News from the ANNIE Experiment: LAPPDs

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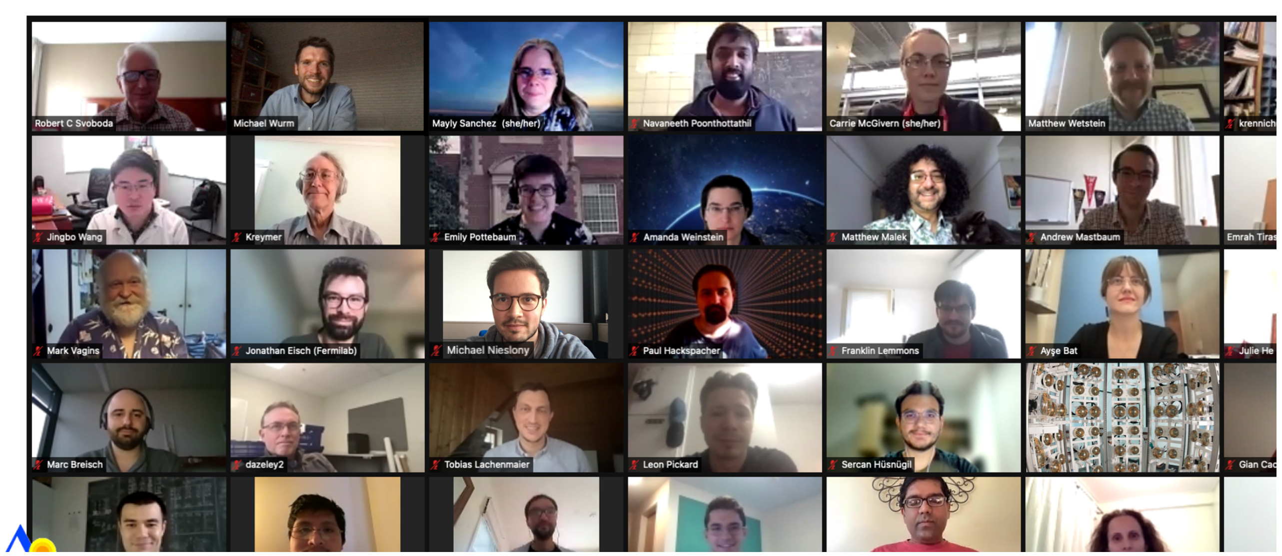
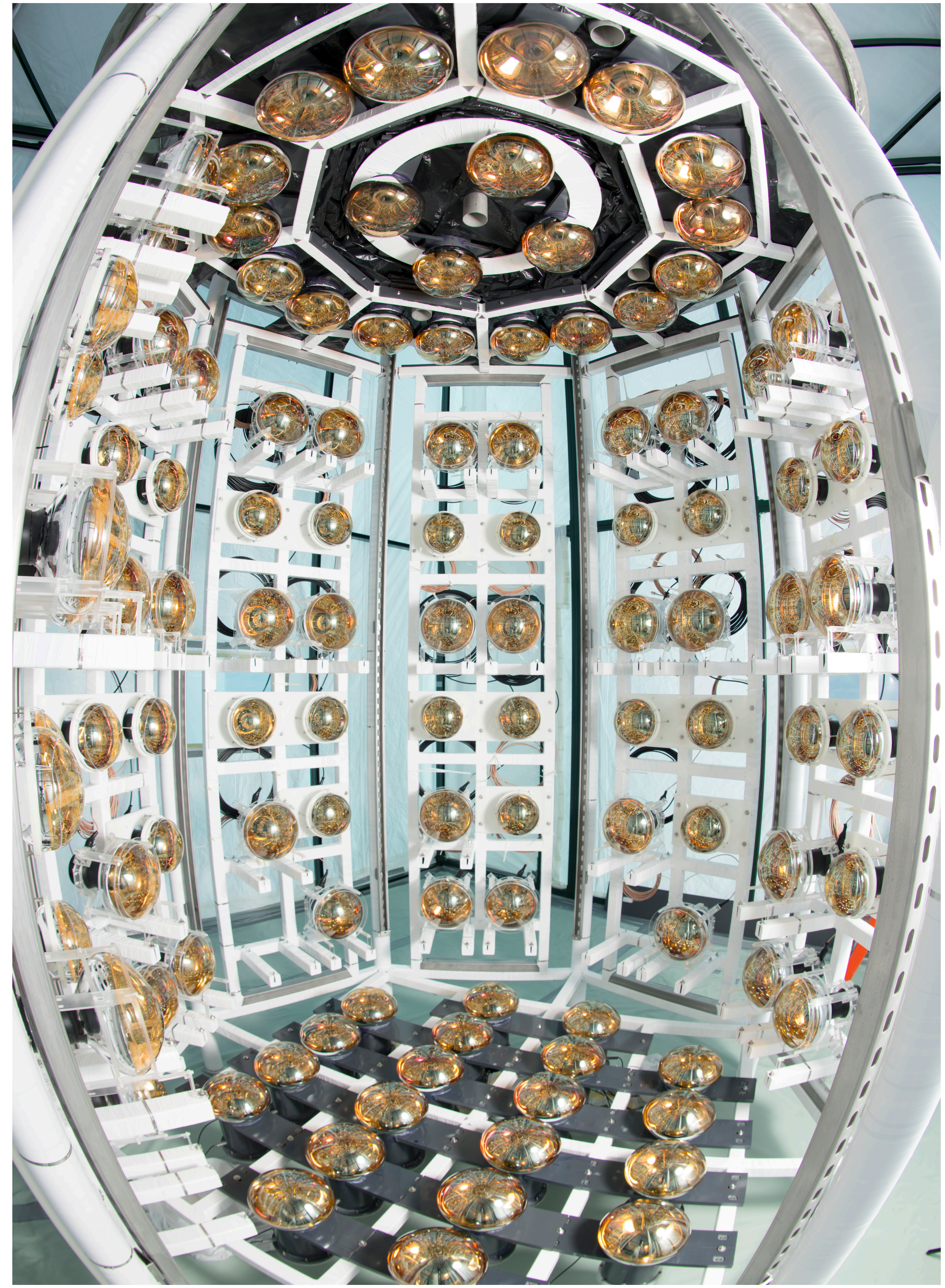




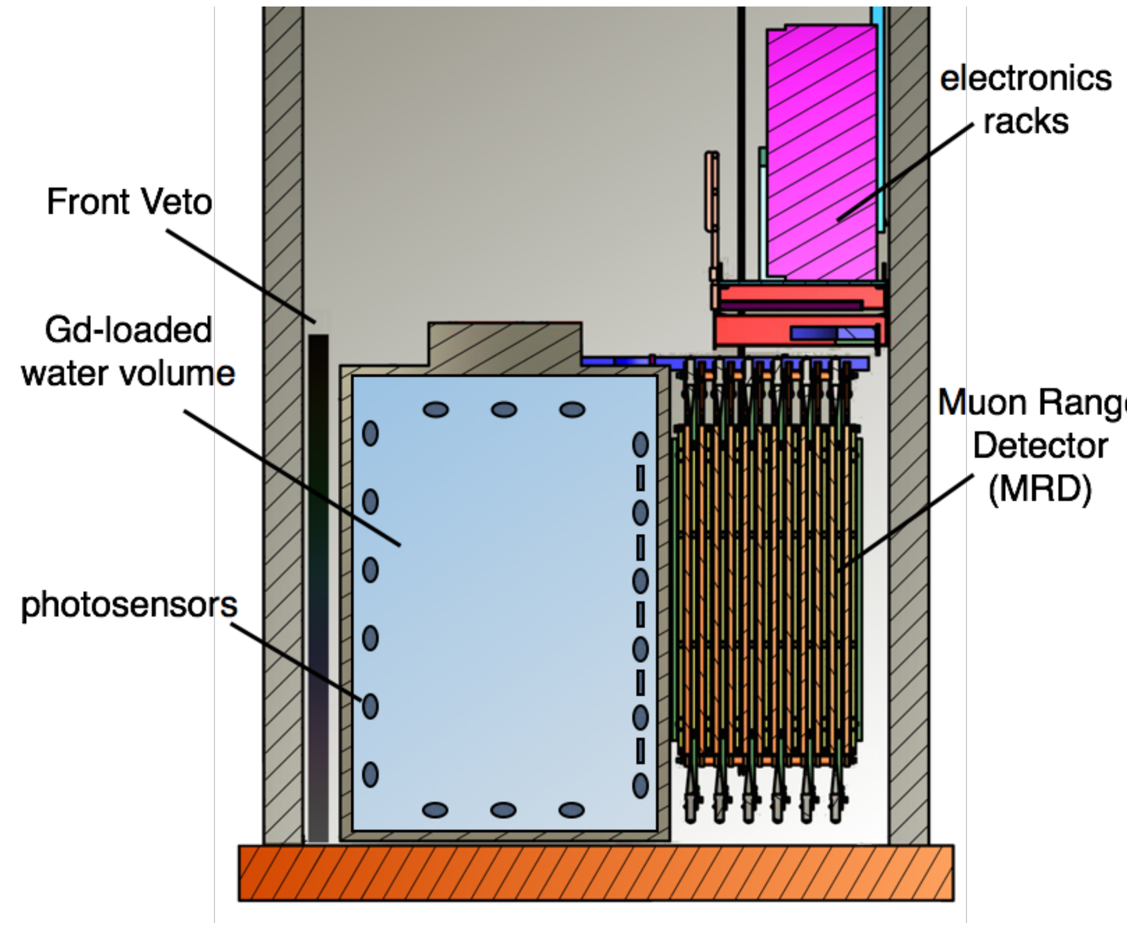
The Accelerator Neutrino Neutron Interaction Experiment
(ANNIE)

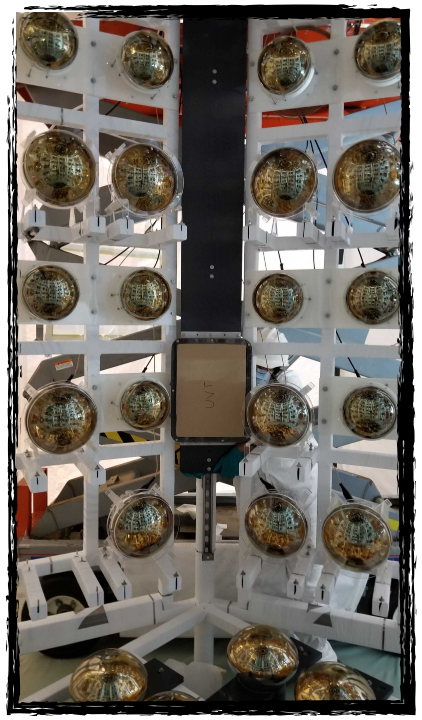
- ANNIE is a neutrino experiment deployed on the Fermilab Booster Neutrino Beam.
- Physics: Measure final-state neutron yield from neutrino-nucleus interactions.
- Technology: R&D platform for new neutrino detection technologies/techniques:
  - Fast photosensors (LAPPDs)
  - New detection media (Gd-loaded water and water-based liquid scintillator).

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

The ANNIE Detector

- Steel tank holding
  26 tons of **Gd-loaded water**
- **132 PMTs** (8"-11")
- Initially 5+ Gen 1 **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

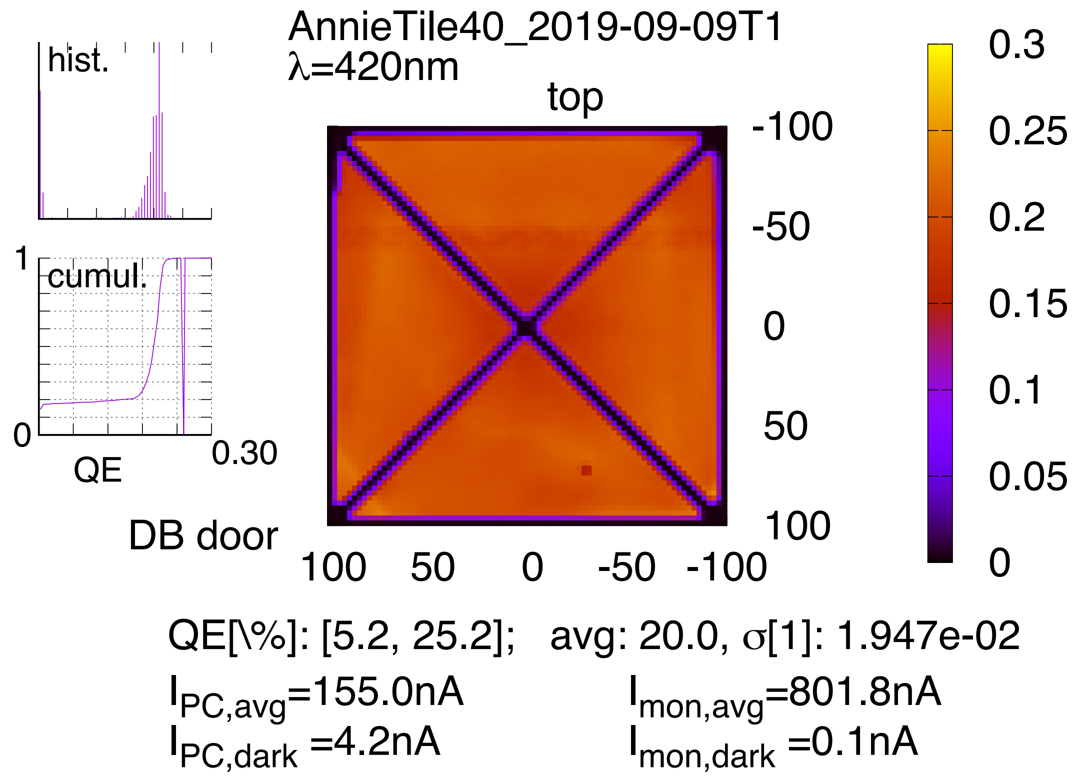


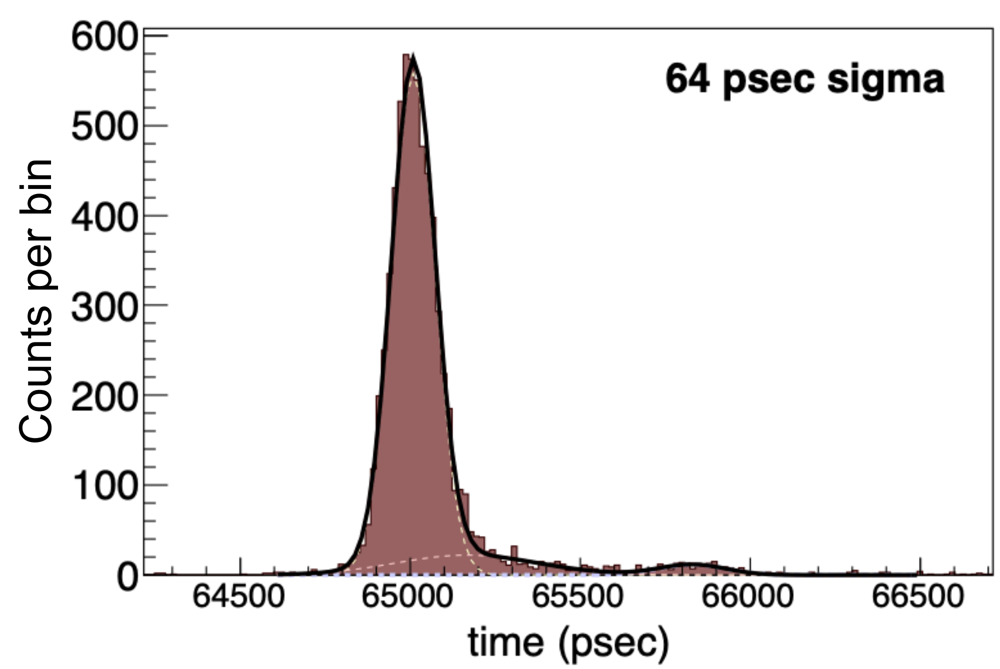


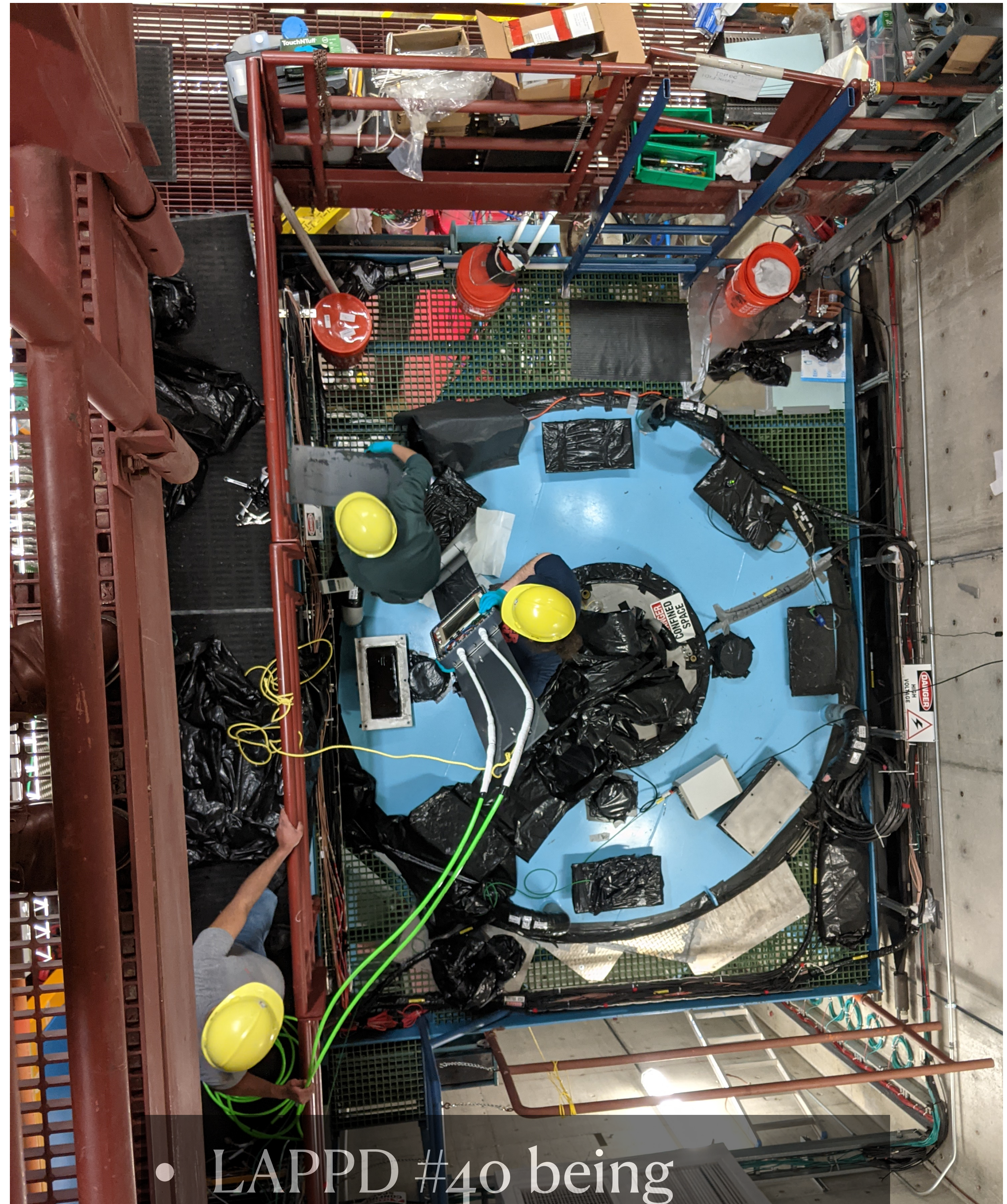
LAPPDs are inserted on slide rails between PMTs

LAPPD #40

Deployed March 2022







- LAPPD #40 being maneuvered to insertion slot: top-down view

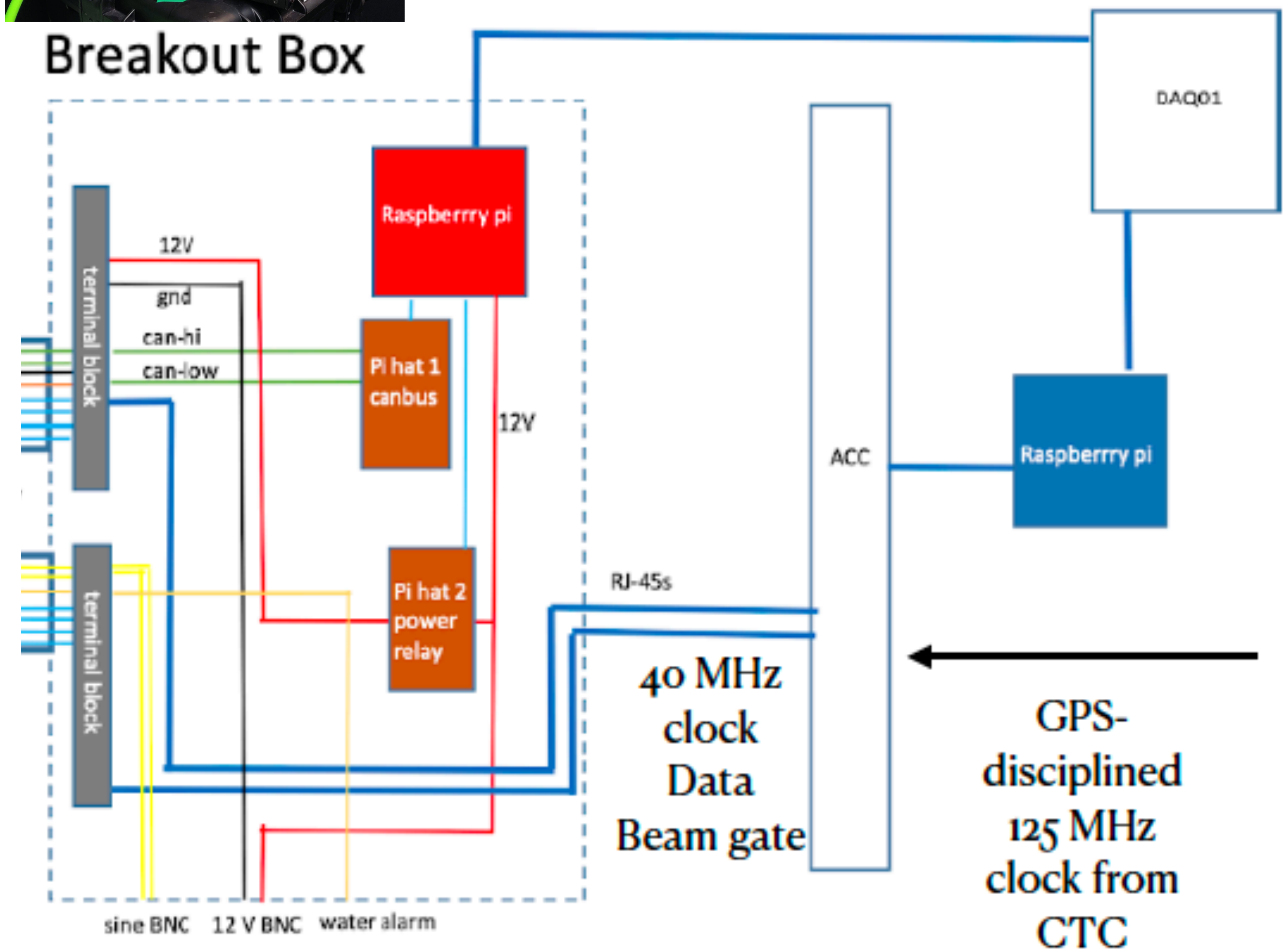
More on LAPPD 40 Deployment

- First LAPPD was deployed March 29 of 2022.
  - Stable operation under water with consistent slow controls monitoring: humidity, temperature and voltage are within specifications.
- Position of the LAPPD on the mounting board is determined to sub-cm level.

First LAPPD deployed in a HEP experiment!

Surface Electronics

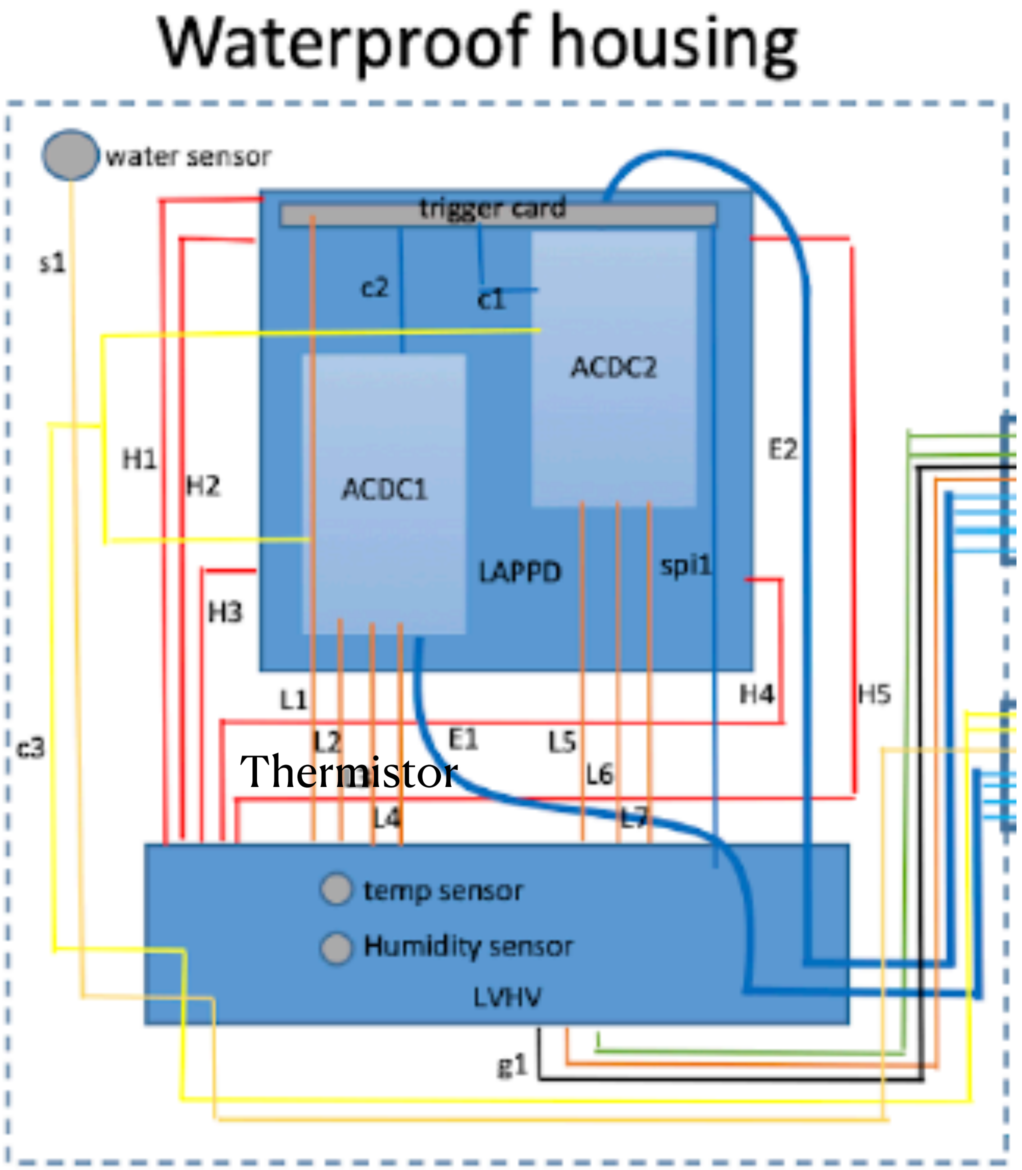
DAQ, Timing, Slow Controls Interfaces

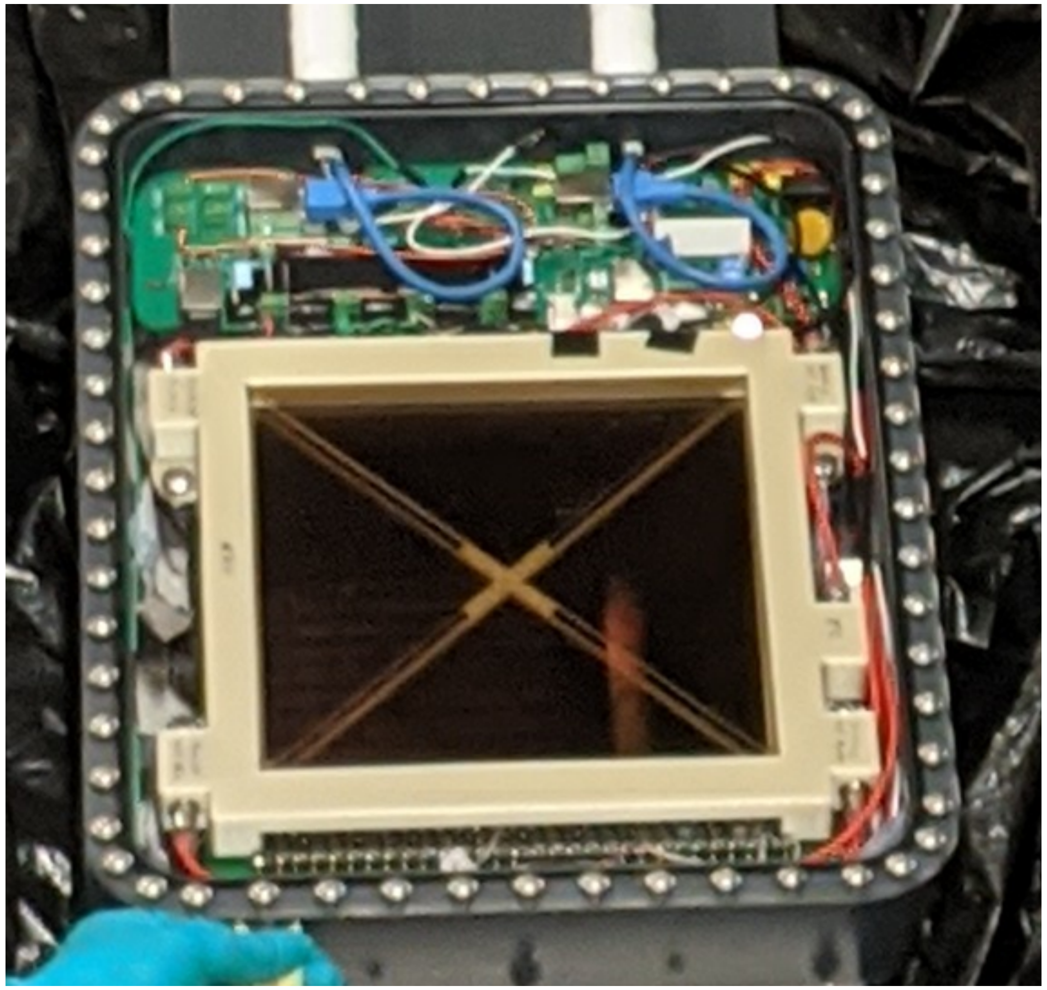


- Breakout box handles slow controls (e.g. power, trigger configuration, environmental monitoring)

- The ANNIE Central Card (ACC) is a custom card designed to operate in tandem with the PSEC electronics (ACDC) cards mounted on the LAPPD.
  - ACC receives both a central clock (125 MHz) and beam spill start information from CTC, processes and redistributes them to ACDC card.
    - Internal 40 MHz clock is latched to central clock via PLL.
  - It also receives data back from ACDC cards.
  - 1 ACC can handle 2-4 ACDC cards (1-2 LAPPDs)

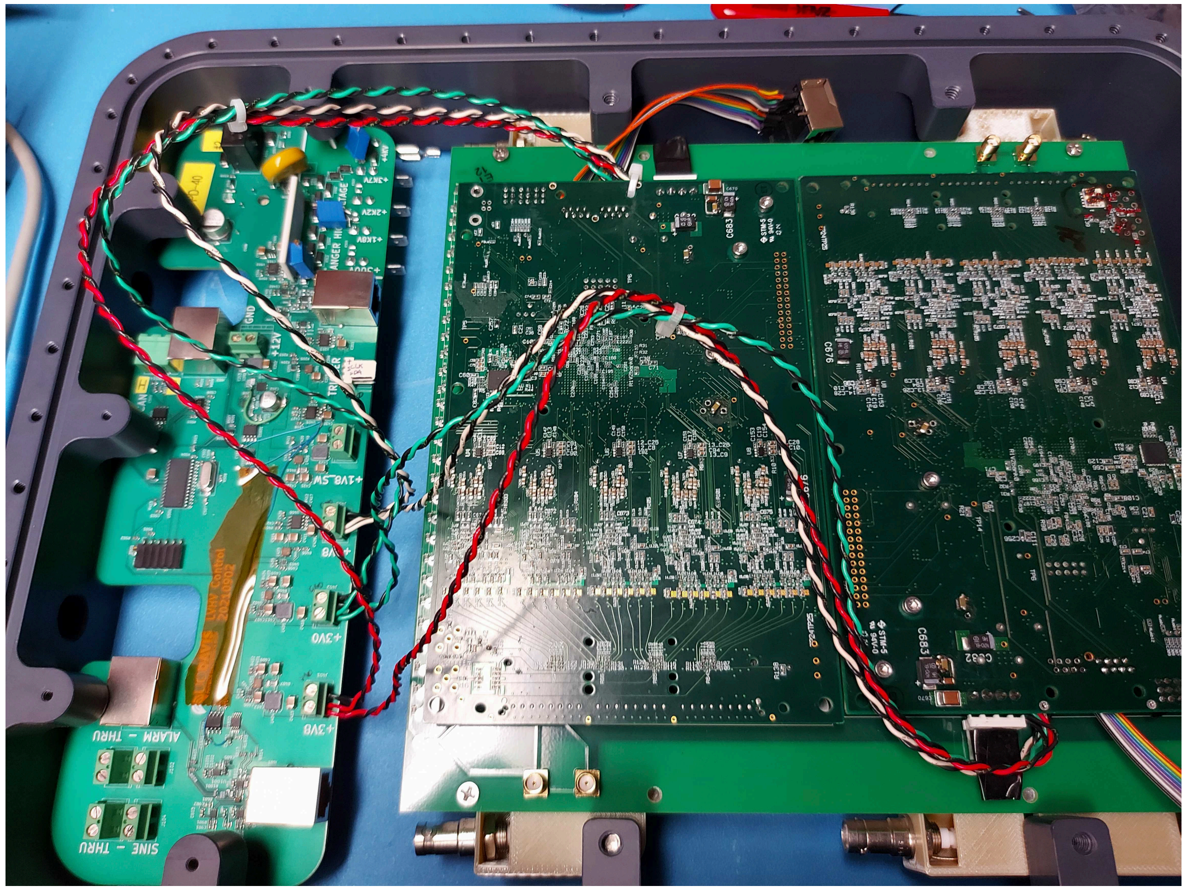
LAPPD Deployment Package





- Technical challenges of underwater operation:
  - Communication over long cables (7-10 m)
  - Water tightness (custom housing, special connectors and cables from SubConn and Falmat)
  - Noise, thermal issues from readout electronics close to LAPPD.

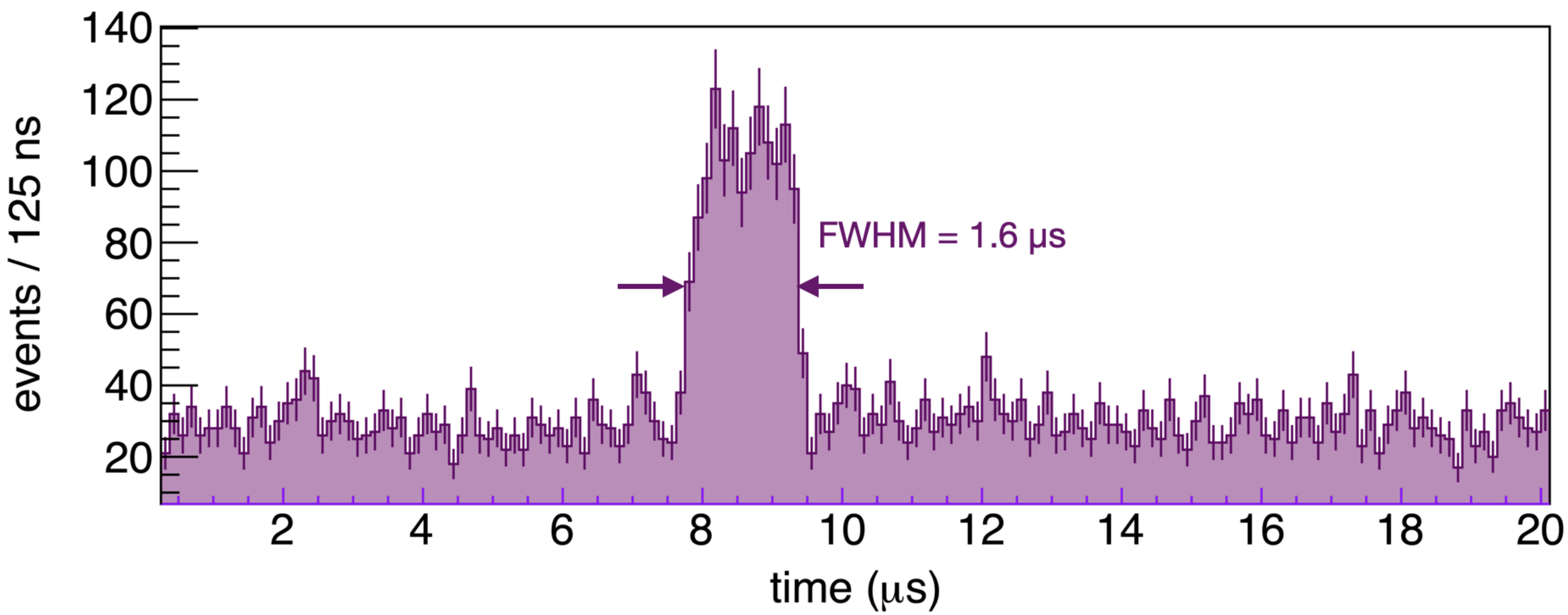
Trigger and Readout



- 2 ACDCs mount to analog pickup card which mounts to LAPPD.
  - PSEC chips capture signals from both sides of each stripline.
  - 10 GS/s, 25 ns buffer
- LAPPD triggers asynchronously within a 20 us (programmable) beam window.
  - External trigger card replaces ACDC onboard triggering for this iteration.
  - 40 MHz X8 for ~3ns timestamping of beam window start and trigger arrival.
  - Fit analog signal to obtain exact time within clock cycle

ANNIE First LAPPD Neutrinos

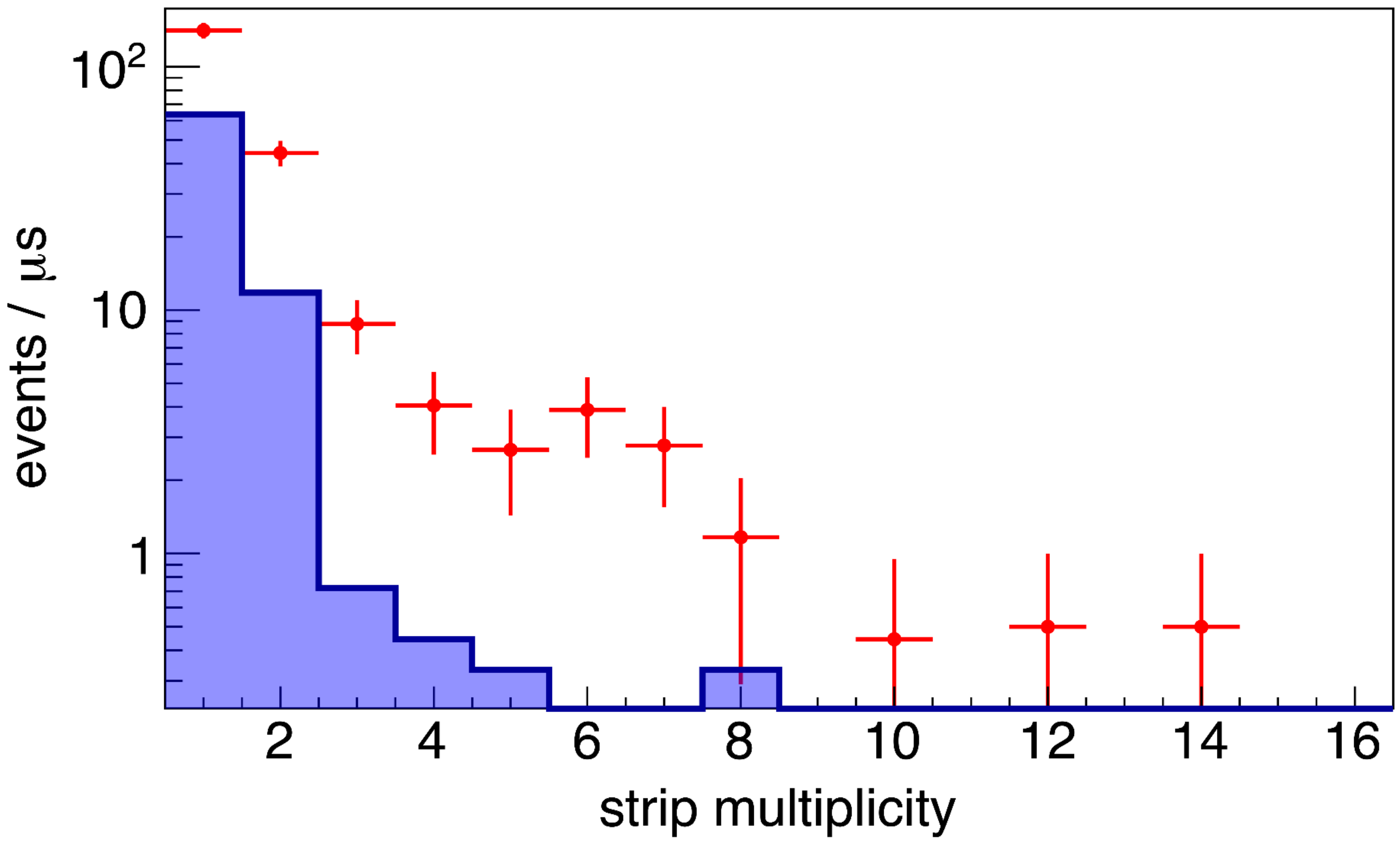
- The excess above background are LAPPD-triggered events in-time with the BNB. The excess has a width of 1.6 μsec.
- Requiring a single MRD track is enough to effectively eliminate background.



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.

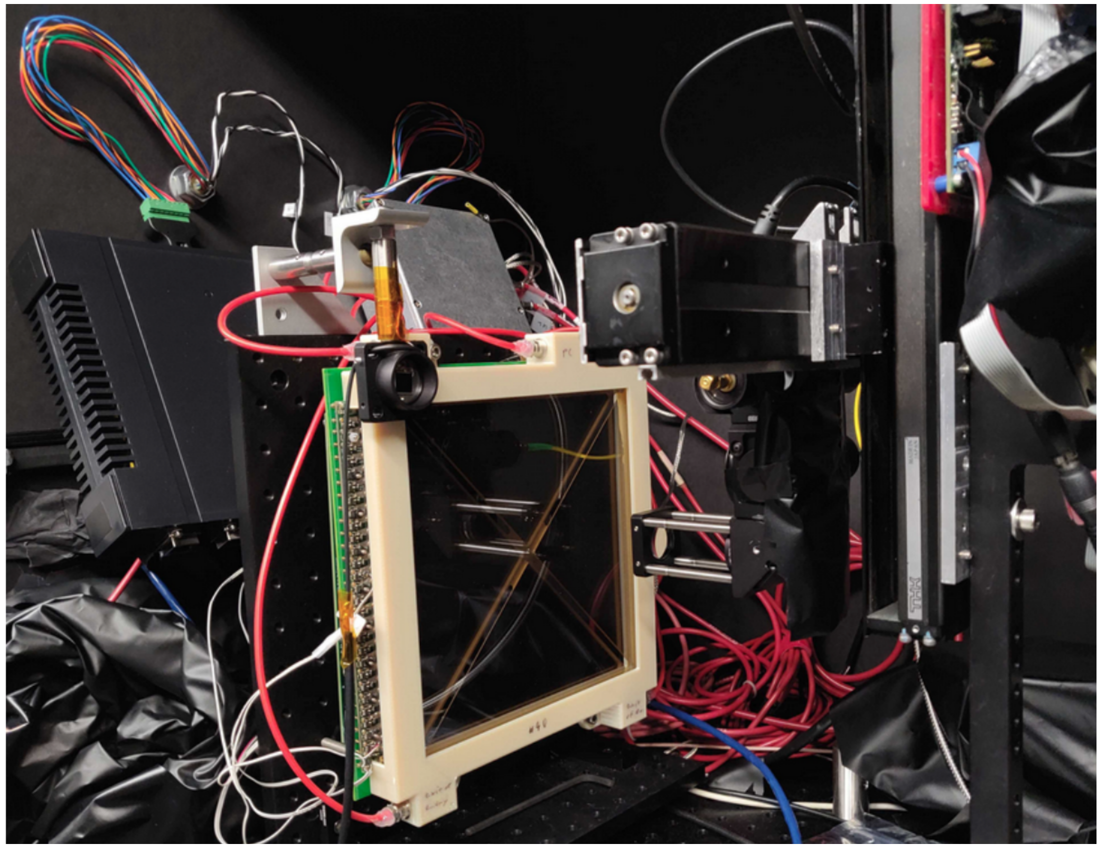


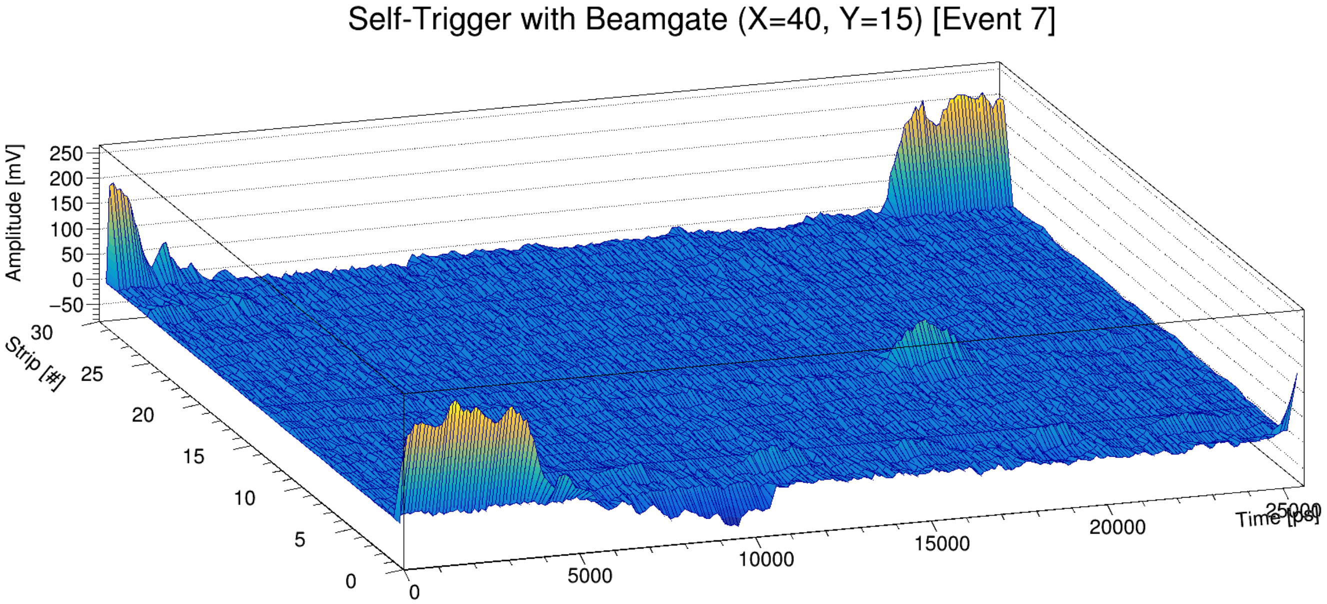
World's first: neutrinos observed with LAPPD!

LAPPD Testing

Characterization and Integration Testing

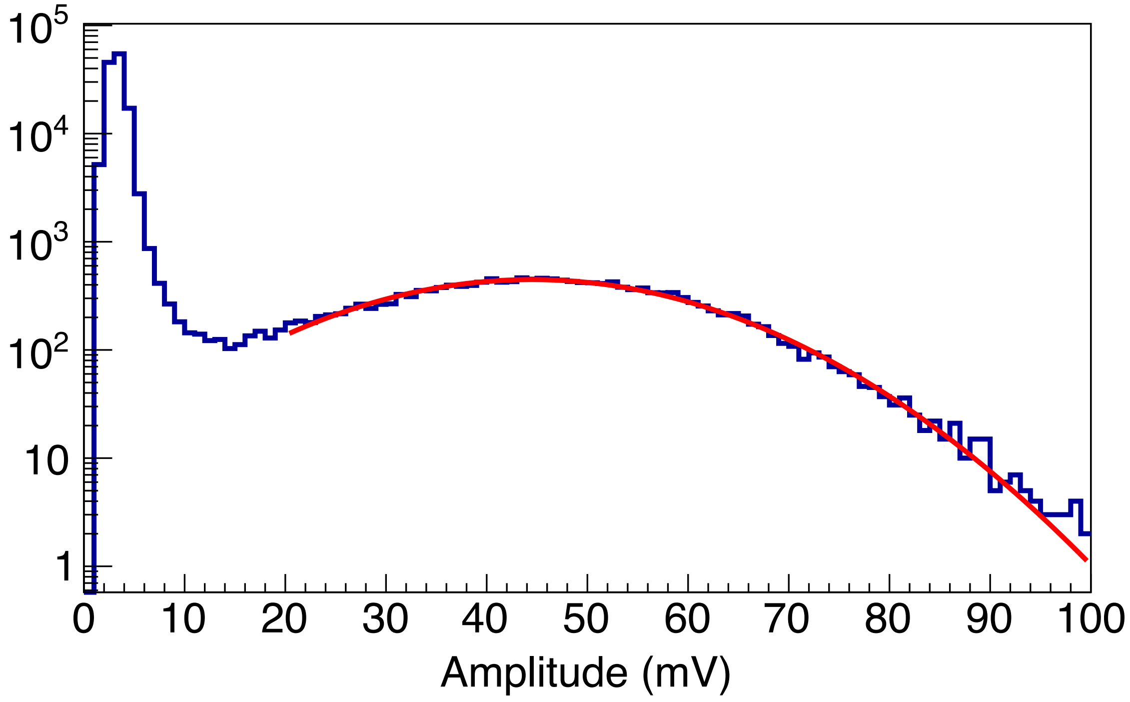
- Done in dedicated dark box facility at FNAL
  - 30 ps pulsed PiLAS laser mounted on 2D motor scanning stage.
  - Characterize gain (single P.E. response), timing, QE
  - meet the ANNIE requirements: QE~20%, gains >10^6, time res < 100 ps.
  - Test full deployable package, DAQ

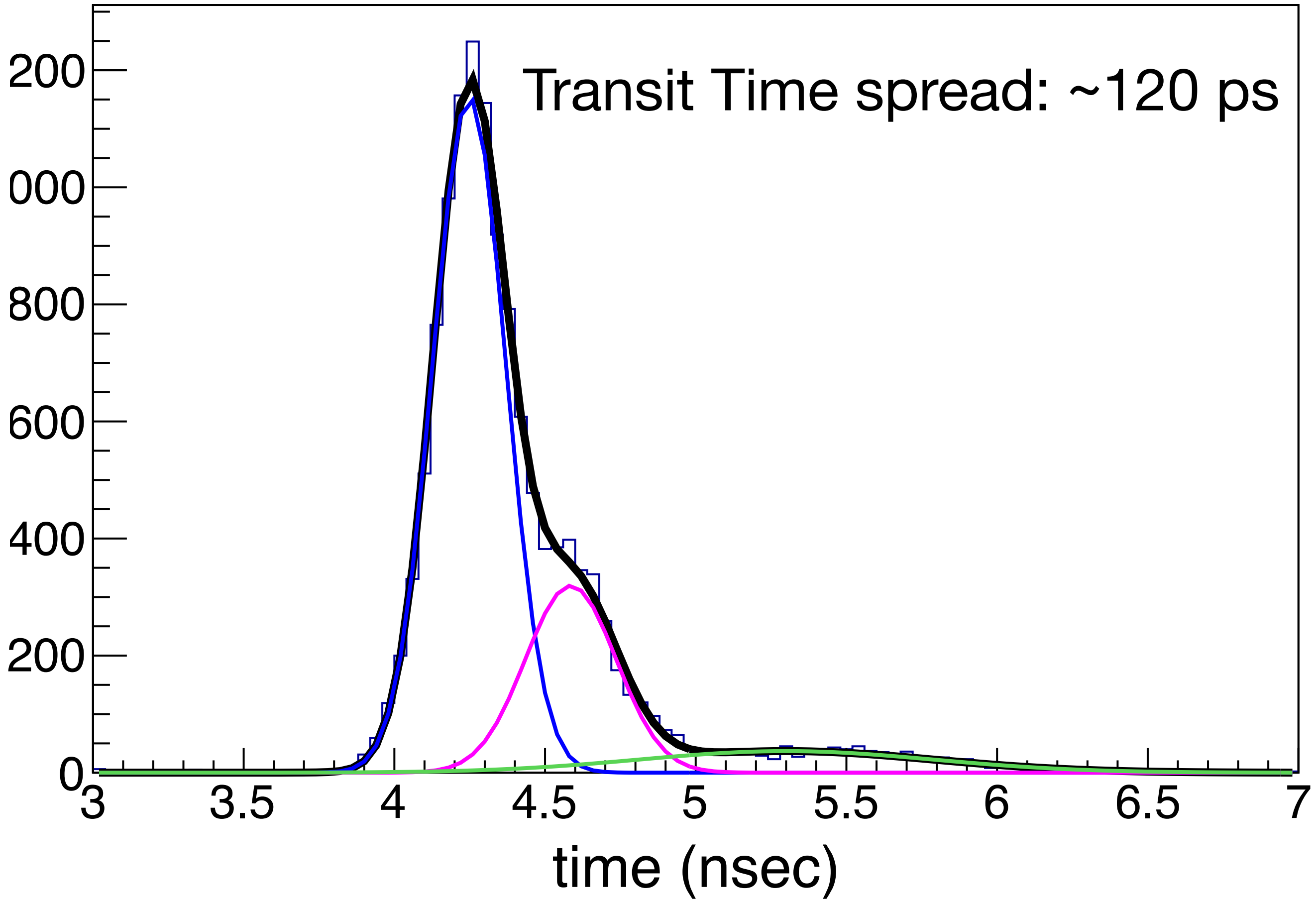




Next steps

- In the process of testing and deploying 4 more LAPPDs in 2 sets of 2.
    - See significant variability: next LAPPD is significantly higher gain than LAPPD 40.





- Mean gain: 1.7 x 10^7

Technical challenges

- Keeping noise and heat sources away from LAPPD is essential.
  - Power management belongs on an auxiliary board, not LAPPD-mounted readout.
- Gain / optimal HV settings and MCP resistances vary significantly between LAPPDs.
  - Can mitigate with a design that independently controls high voltage settings for different LAPPD layers. Difficult to do with limited real estate.
- Changes to certain electronics elements currently require opening LAPPD frame. A generic design that limits need for this is desirable.
- Work on photon disambiguation in Gen 1 LAPPD in realistic multi-P.E. scenarios is on-going.

ANNIE Summary

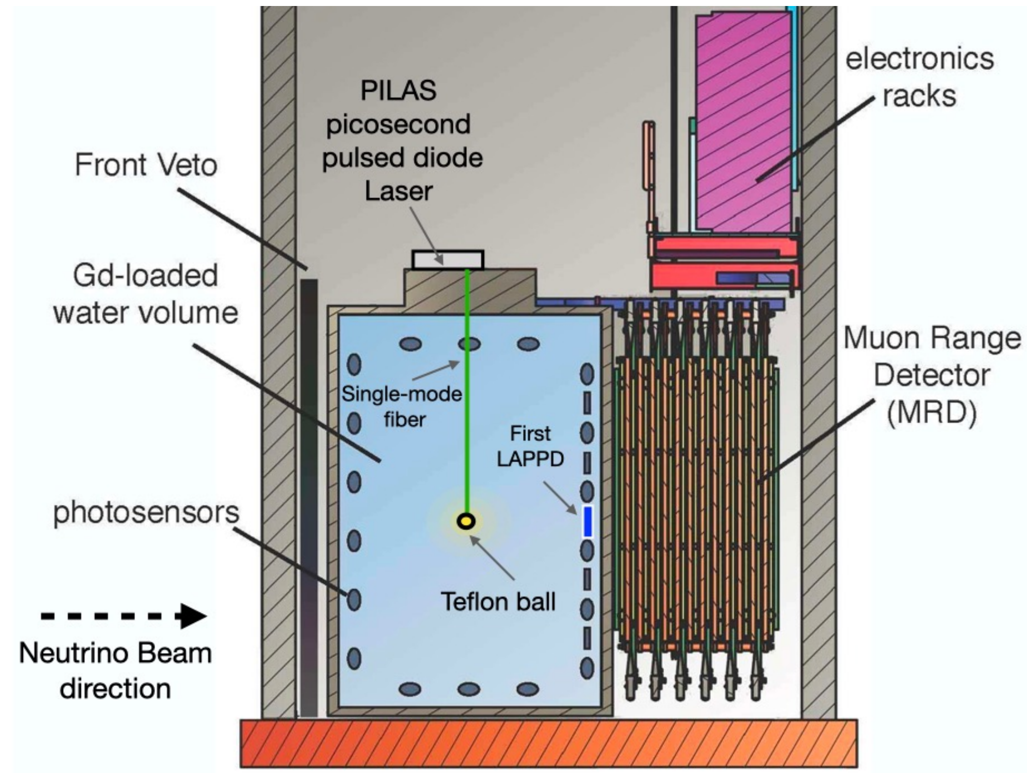
- The ANNIE collaboration has constructed, assembled and installed the detector which is taking neutrino beam data.
  - Gd-loading of the detector a success.
  - ANNIE sees neutrons from beam (& calibration source)
- We have taken LAPPDs from prototypes in test stands to deployable technology
  - On track for the World's first multi-LAPPD deployment (1 down, 1 in process, 3 to go)
  - ANNIE sees neutrinos in an LAPPD!
- Preparations to deploy WbLS in progress.

Exciting times for ANNIE, new collaborators are welcome!

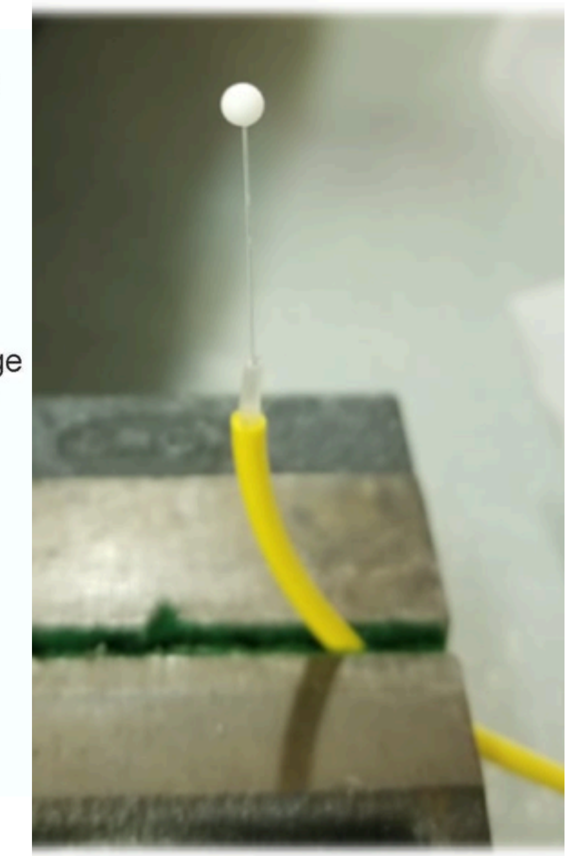
Backup

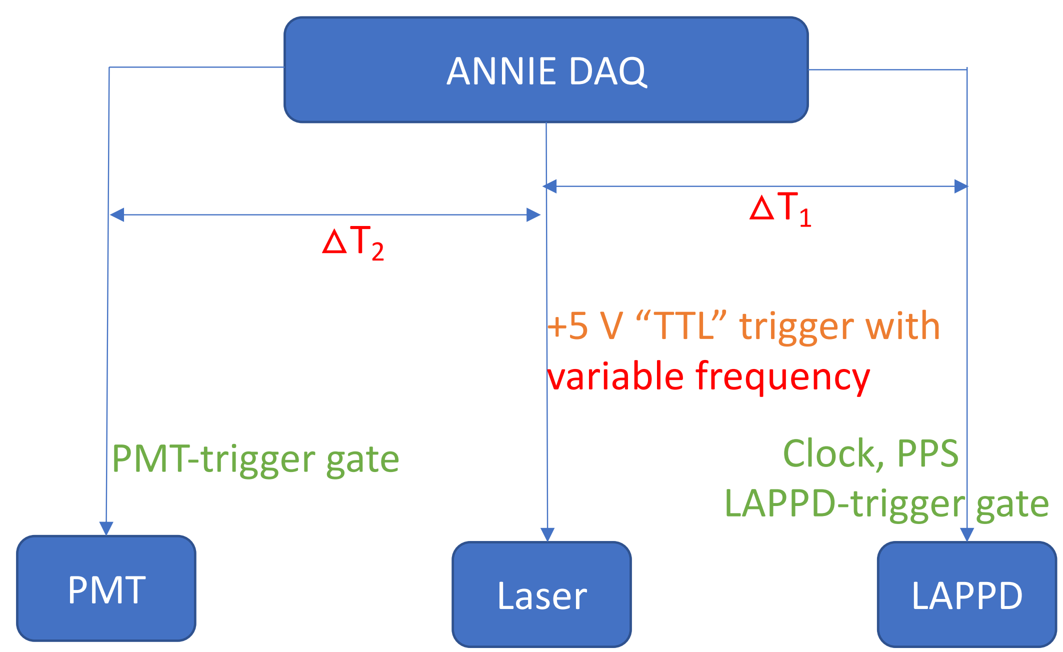
ANNIE LAPPD/PMT Calibration: Laser system

- 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.



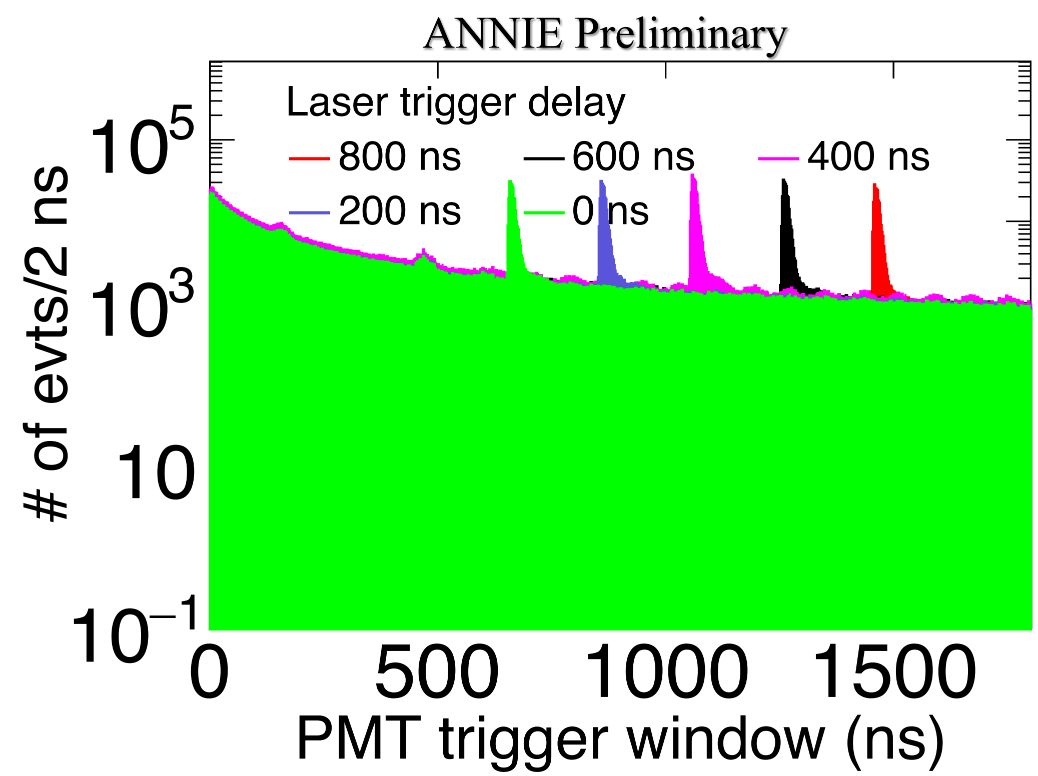
Laser setup in ANNIE Phase II detector

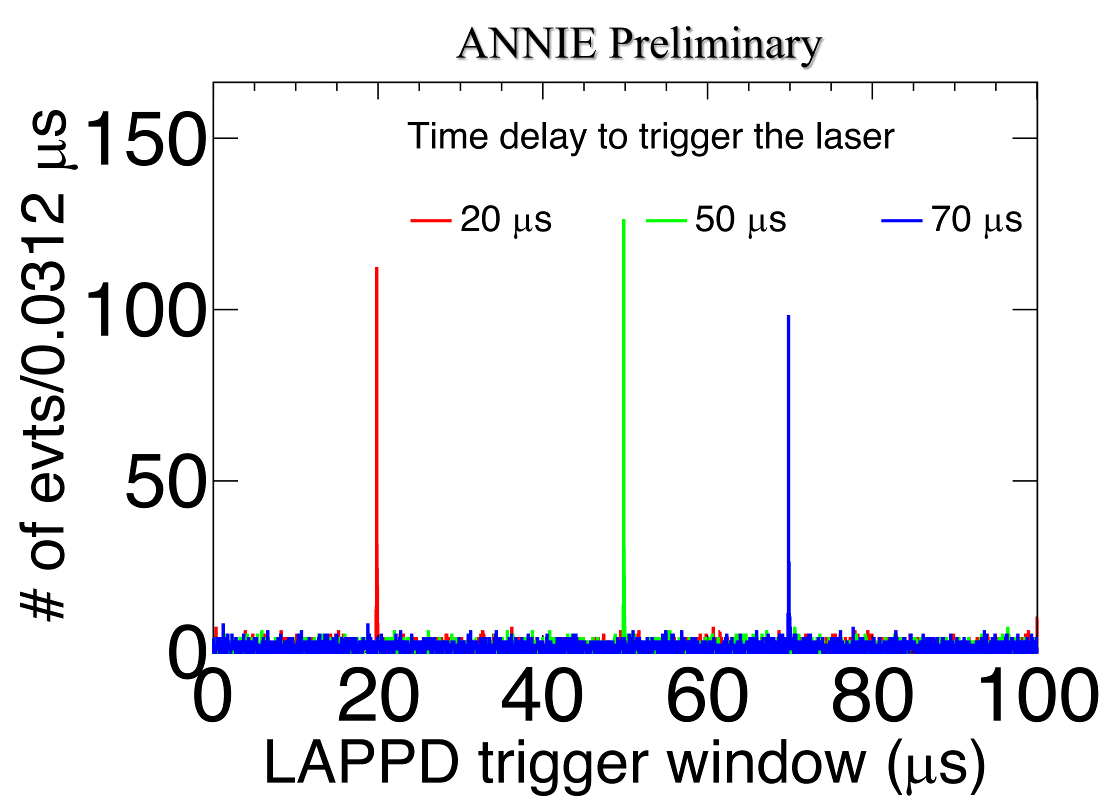




ANNIE LAPPD/PMT Calibration: Laser system

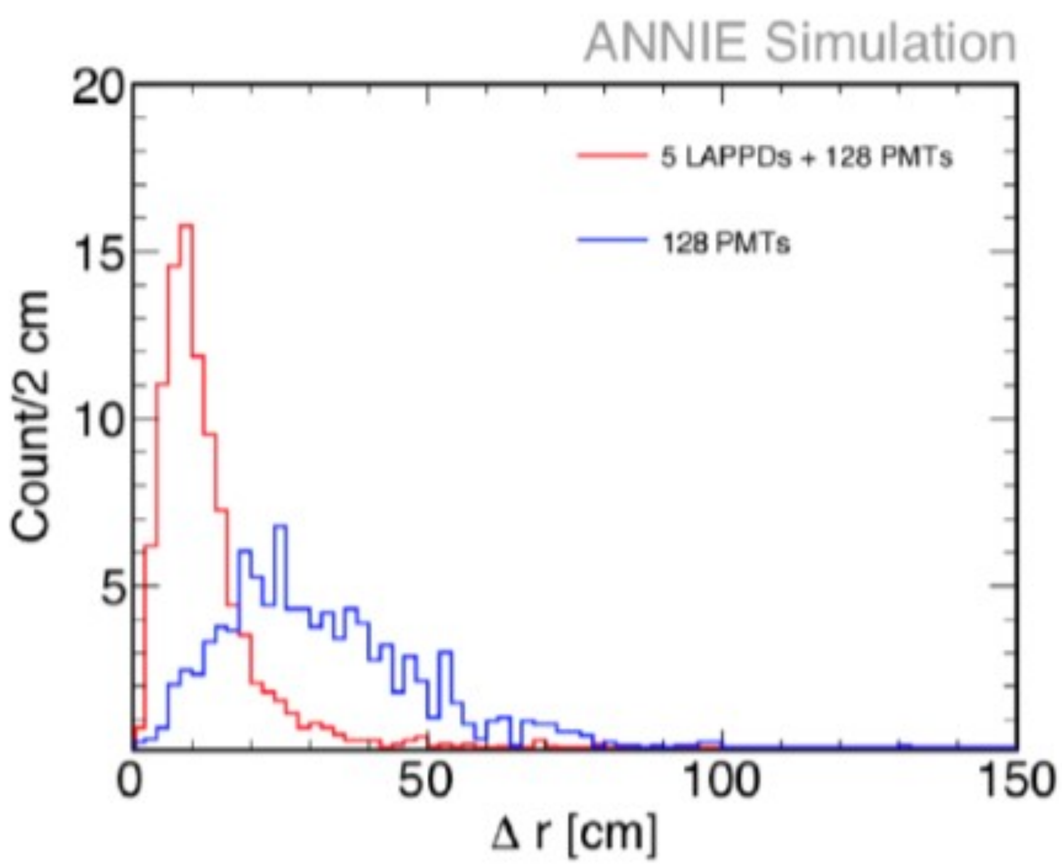
- The arrival time of PMT pulses as a function of time since the beginning of the trigger window initiated by the laser.
- The time-stamps of LAPPD self-trigger events relative to the trigger window initiated by the laser.
- The peaks correspond to laser induced signals above background for different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

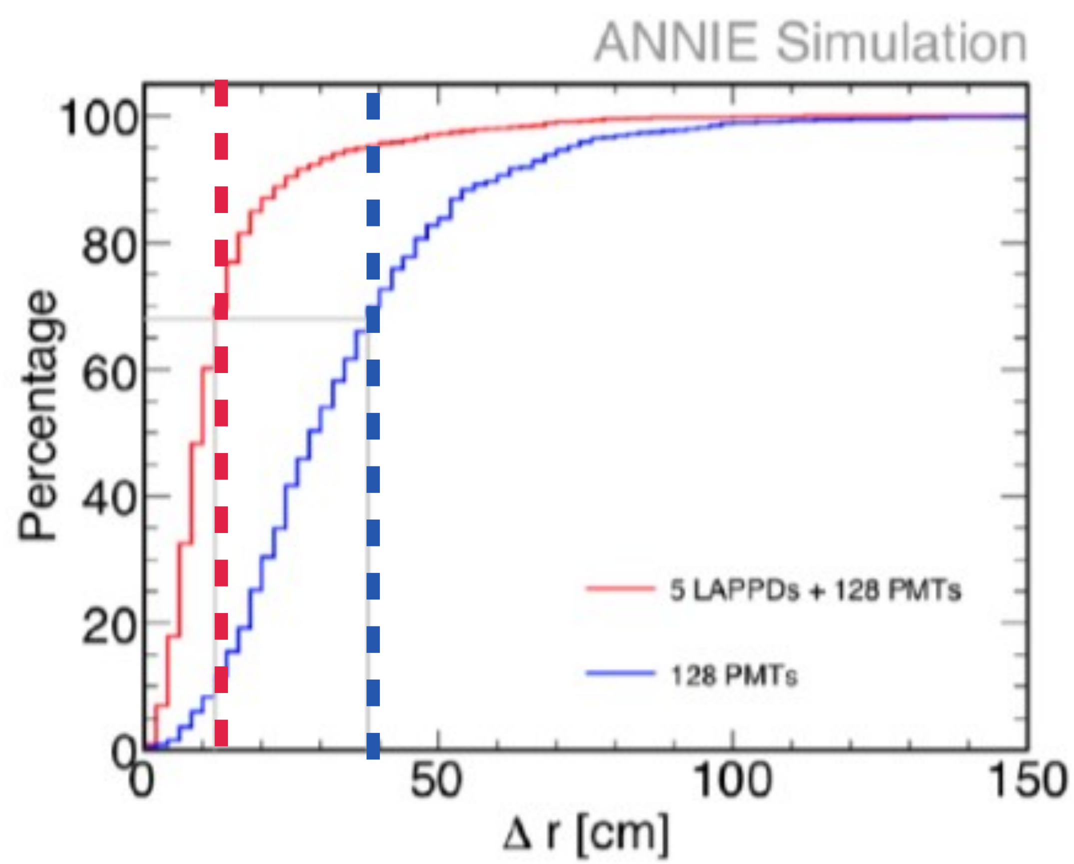




Enabling Technology: LAPPDs

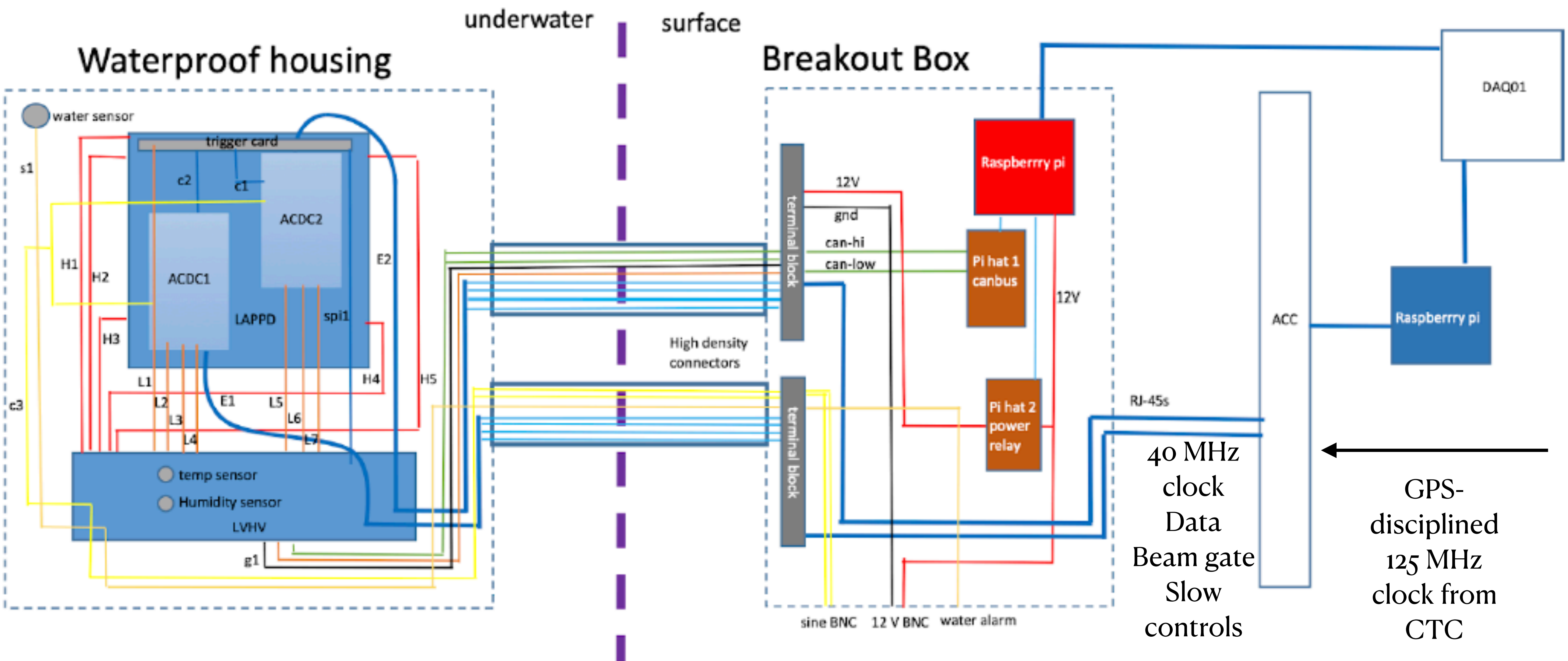
- Adding 5 LAPPDs to the existing PMTs improves neutrino vertex reconstruction accuracy by a factor of >2 and allows more precise reconstruction of muon kinematics (momentum, angle)
  - Improved knowledge of neutrino energy
  - Better interaction point reconstruction, neutron containment





Vertex Radial Displacement: Δr

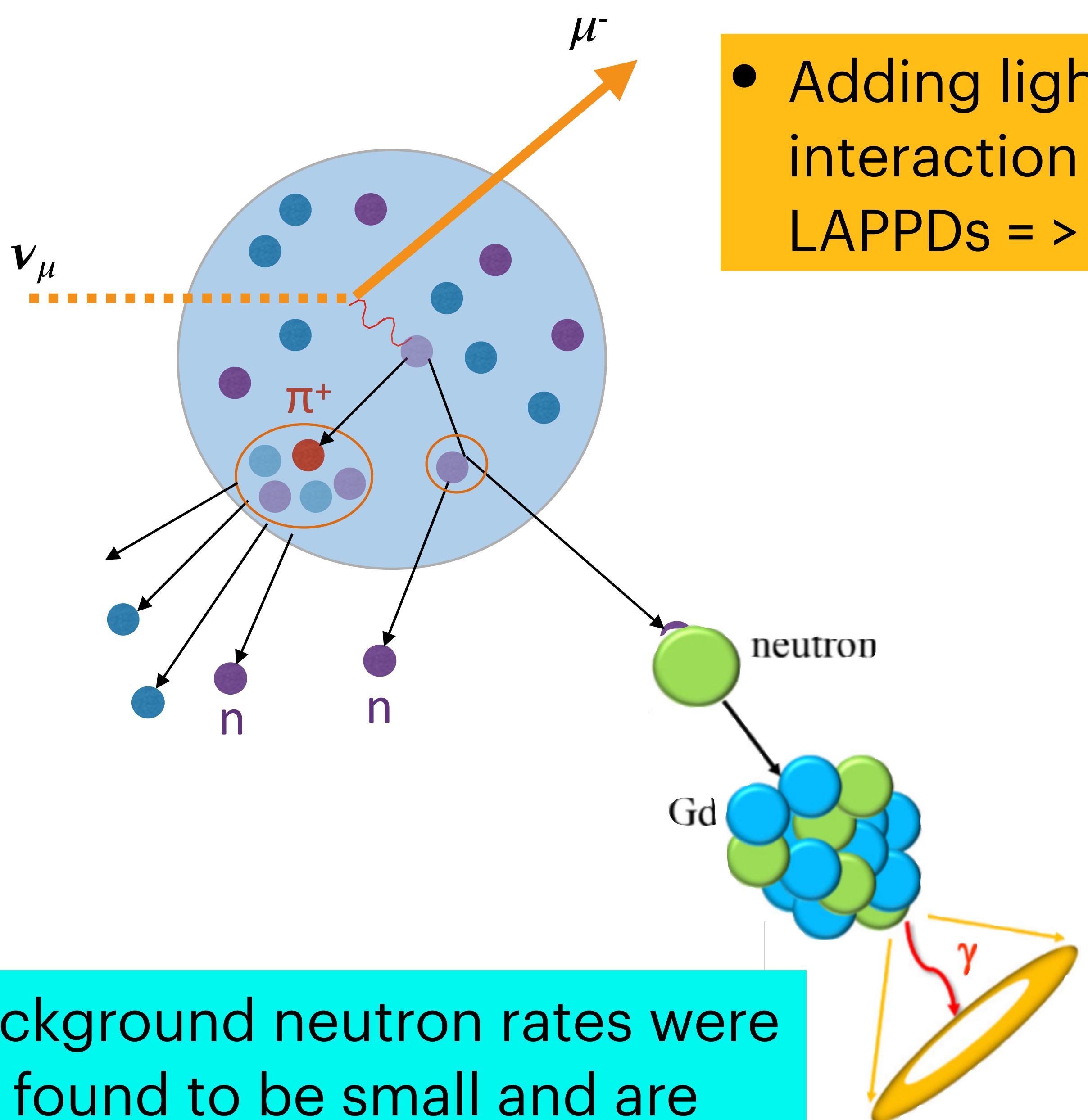
Full LAPPD Electronics



- Custom waterproof housing contains LAPPD and readout electronics.
- Two waterproof cables communicate between surface and ground.

- Surface electronics provide data acquisition and slow controls interface.

New Technology and ANNIE Physics



- Adding light from LAPPDs enhances interaction vertex resolution (5 LAPPDs = > 2 improvement).

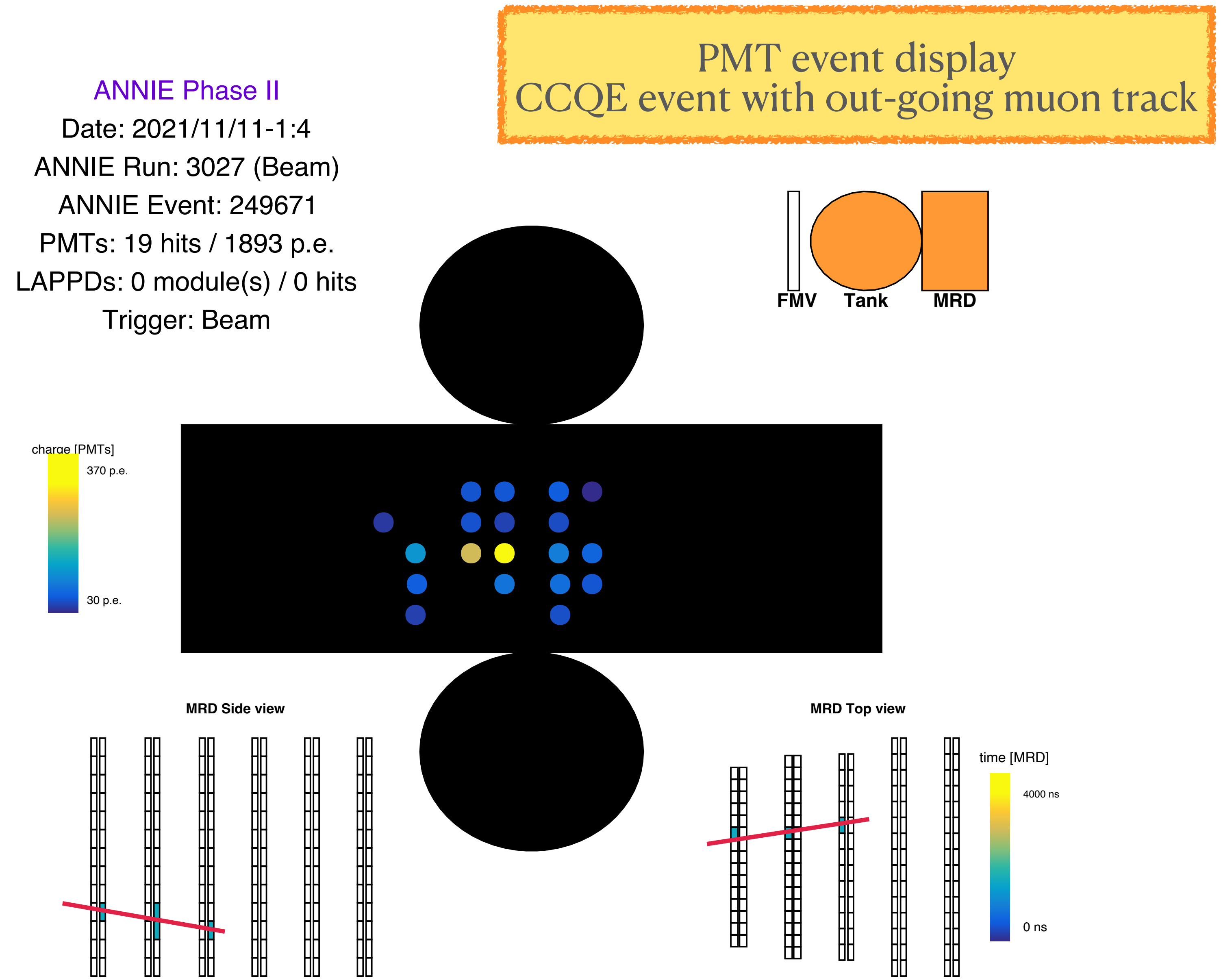
- Gd
  - Enhances thermalized neutron capture efficiency from 10 to 70%.
  - Shortens capture time by an order of magnitude to ~30 µsec.
  - Shifts de-excitation gammas from 2.2 MeV to 8 MeV

Background neutron rates were found to be small and are mitigated by the buffer layer of water above the detector. *JINST* 15 (2020) 03, P03011 arXiv:1912.03186.

Goal: Measure multiplicity of final state neutrons as a function of the outgoing lepton momentum and direction.

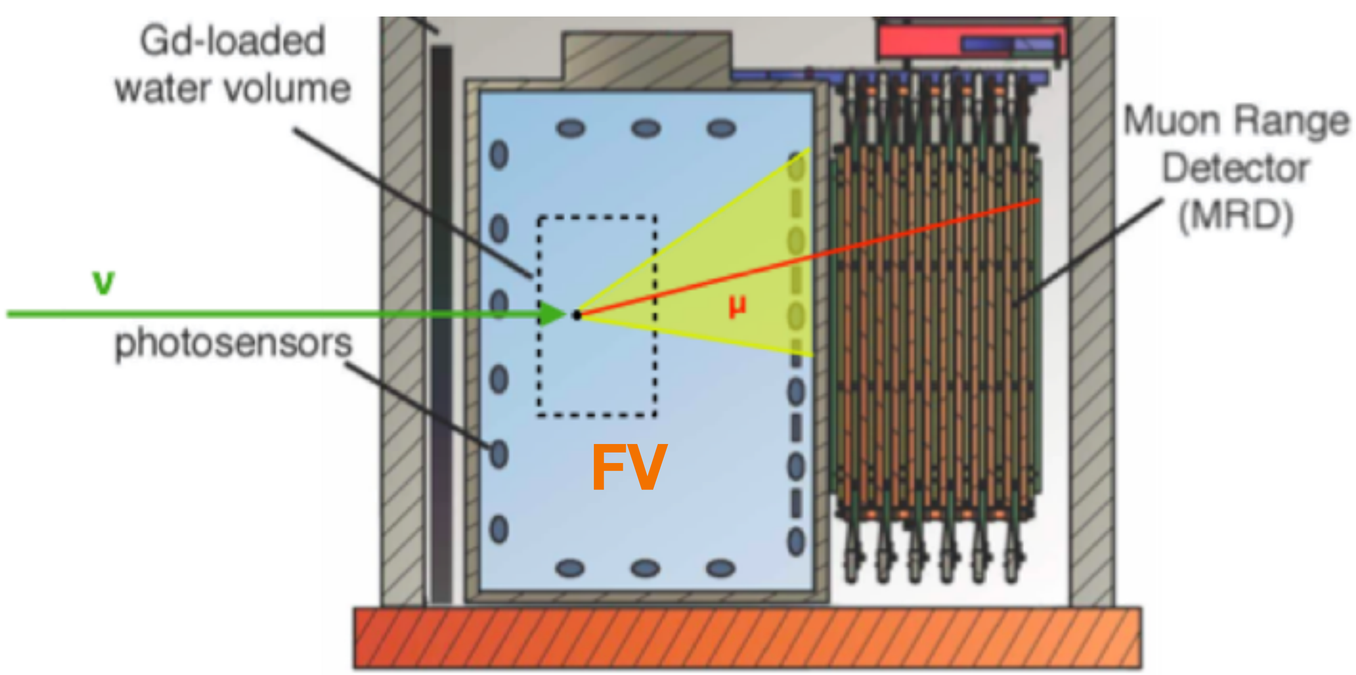
ANNIE Neutrino Beam Data

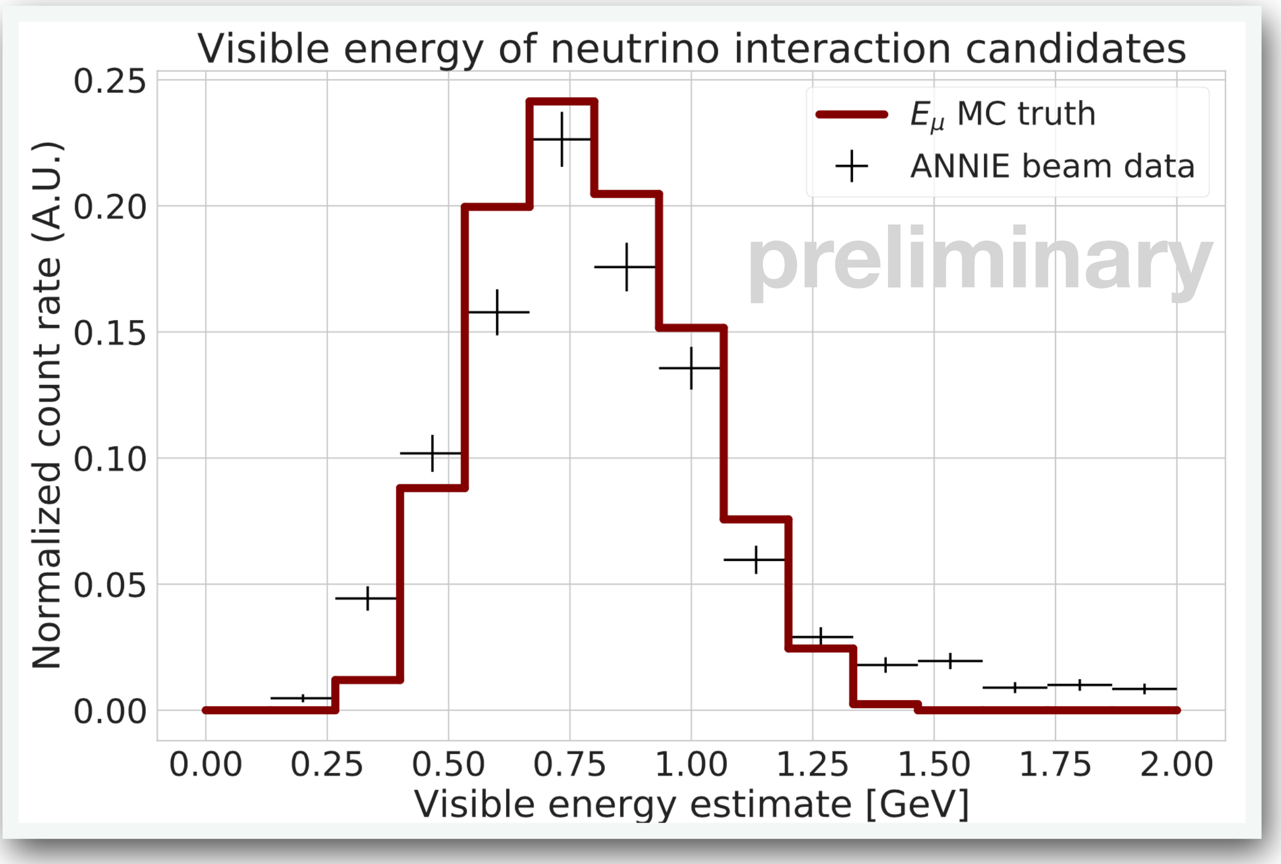
- All “conventional” ANNIE systems up to specs and running on high duty factors. Beam data taking in the Booster beam since January 2021.
- Charge Current (CC) quasi-elastic (QE) neutrino interactions are the golden signal for the determination of neutron multiplicity.
- Candidates are identified by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



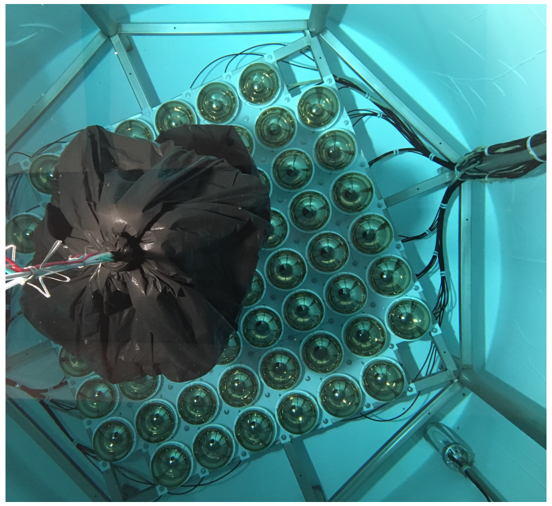
Reconstructing energy in CCQE events

- 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.**





ANNIE Phase I (2016-17)



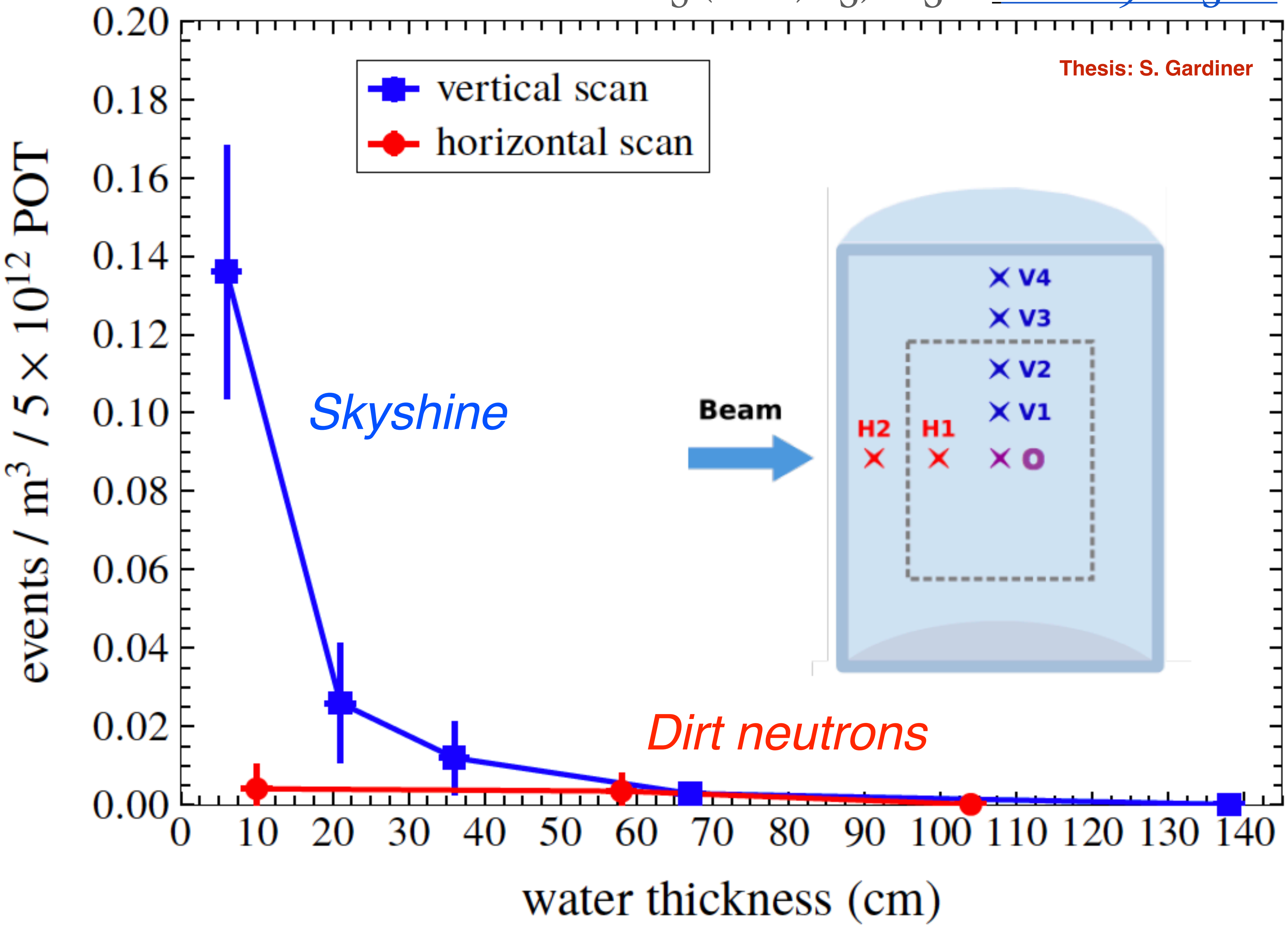
- Partially-instrumented detector
- Engineering, beam-correlated background neutron characterization

JINST 15 (2020) 03, P03011 [arXiv:1912.03186](https://arxiv.org/abs/1912.03186).

Skyshine: beam dump neutrons that enter the tank after leaking into the atmosphere.

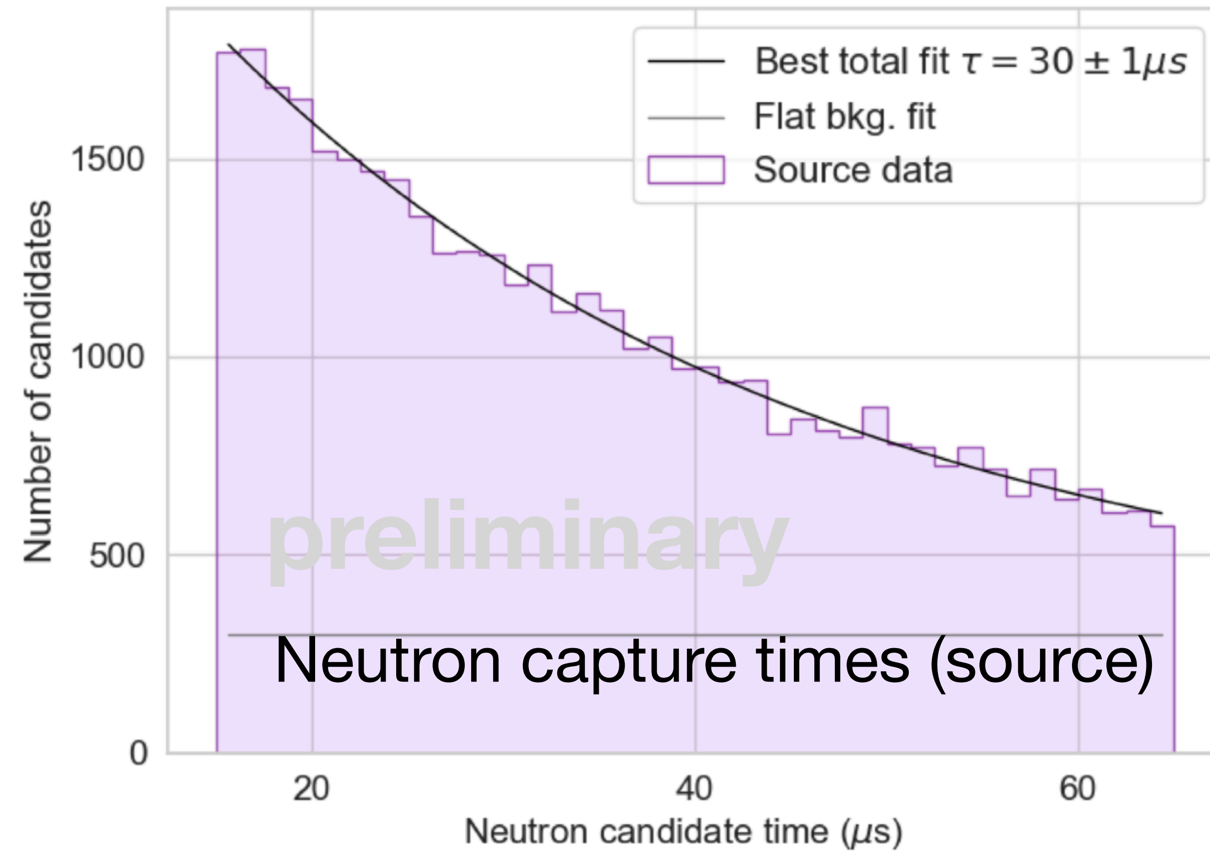
Dirt neutrons: neutrons from beam neutrino interactions in the upstream rock.

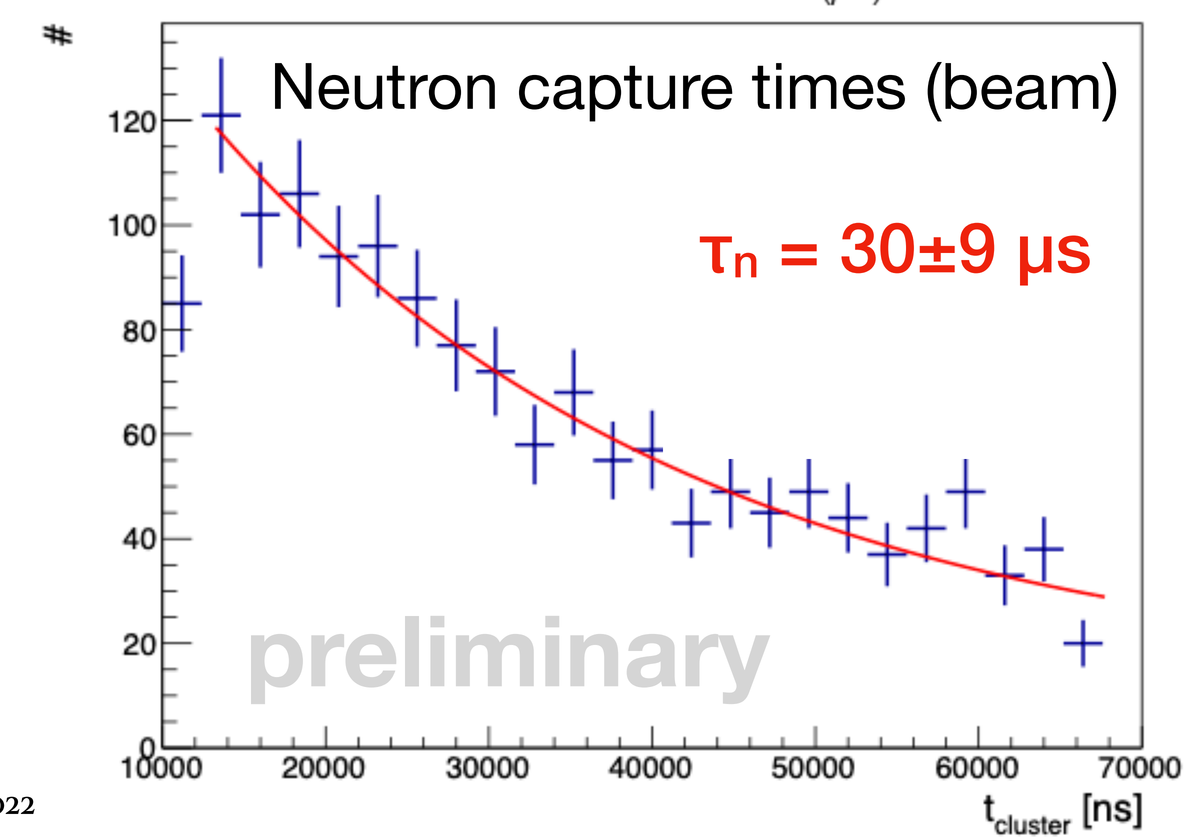
Backgrounds small, mitigated by the buffer layer of water above detector. .



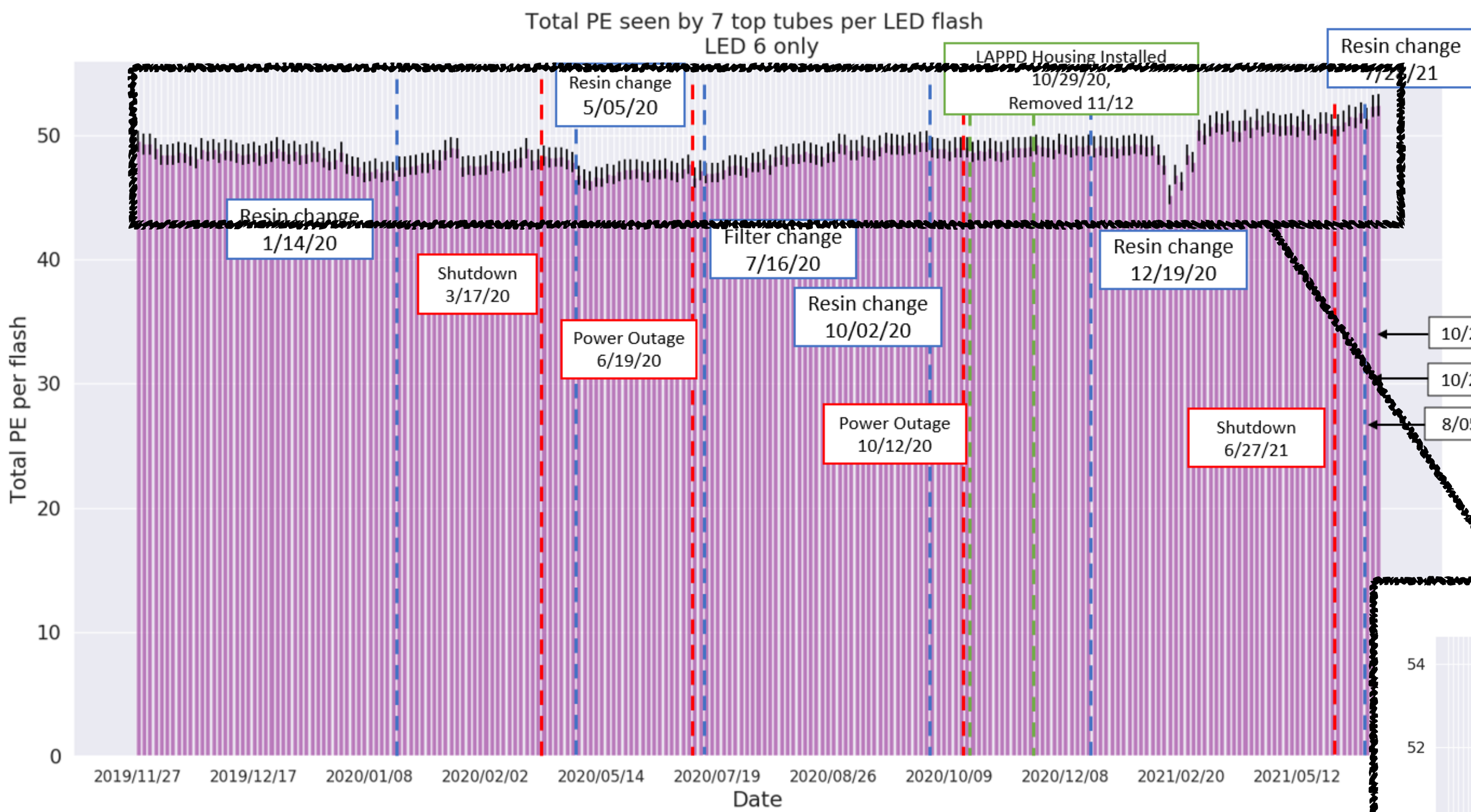
ANNIE Neutron Capture Calibration

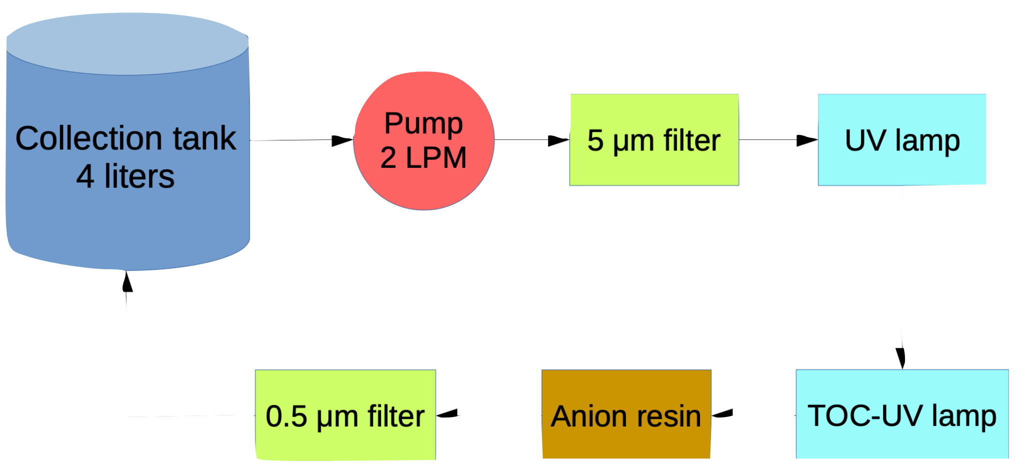
- A tagged AmBe neutron source was deployed inside the water volume to map neutron capture efficiency.
- Neutron capture time from source runs matches expectation for a Gd concentration 0.1% by mass.
    - This capture time is also consistent with beam data.
- Position dependent neutron capture efficiency has been measured to be consistent with expectations: ~55-70%.

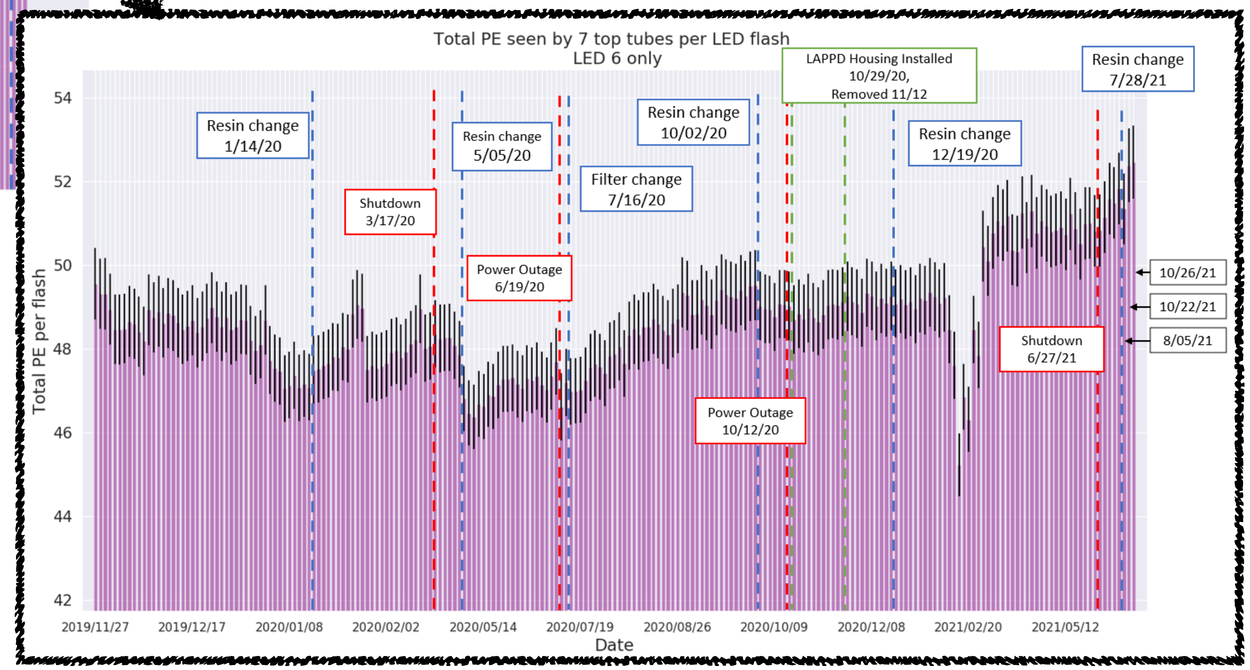




Enabling Technology: Gd-loaded Water



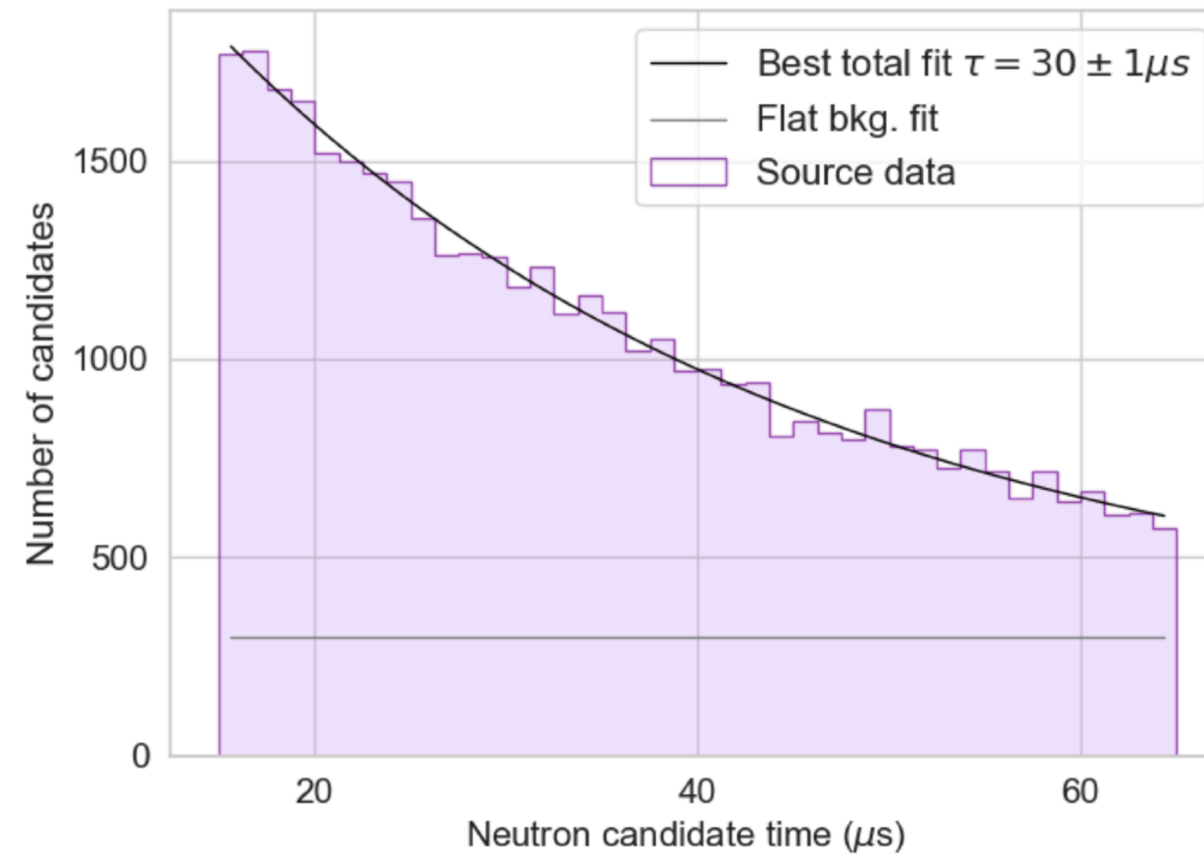


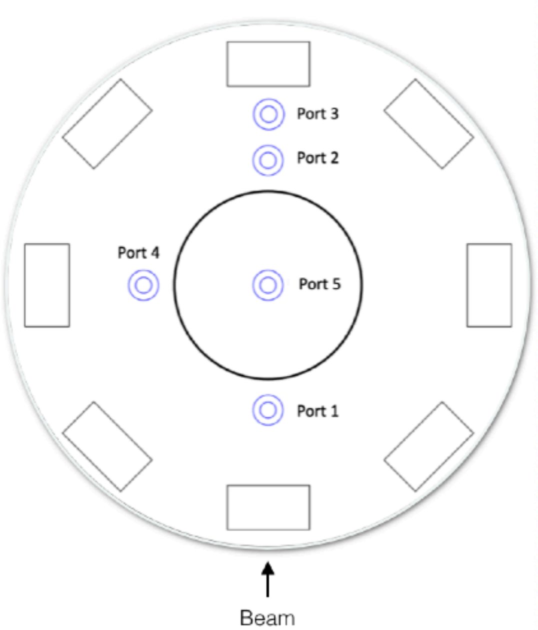


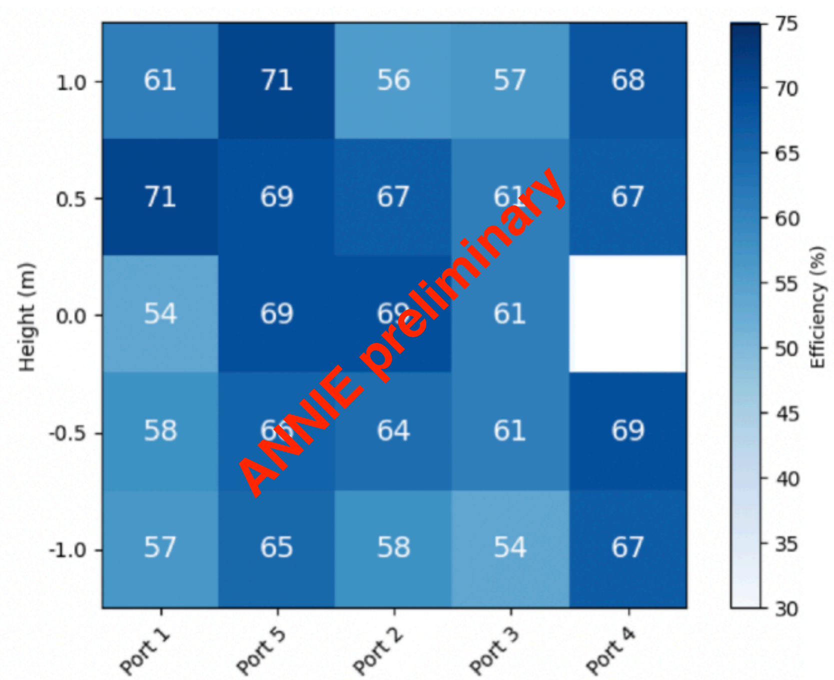
- ANNIE is the most gadiated neutrino detector in the world.
- ANNIE monitors water transparency by measuring intensity of LED flashes with PMTs across the water volume.
- **ANNIE's custom-designed purification & circulation system** maintains high water transparency level (~2 years now).

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.



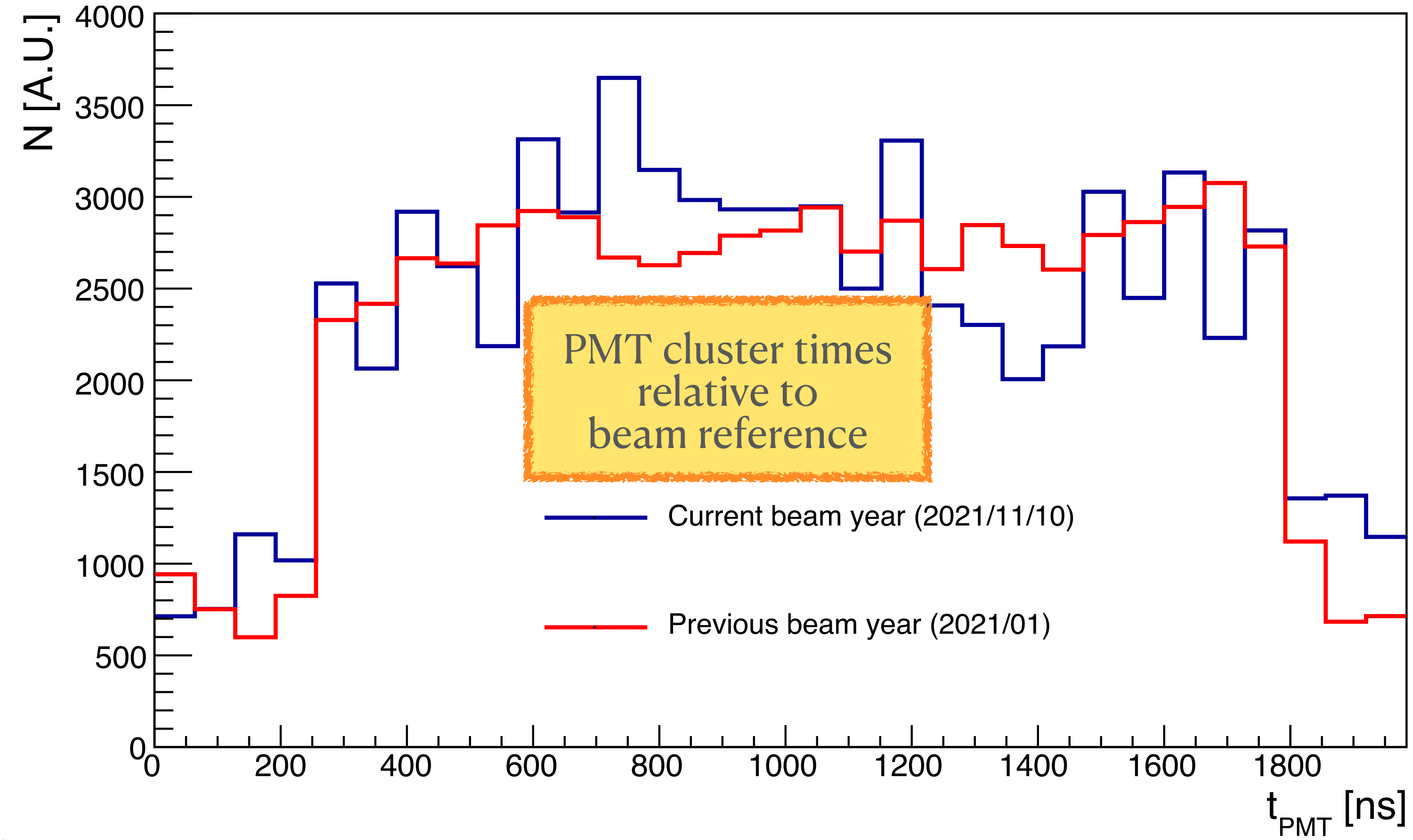


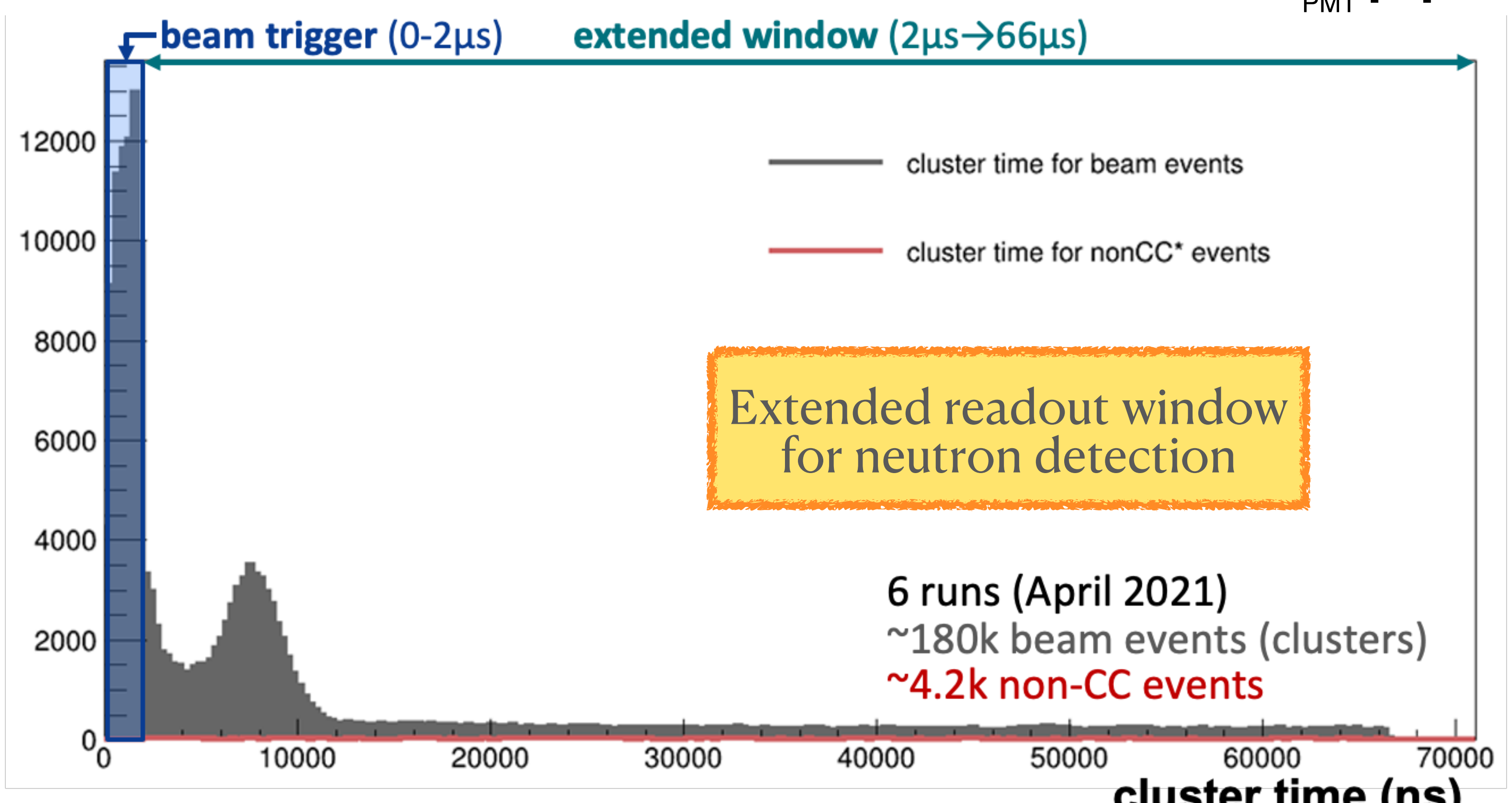


- Position dependent neutron capture efficiency has been measured to be consistent with expectations: ~55-70%.

ANNIE Neutrino Beam Data

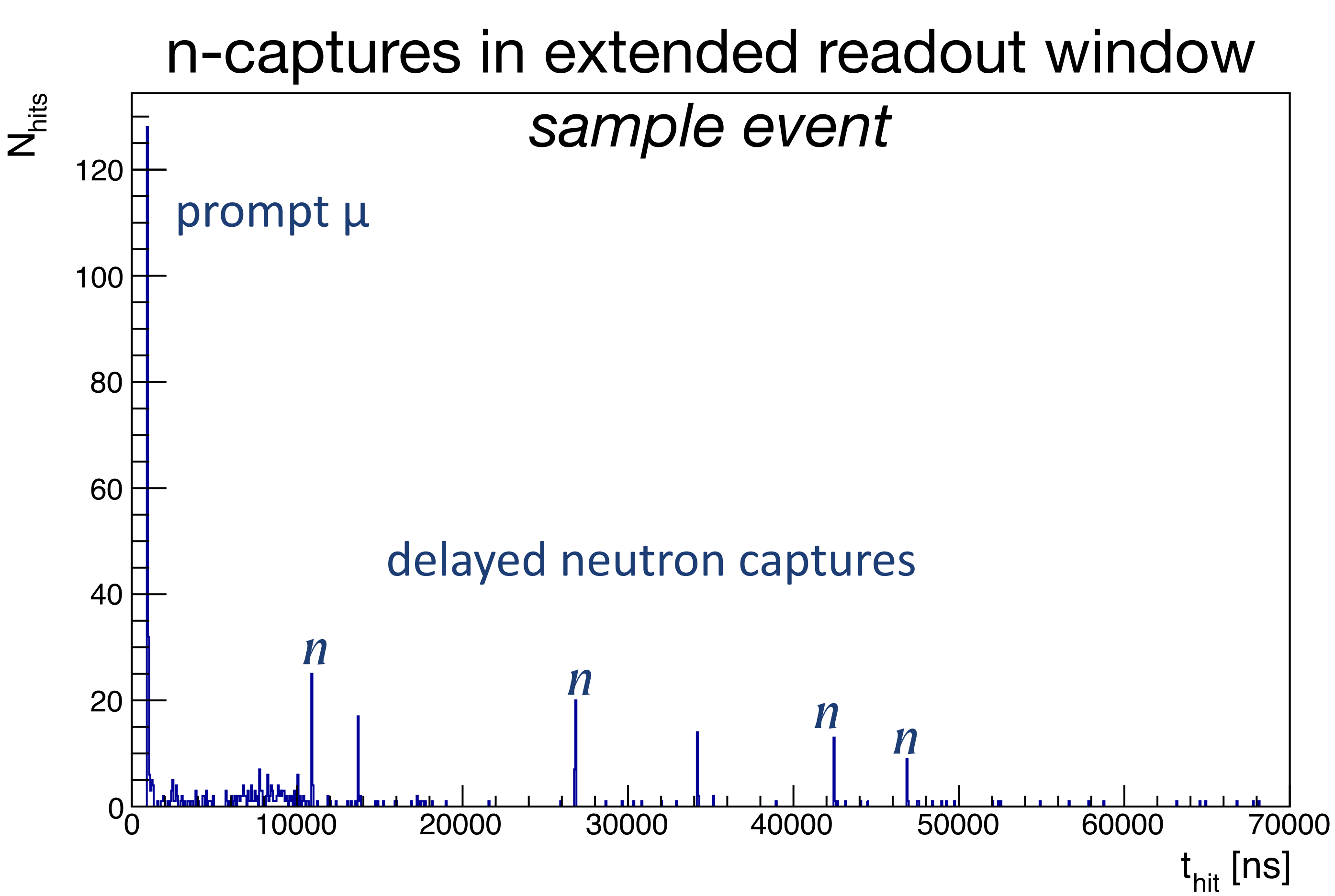
- Selecting PMT cluster times relative to the beam shows an excess in-time with the expected timing of the BNB.
- For beam triggers (<2 μsec) an extended window (2-66 μsec) is recorded to enable neutron detection.

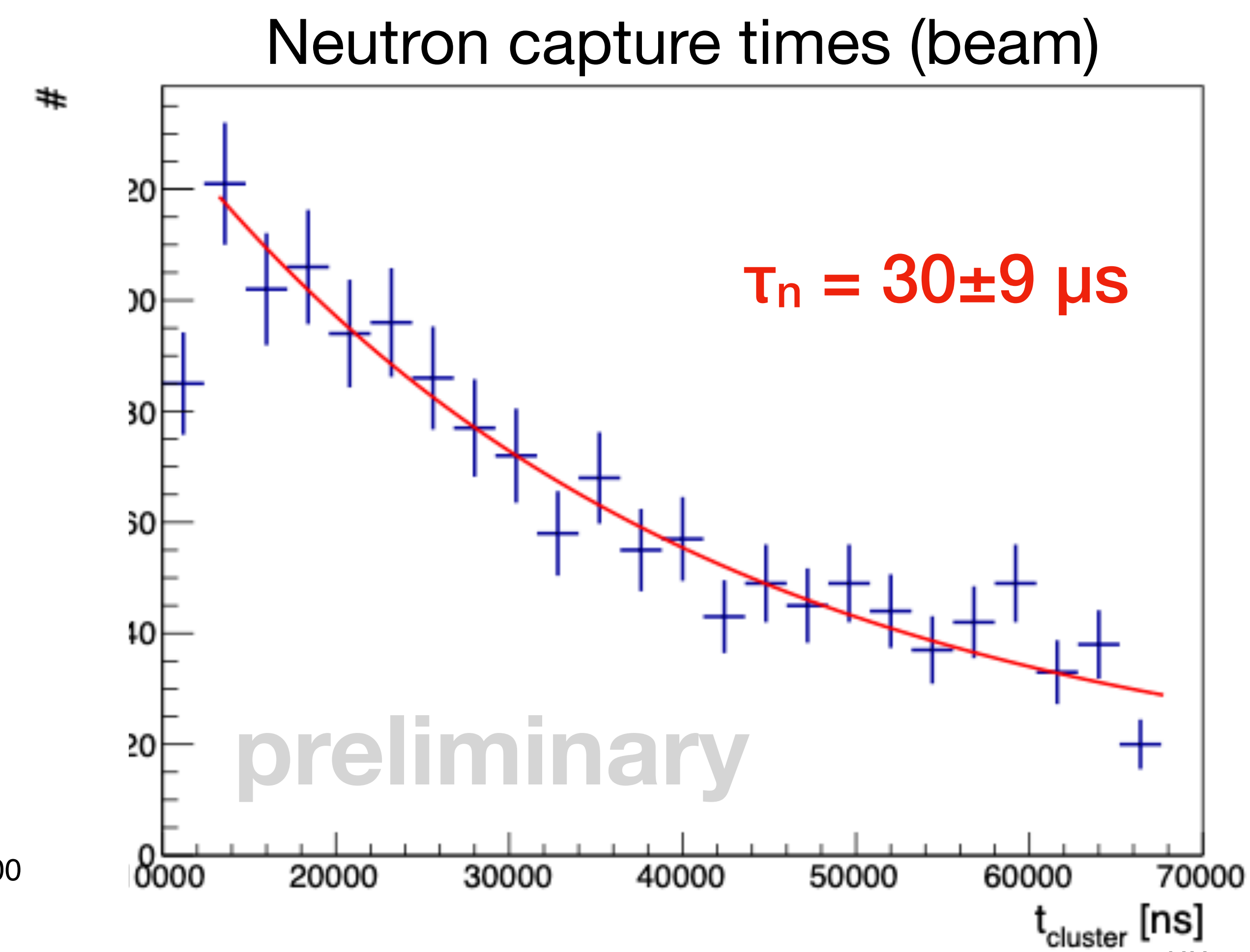




Neutrons in ANNIE Neutrino Beam Data

- 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.

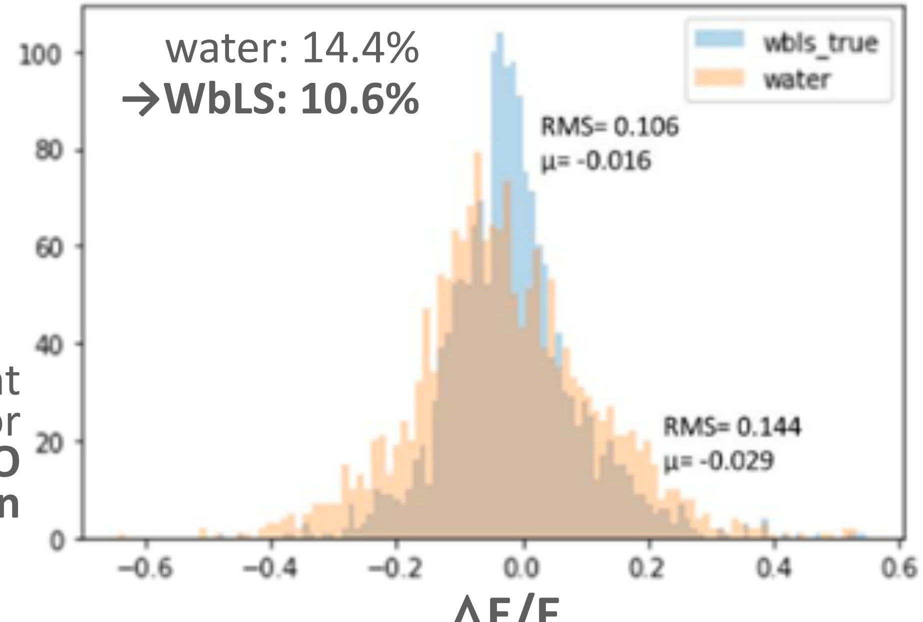




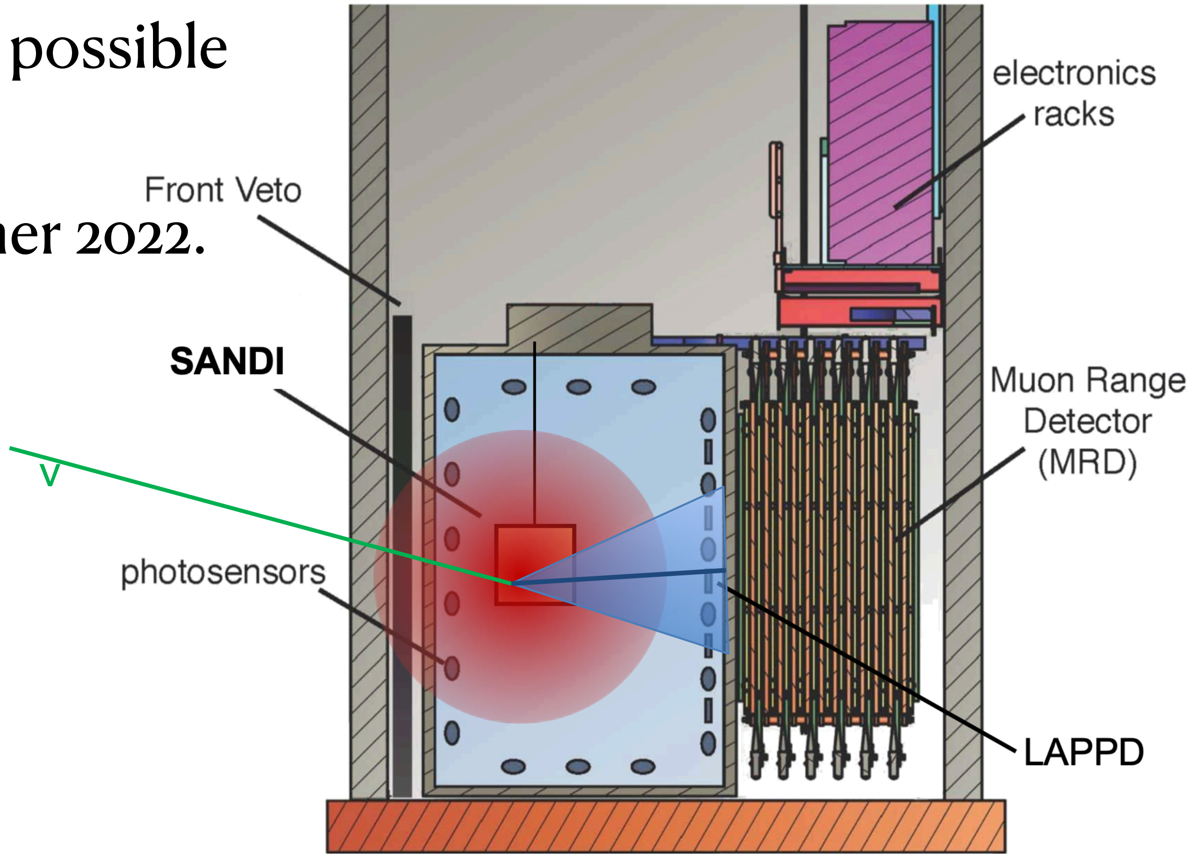
Testing water-based scintillator (WbLS)

- 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