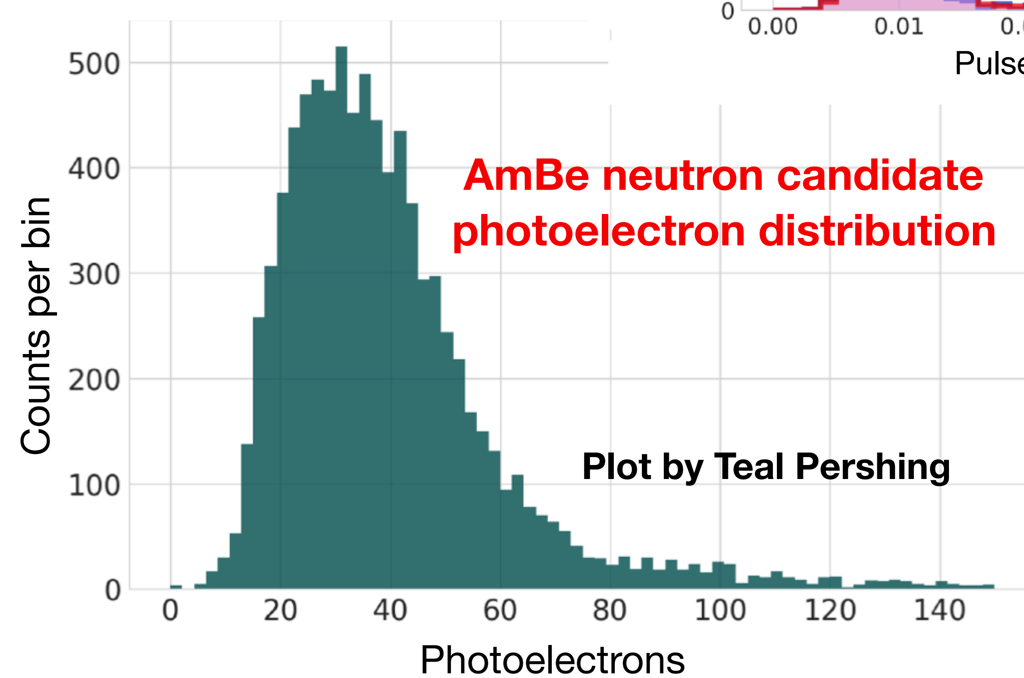


ANNIE Neutron Capture Calibration

- The data selection requires both SiPMs triggering in coincidence with 6 mV amplitude and no more than one pulse.
- No neutron candidates within 2 µsec of SiPM trigger in order to reduce through-going muon backgrounds.
- Selected signal requires 5 PMTs with a pulse within 50 ns.

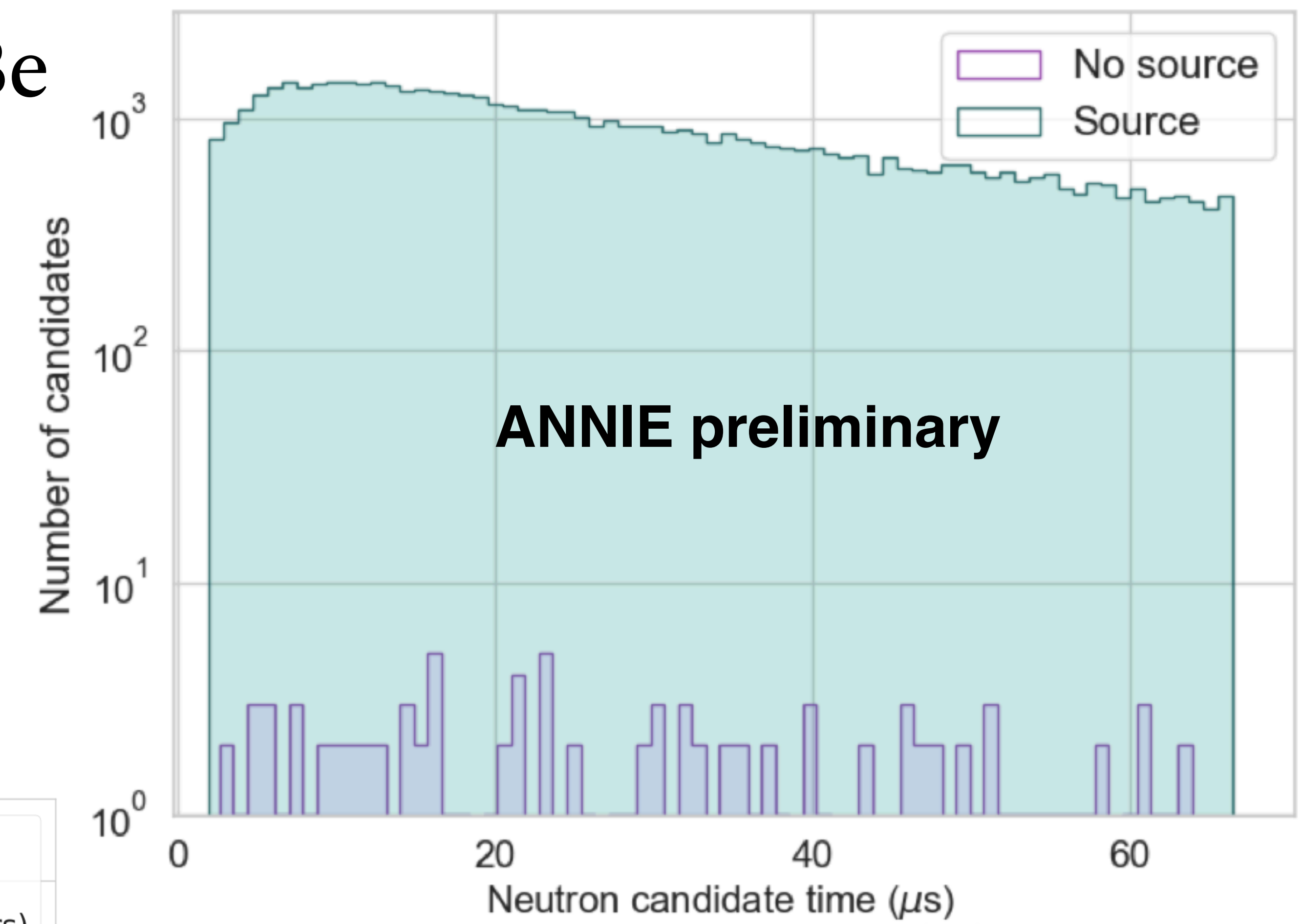


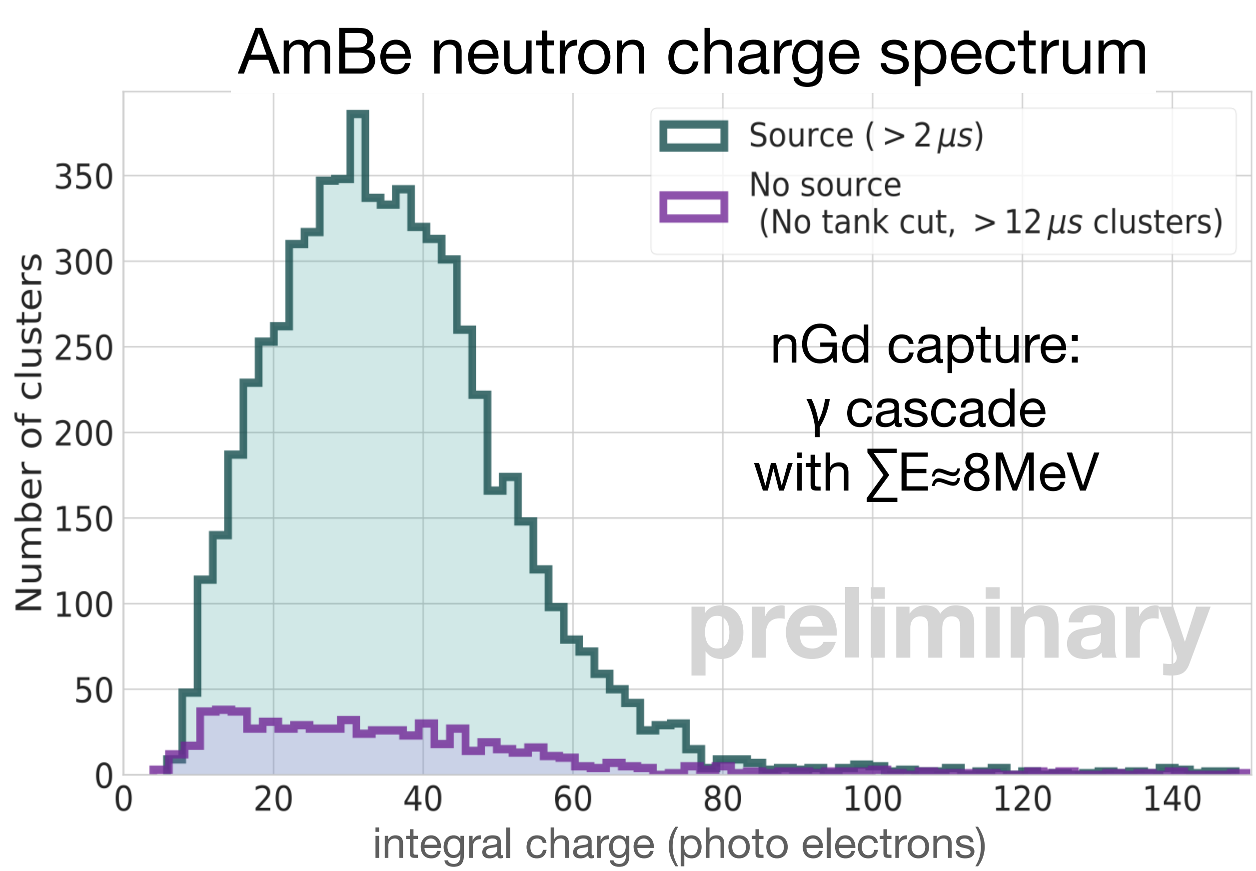




ANNIE Neutron Capture Calibration

- Deployment of a tagged AmBe neutron source inside the water volume.
- Selection cuts provide a pure neutron sample.





- Reconstructed neutron capture candidates with and without AmBe source deployed.

Modeling the neutron multiplicities to extract the true detection efficiency

Position dependent multiplicity

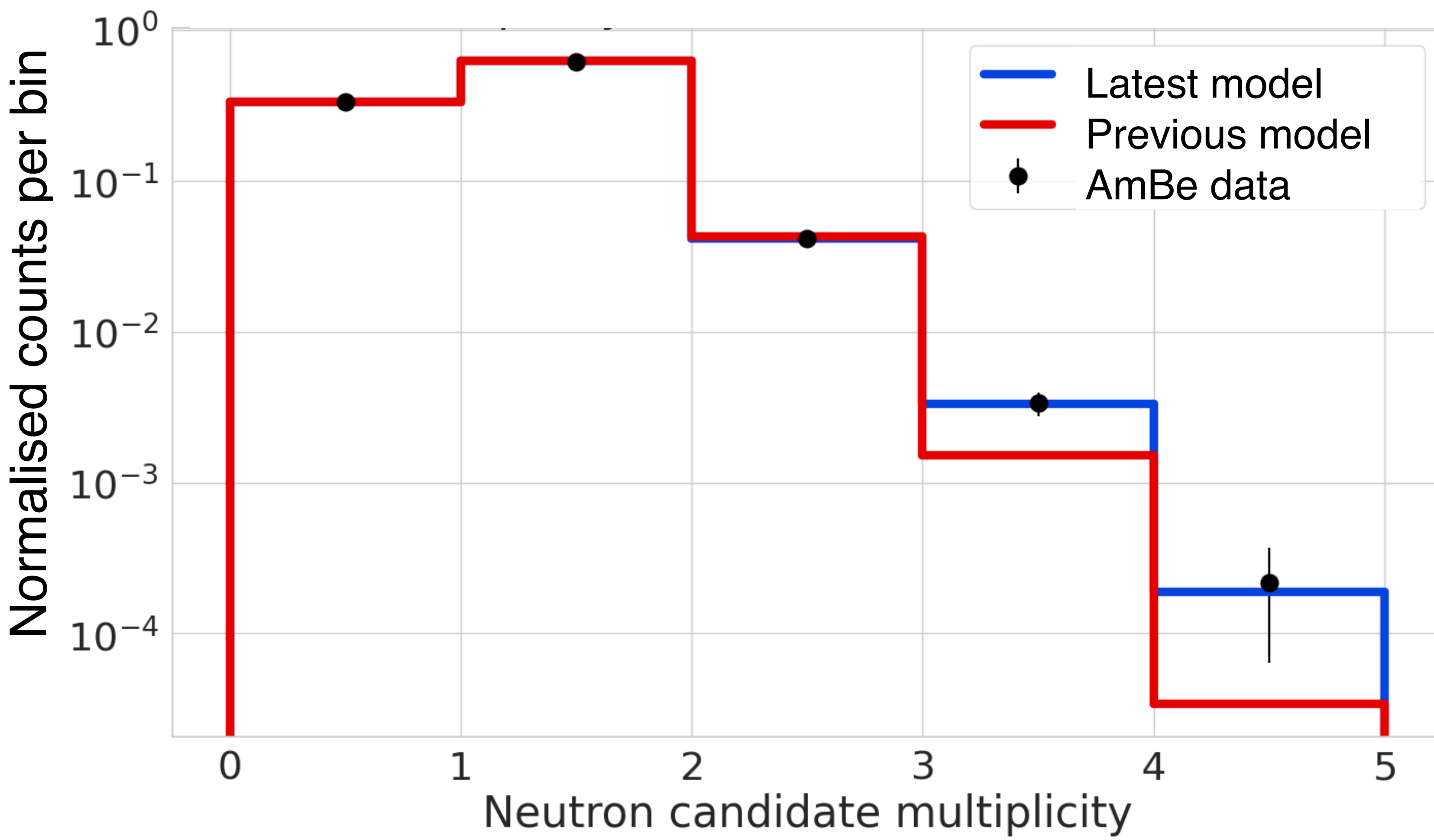
Uncorrelated background

Uncorrelated neutron-gamma pairs from AmBe source

$$M(x) = B(n;\epsilon_n) + \frac{\lambda_b^x e^{-\lambda_b}}{x!} + \frac{\lambda_{un}^x e^{-\lambda_{un}}}{x!} + \left(\frac{\lambda_\gamma^x e^{-\lambda_\gamma}}{x!} + M_{\gamma n}(n_\gamma)\right)$$

Bernoulli distribution for a given neutron detection efficiency

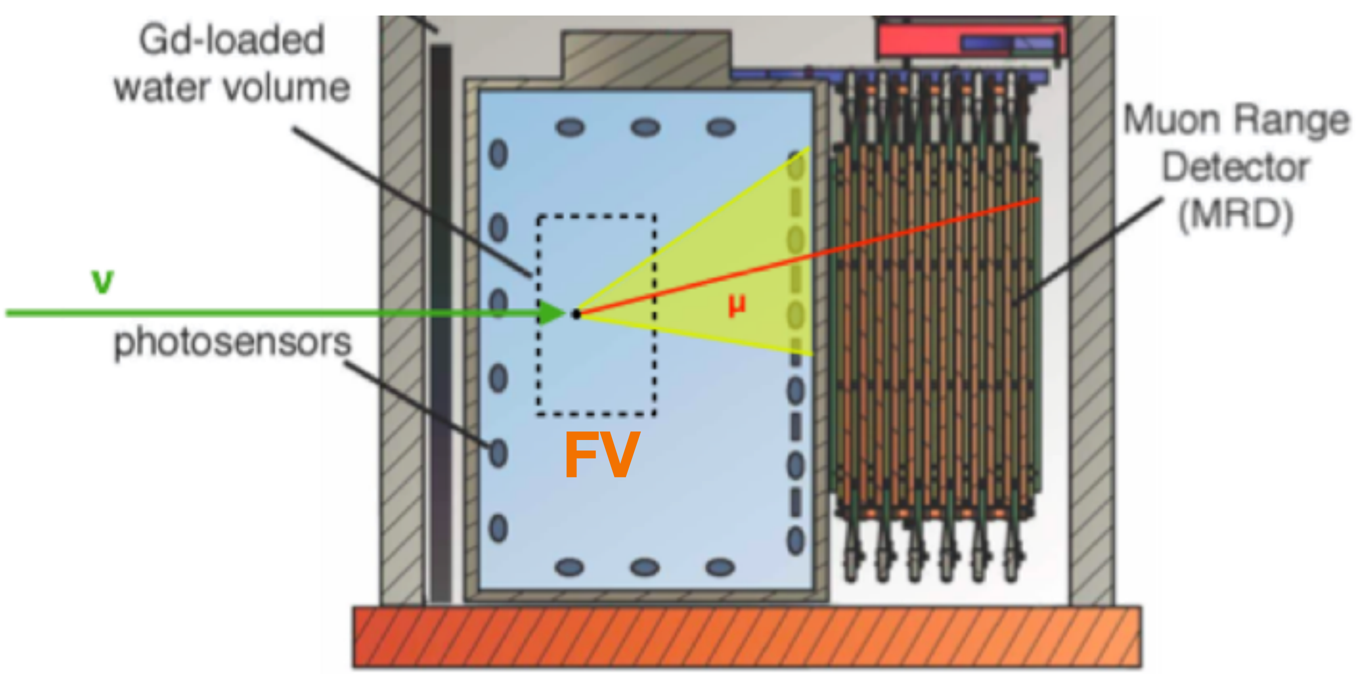
Uncorrelated neutrons from AmBe source

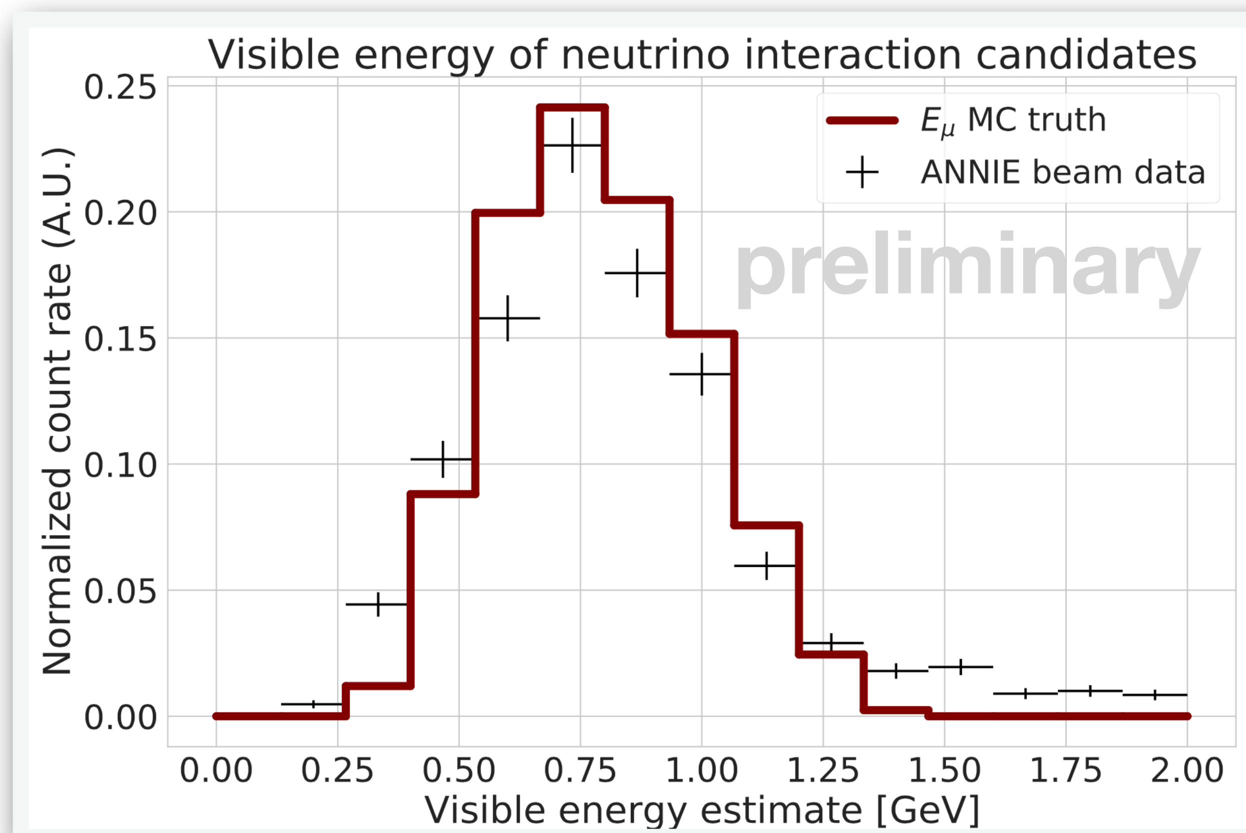


- By floating the background rates and efficiency the best fit to the multiplicity distribution can be found.
- A X^2 best fit is used to determine the free parameters.
- The corresponding efficiency is calculated on a position-by-position basis.

Reconstructing energy in CCQE events

- Muon energy reconstruction in ANNIE relies on PMT light pattern and the track information of the MRD.
- We define a fiducial volume (**FV)** to optimize detection efficiency for subsequent muons.
- Current reconstruction algorithms nicely reproduce in **data** the expectation from detector **MC.**

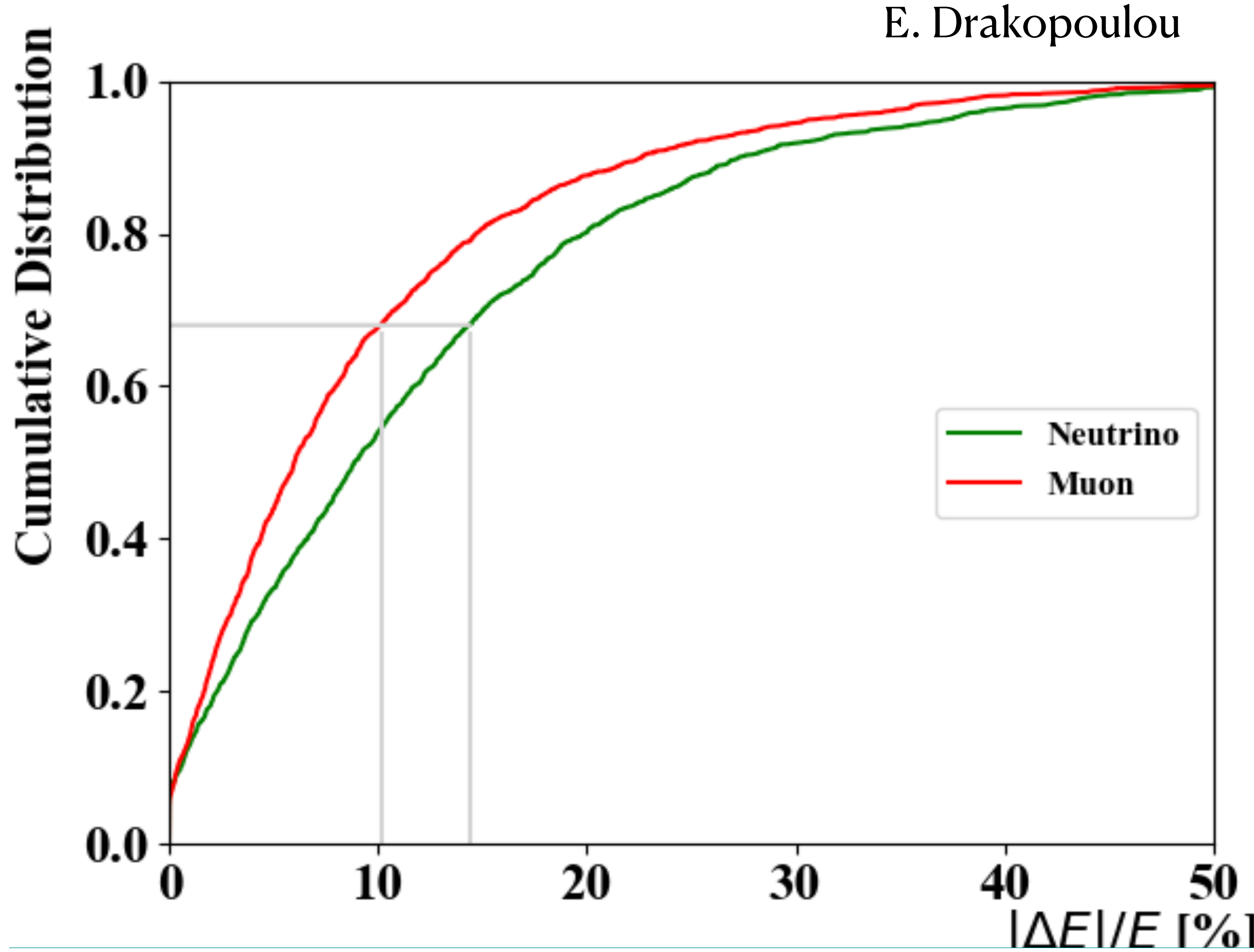




Reconstructing energy using Deep Learning

- Improvements over standard reconstruction using the muon track length in a Deep Learning Neural Network and then passing it to a Boosted Decision tree with other variables allows to reconstruct muon and neutrino energy.
- The resulting muon and neutrino energy resolution at the 68th percentile are 10% and 14% respectively.

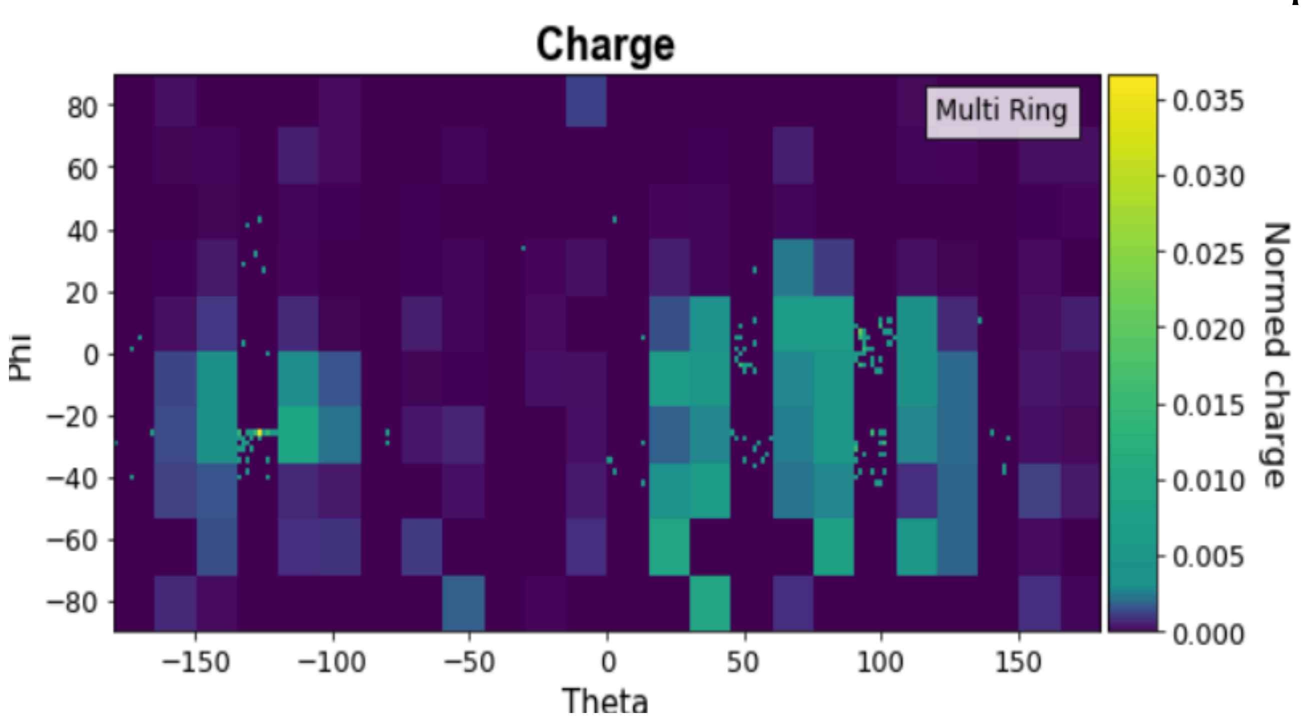
E. Drakopoulou

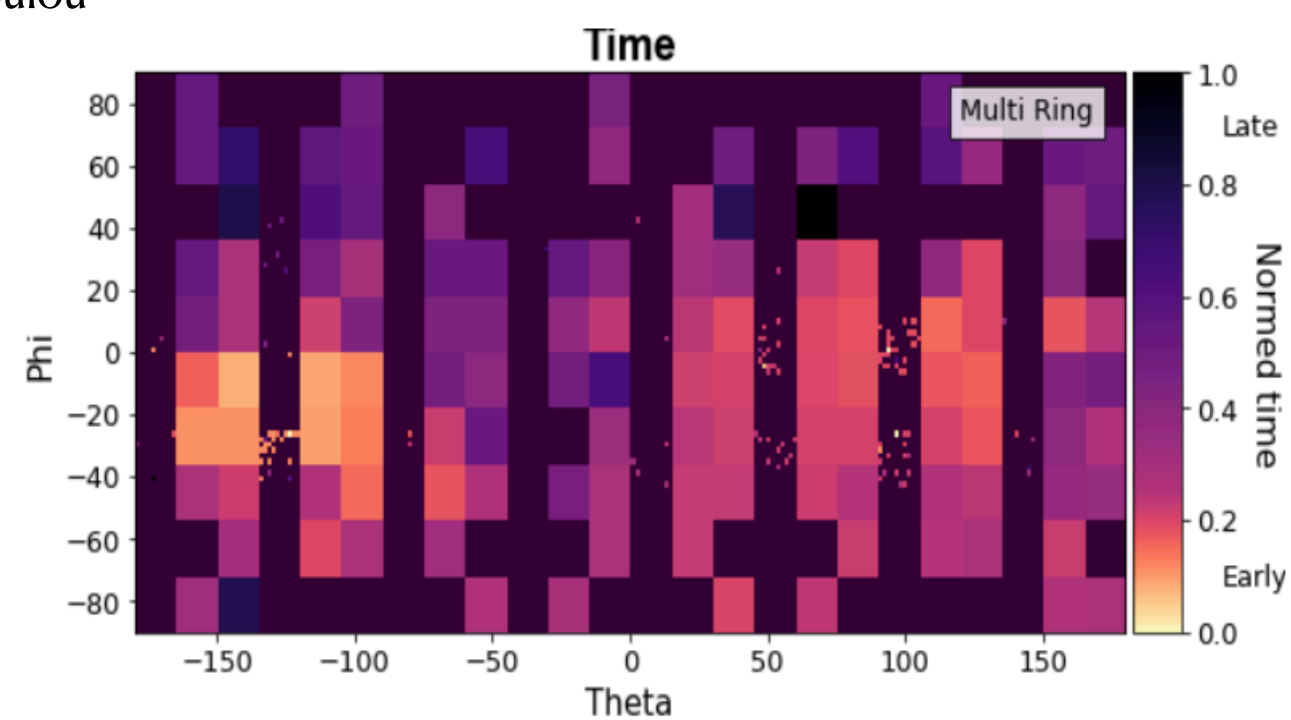


Reconstructing energy using Deep Learning

- Deep Learning is also used in the selection of Charged Current 1μ-0π sample using two Convolution Neural Networks.
- The first CNN selects events with a single particle track (single-ring) versus multiple tracks (multi-rings). Accuracy of ~81% on single-ring events.
- The second CNN discriminates between muon and electrons with an accuracy of 94%.

E. Drakopoulou





Input image for multi-ring event for the convolution neural net in charge and time with respect to angle.