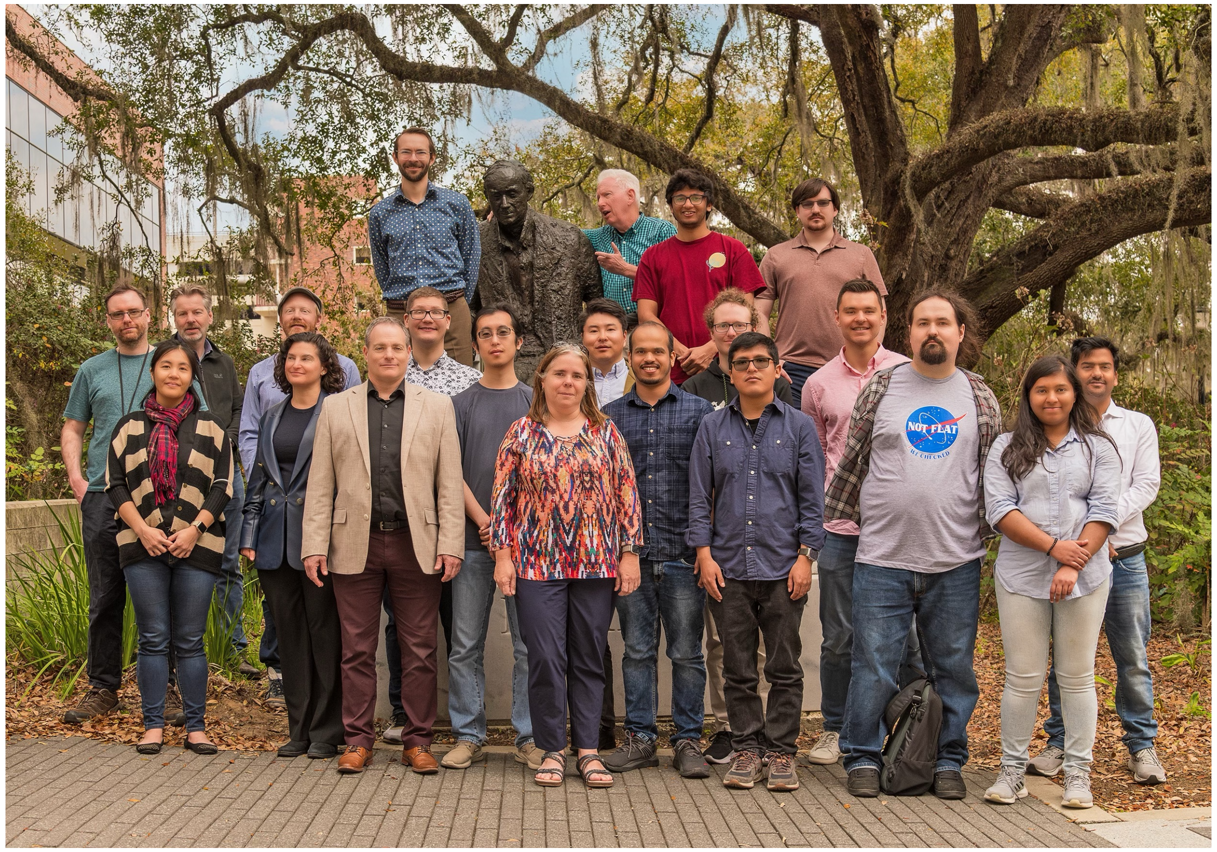
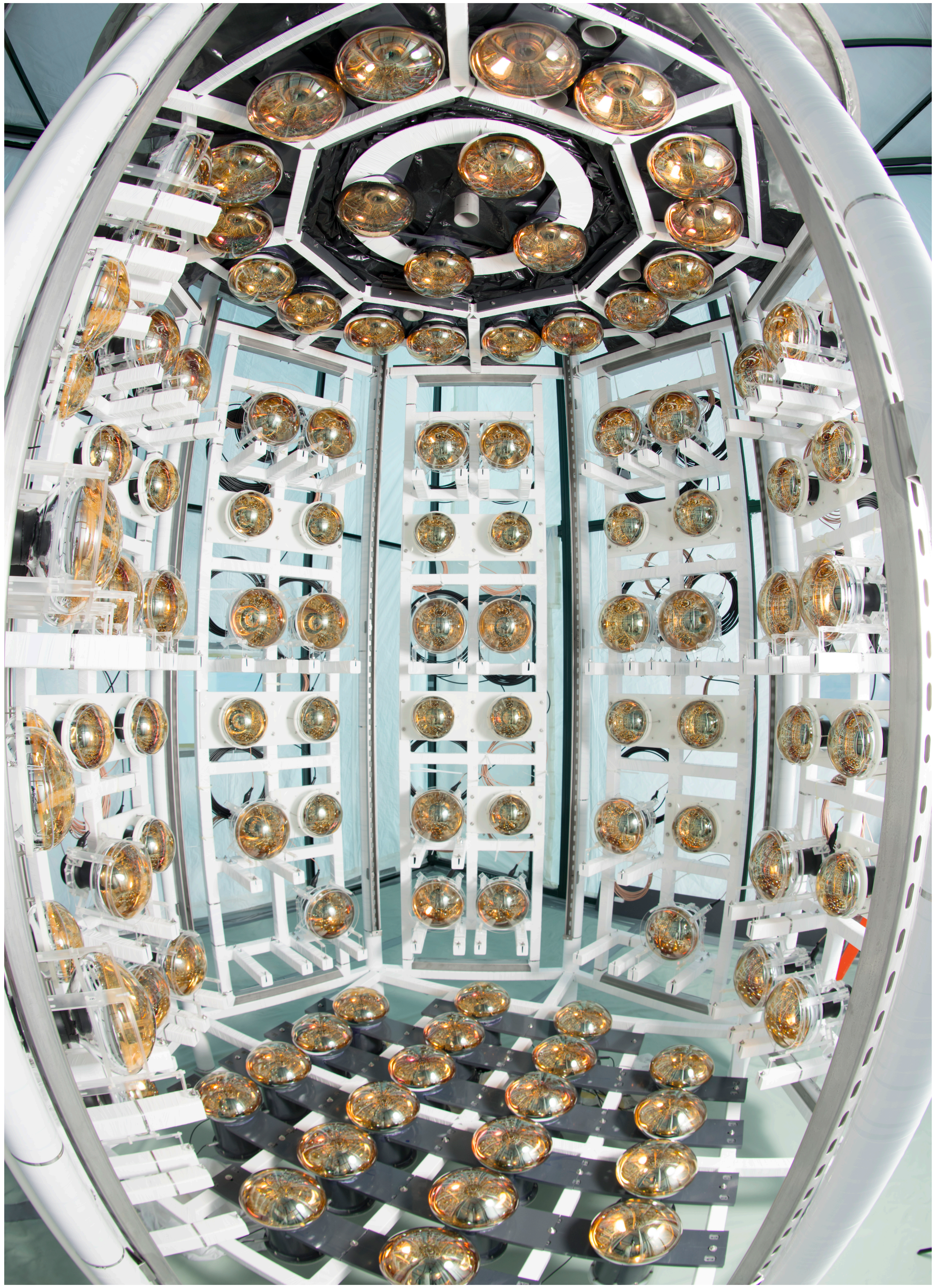
ANNIE Report:

Firsts and Future Plans

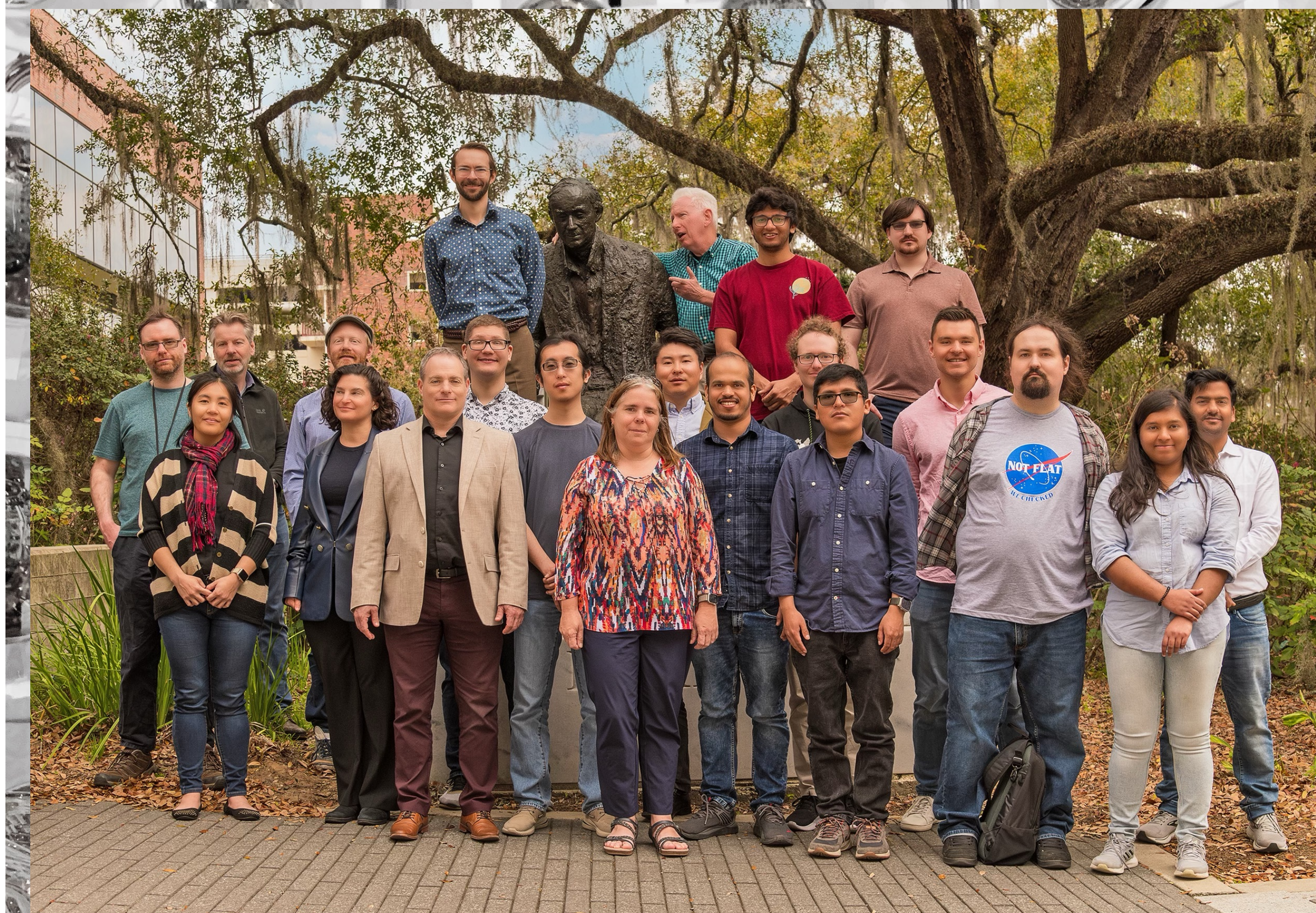
Amanda Weinstein
Iowa State University
On behalf of the ANNIE Collaboration





Fermilab Users Meeting: “Inspirations from P5”   July 11, 2024

The Accelerator Neutrino Neutron Interaction Experiment

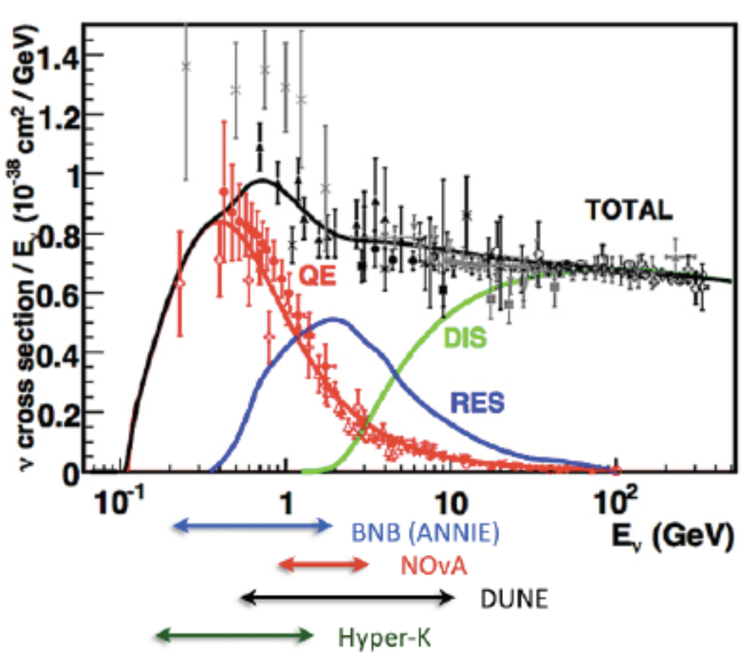


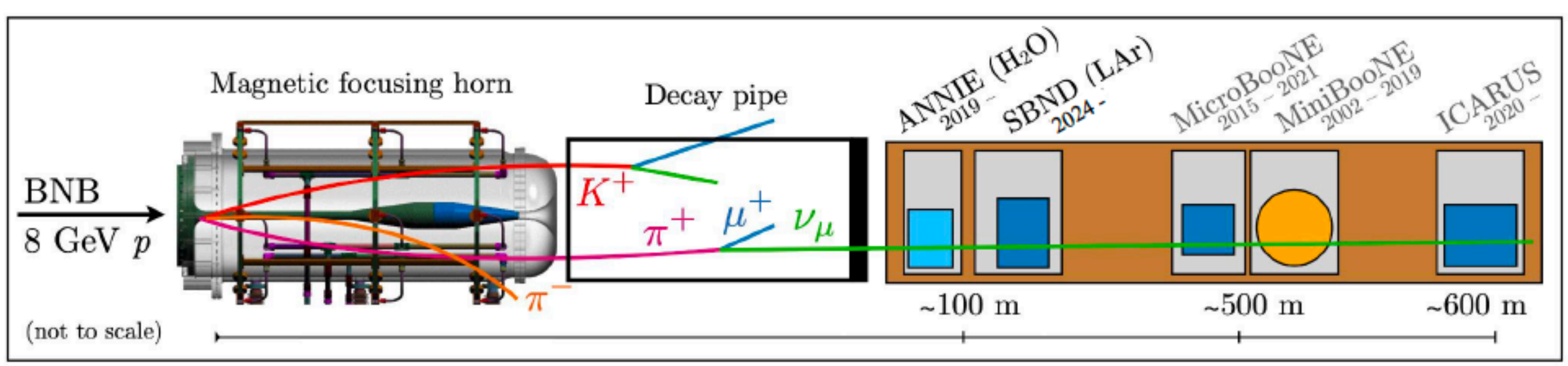
- ANNIE is a neutrino detector deployed on the Fermilab Booster Neutrino Beam.
  - Physics: Study neutrino-nucleus interactions.
  - Technology: R&D platform for new neutrino detection technologies/techniques
  - Training: 10+ ANNIE postdocs/students now have faculty or permanent lab positions.

ANNIE is an international collaboration of 45 collaborators from 17 institutions in 6 countries.

ANNIE Physics Program

- High-flux GeV ν_μ on fixed target →Study of neutrino-nucleus interactions
- Neutrino-induced neutron multiplicity vs. Q^2
  - Probe critical systematic uncertainty for neutrino oscillation measurements.
- Multi-target cross-sections
  - Same neutrino beam as SBN
  - Correlated σ, hadron production with LArTPC $^{40}\mathrm{Ar}$



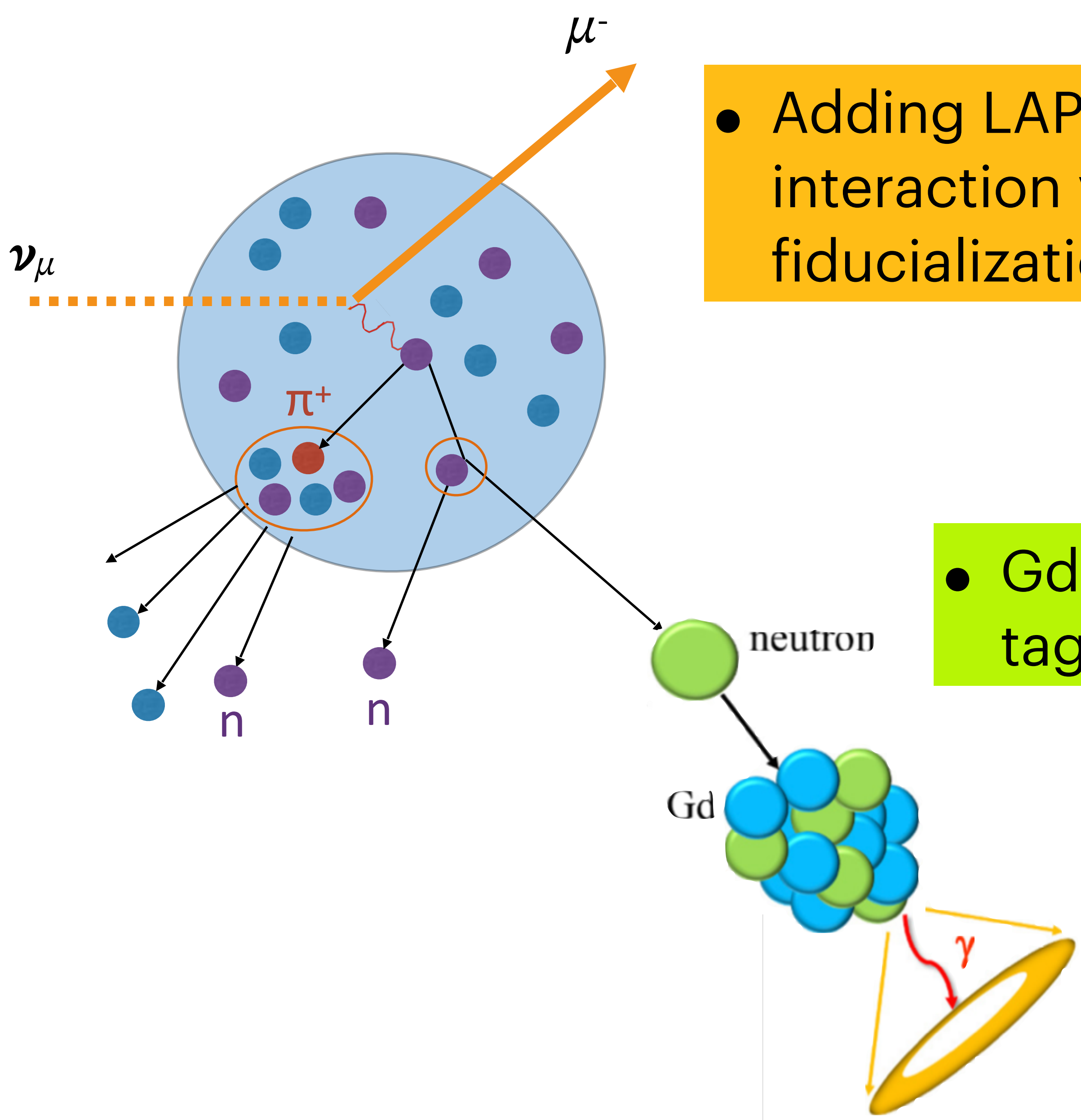


Emerging Technologies

- ANNIE is a flexible test-bed for next-generation detector technologies (novel photosensors/fast timing and novel detection media)

- Adding LAPPDs to PMTs enhances interaction vertex resolution, fiducialization.

- Gd-water (High-efficiency neutron tagging)



Deployable volume of water-based liquid scintillator (WbLS)

(Calorimetry, elements of interaction below Cherenkov threshold)

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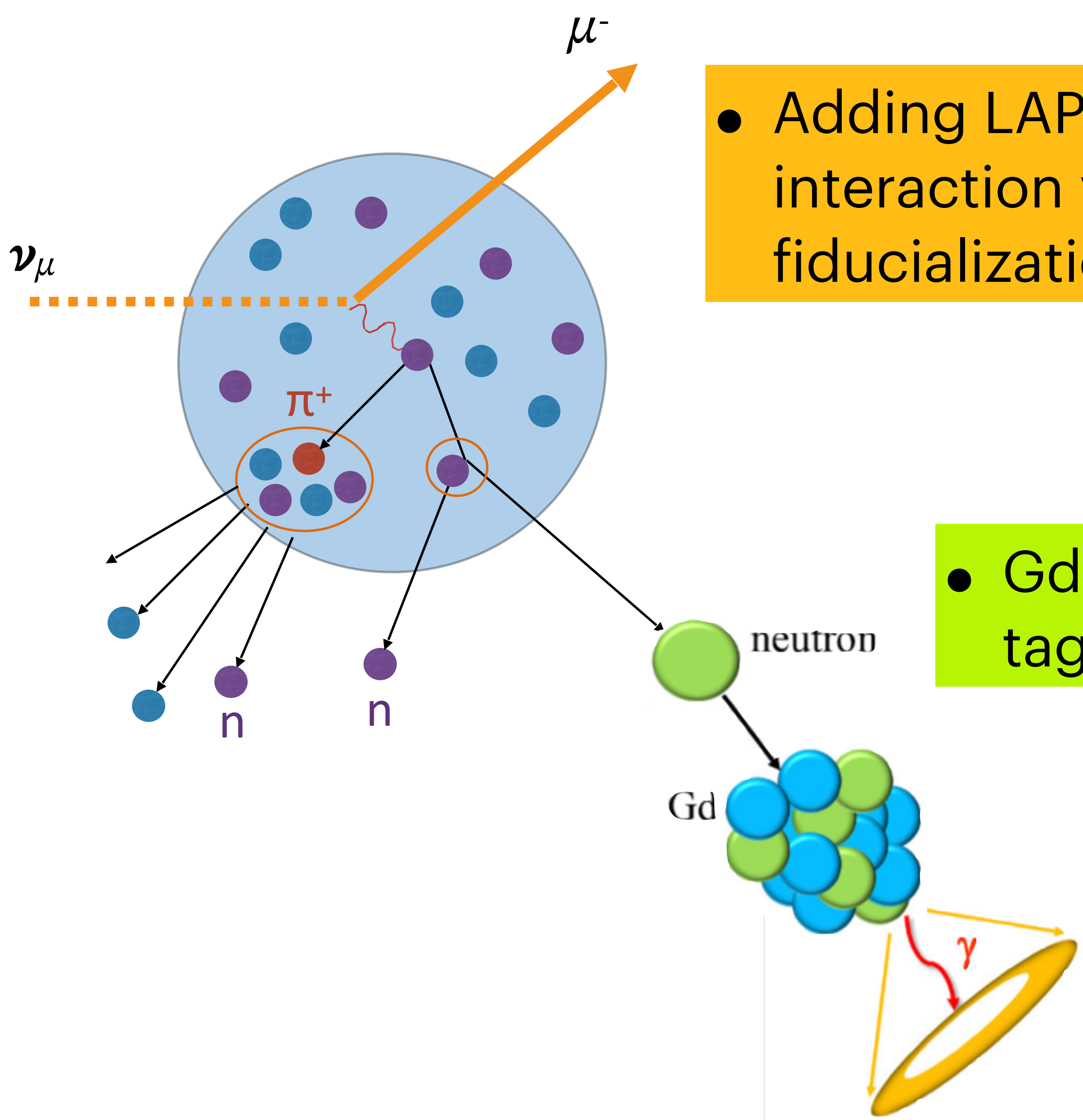


- Adding LAPPDs to PMTs enhances interaction vertex resolution, fiducialization.

First ν in LAPPDs!

- Gd-water (High-efficiency neutron tagging)

First neutrons from νs in Gd-H_20

Deployable volume of water-based liquid scintillator (WbLS)

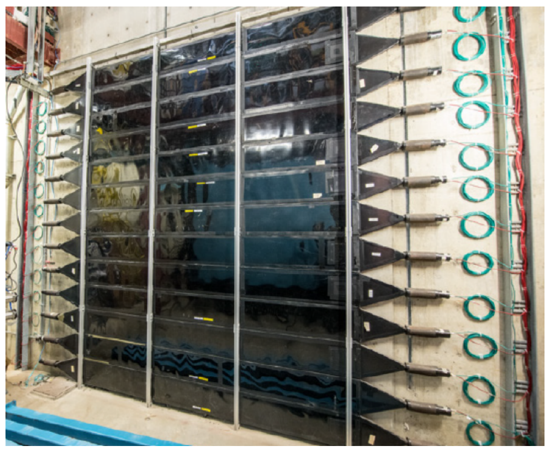
(Calorimetry, elements of interaction below Cherenkov threshold)

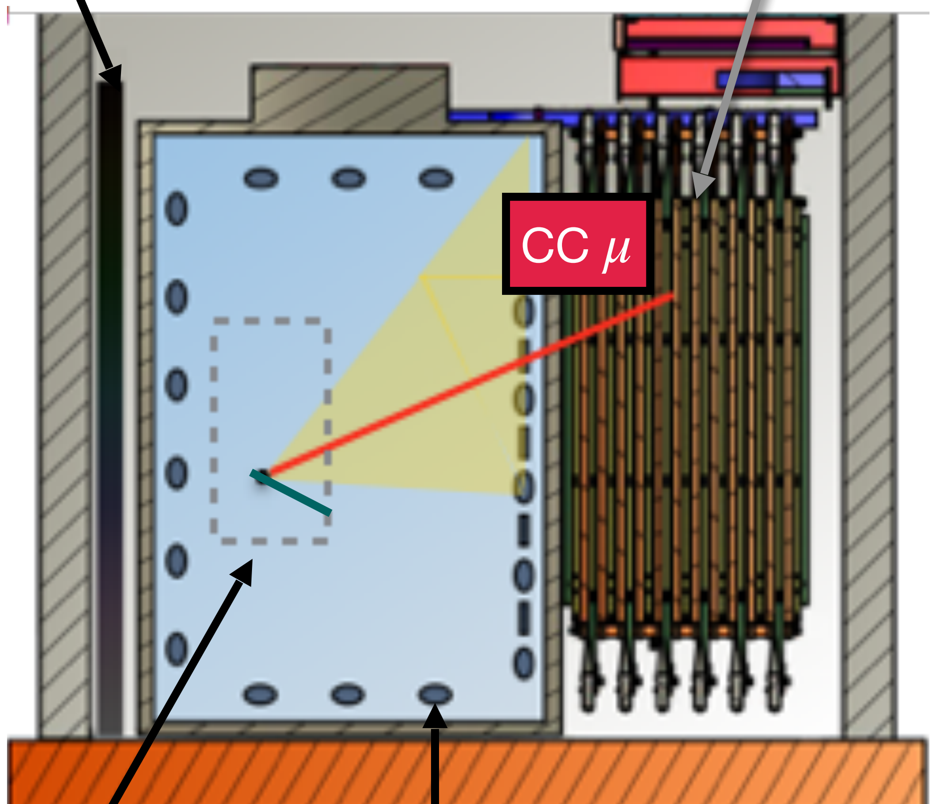
First ν in WbLS!

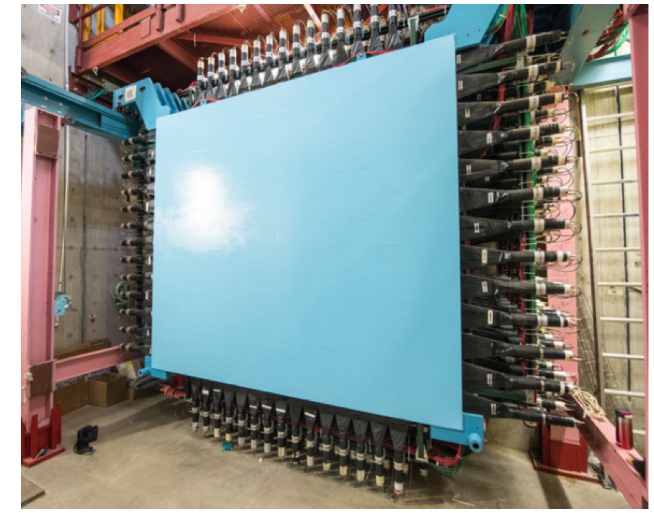
The ANNIE Detector

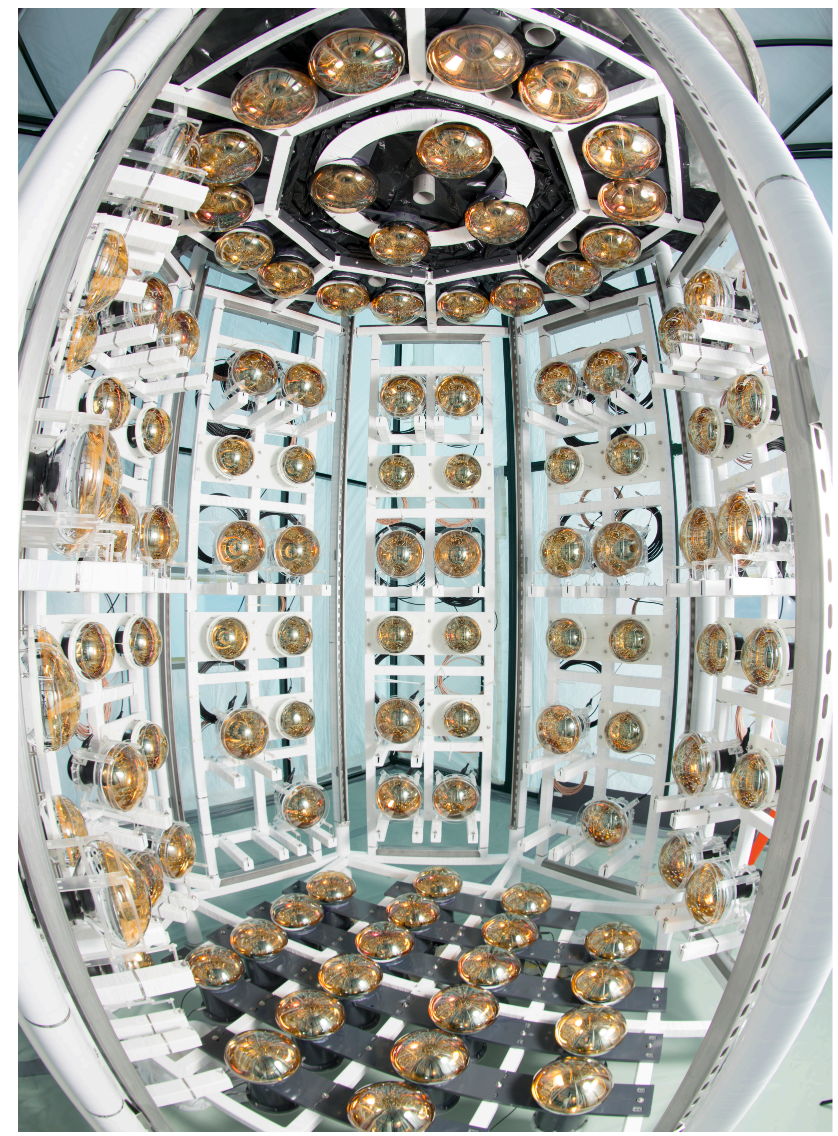
Front Muon Veto (FMV)
(2 overlapping scintillator layers)
Rejects upstream μ

Muon Range Detector (MRD)
11 X-Y layers, alternating scintillator with 5cm iron









132 PMTs (8”-11”)

Water Tank
26 t Gd-H_2O

Prompt μ Cherenkov + MRD track

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(2 overlapping scintillator layers) Rejects upstream μ

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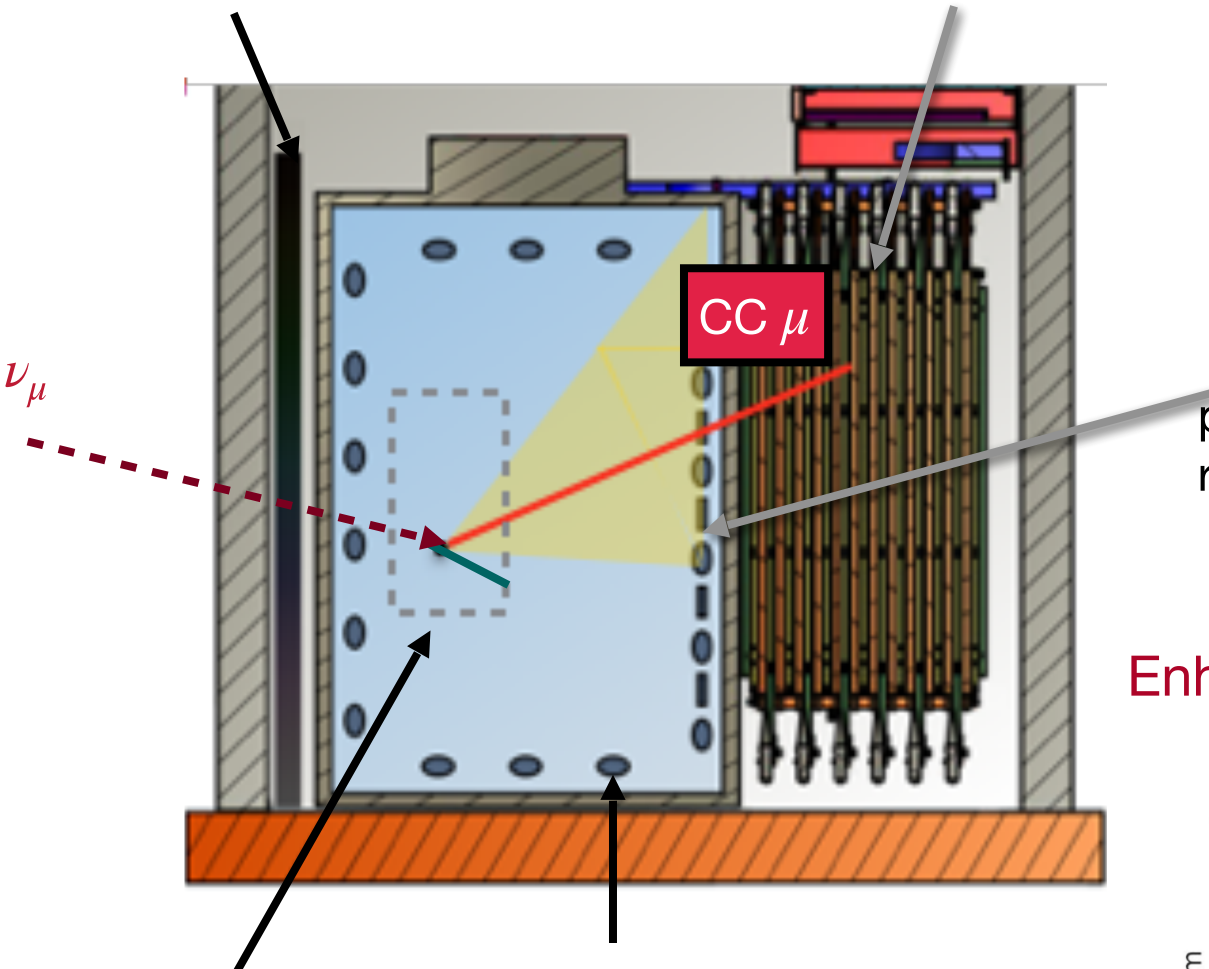
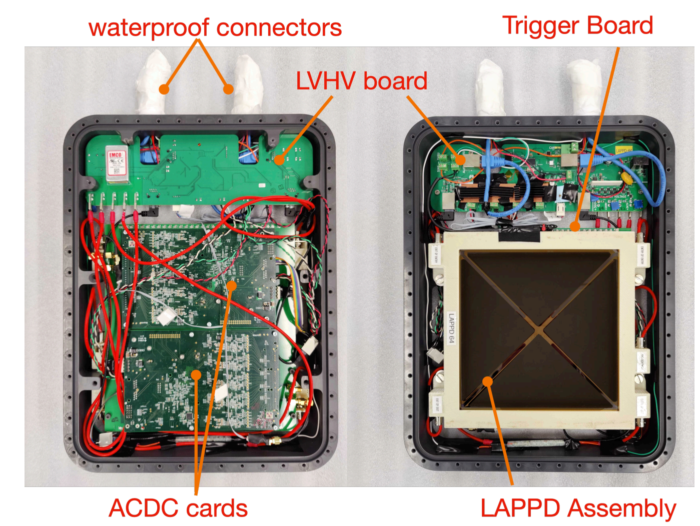
Exploring the Quantum Universe

Potential application in DUNE Phase 2 (MCND)



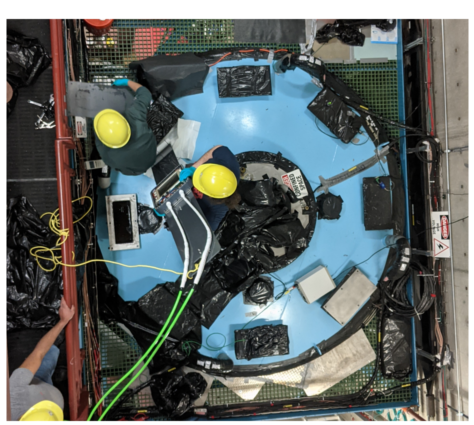
3 20x20 cm LAPPDs (100 ps timing, sub-cm spatial resolution)

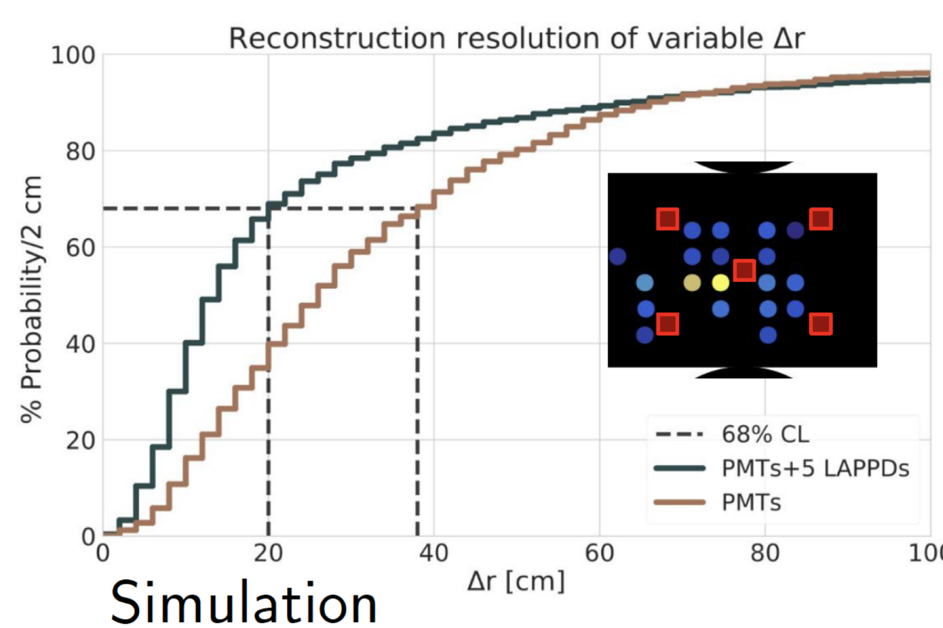


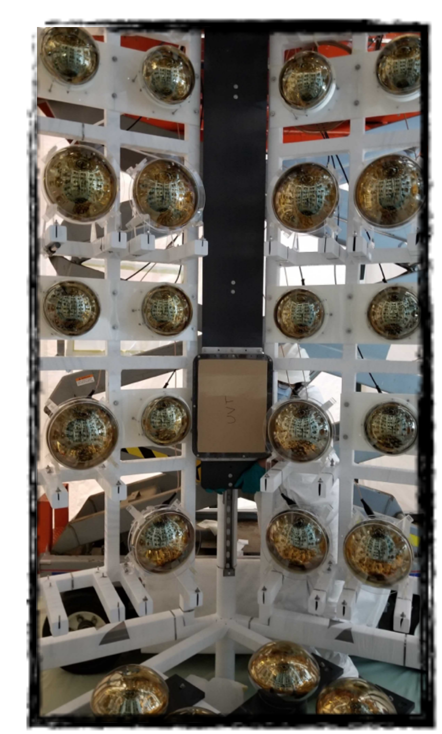
Enhanced μ reconstruction and vertexing

Water Tank
26 t Gd-H_2O

132 PMTs (8"-11")







The ANNIE Detector

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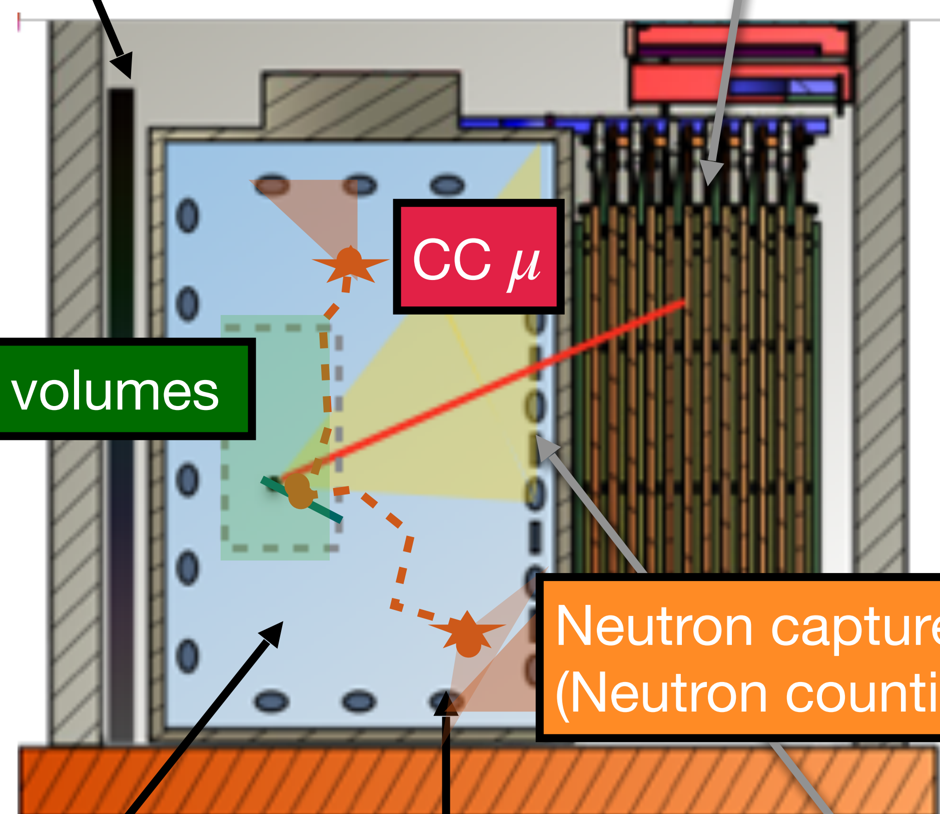


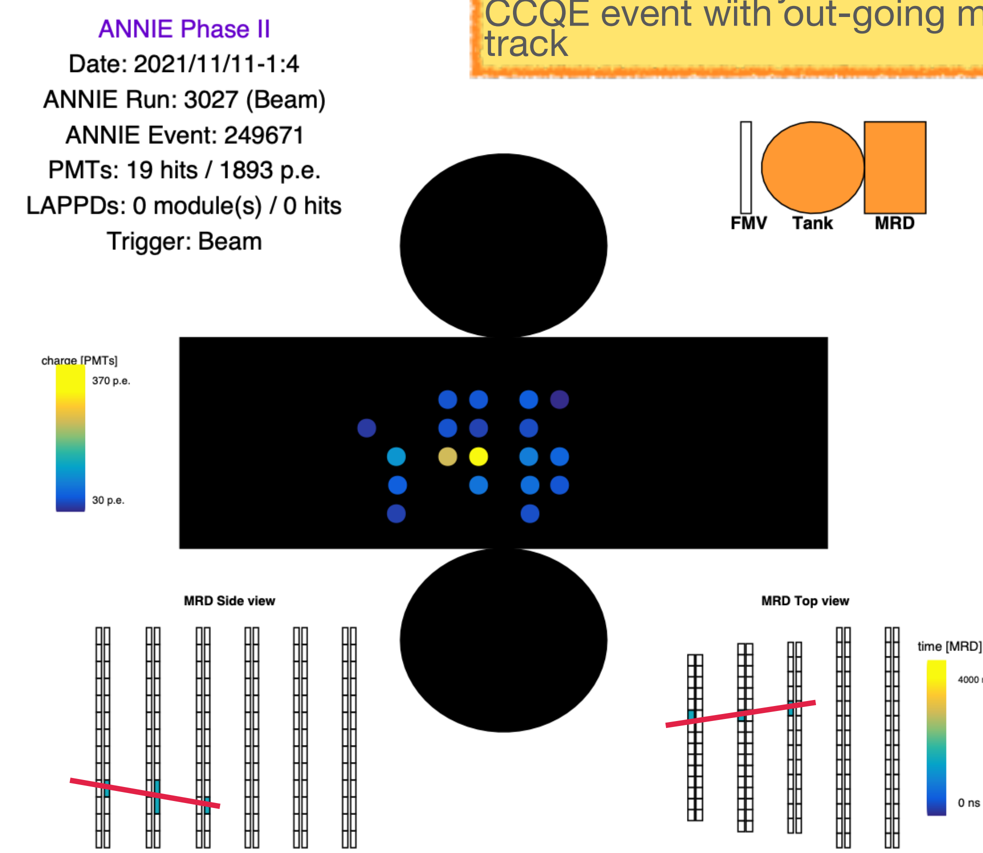
Water Tank
26 t Gd-H_2O

Highest Gd concentration (0.1%)

132 PMTs (8”-11”)

3 20x20 cm LAPPDs (100 ps timing, sub-cm spatial resolution)

PMT event display
CCQE event with out-going muon track

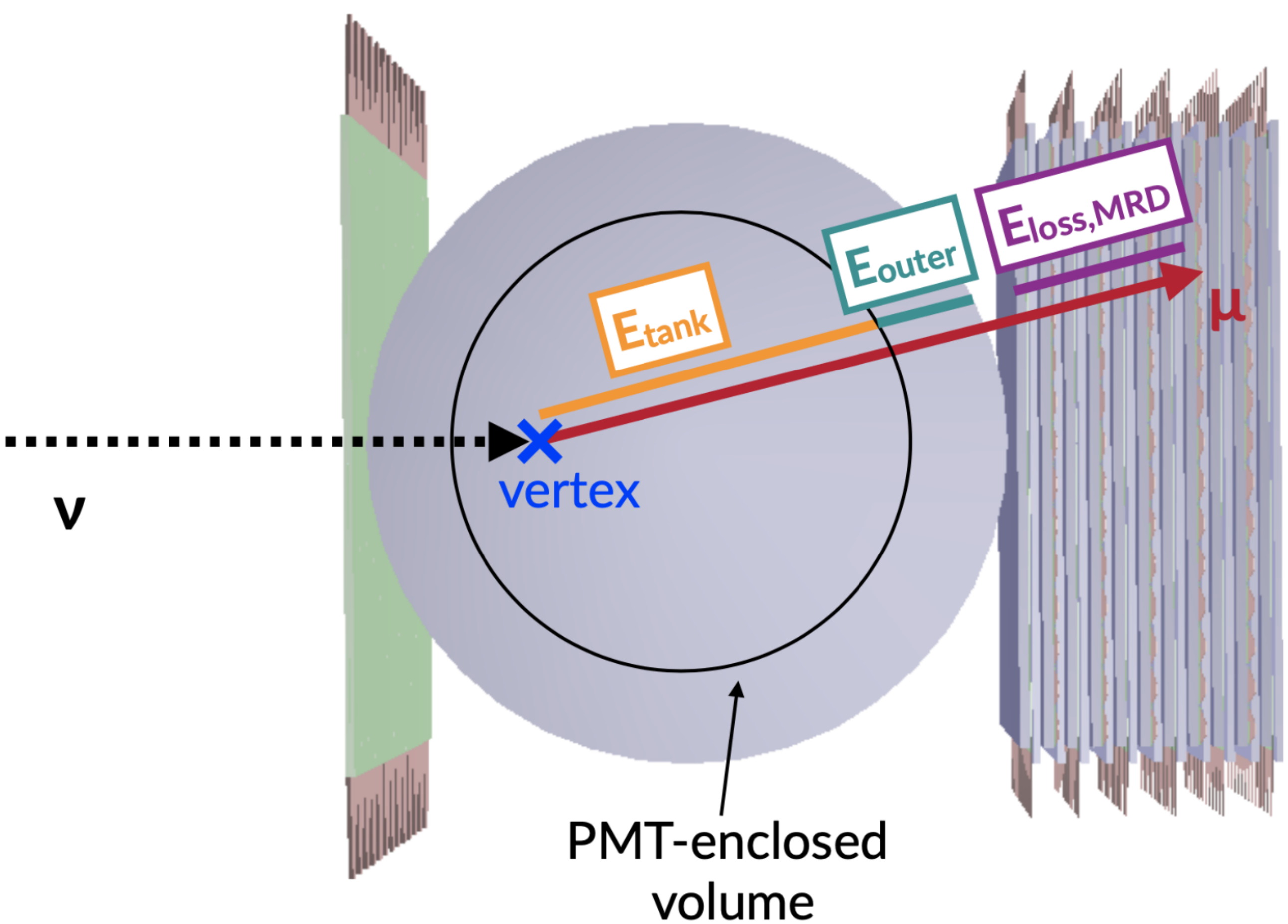


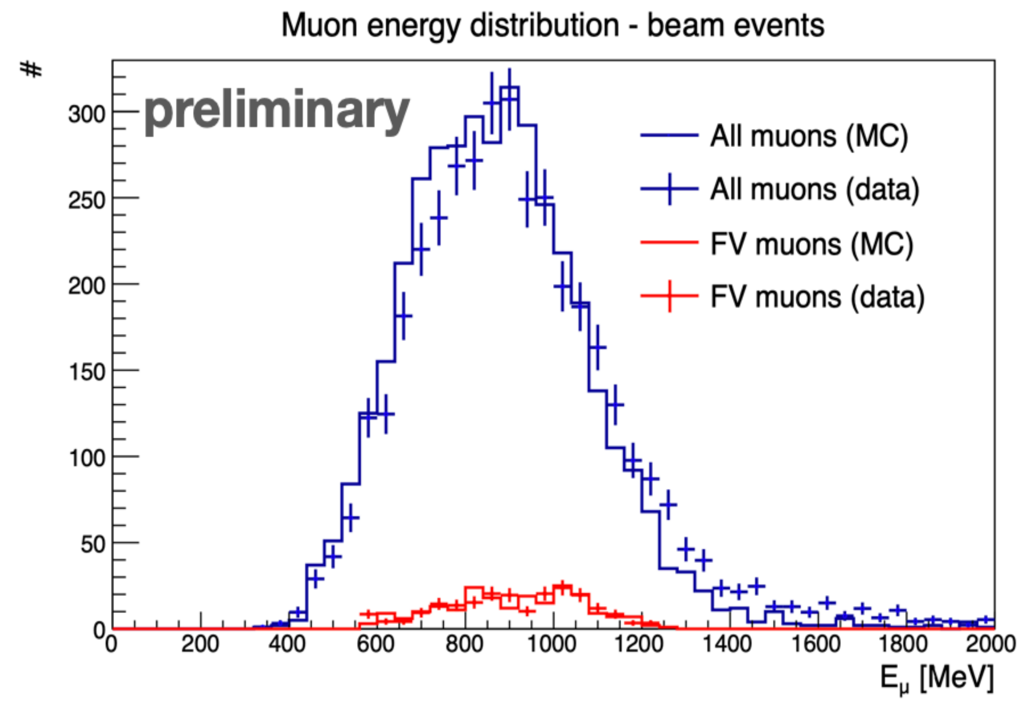
Example Prompt Event

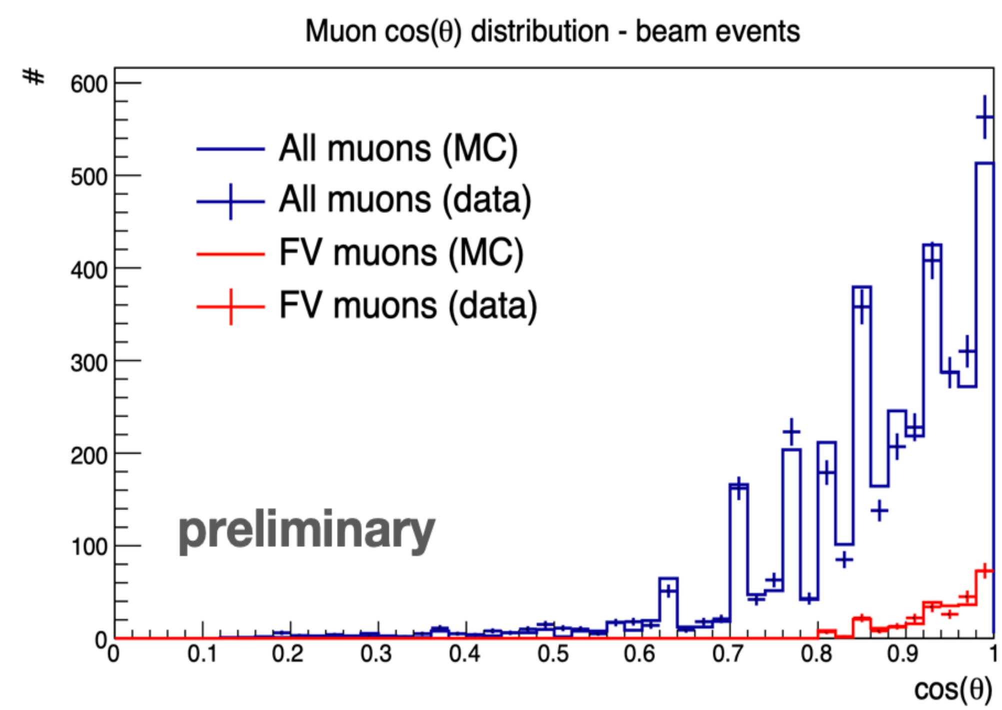
Reconstructing νs in ANNIE

(PMTs only)

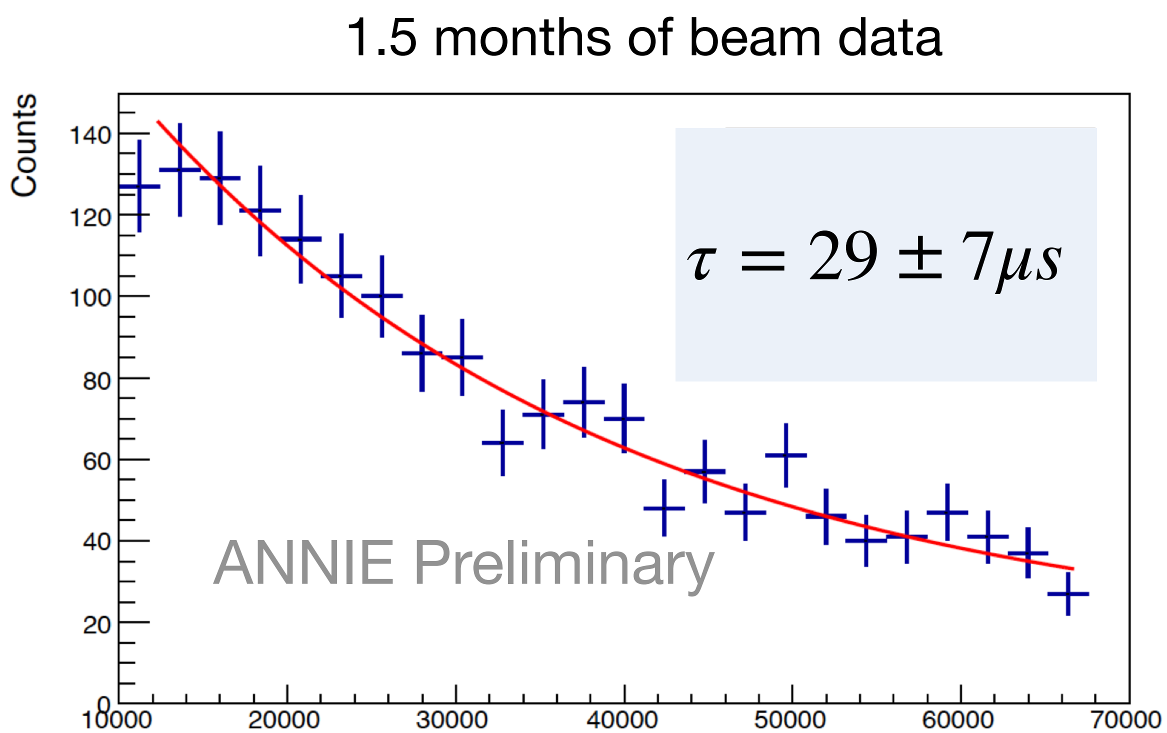
- Reconstruction of final-state muon scattering angle and energy using Cherenkov light output in tank (PMTs) and MRD track information

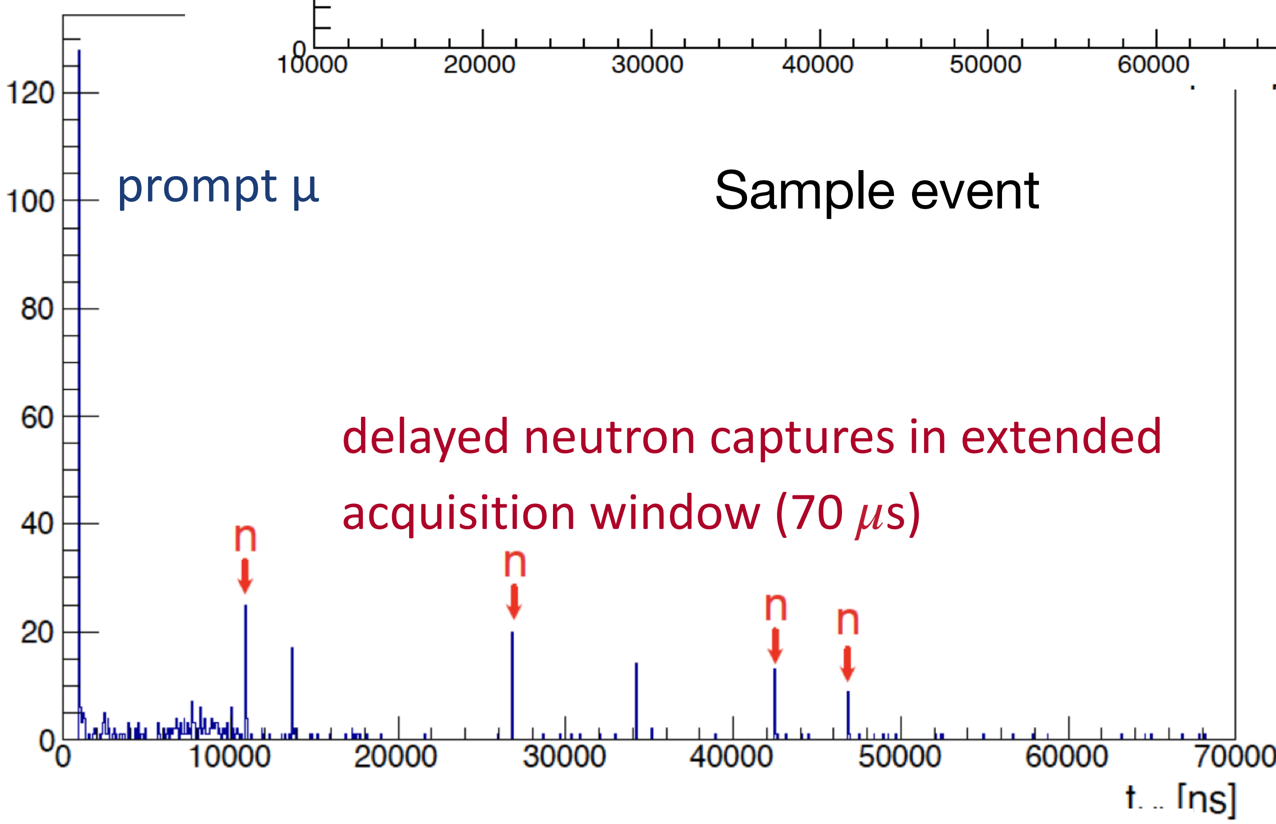






Detecting neutrons in ANNIE

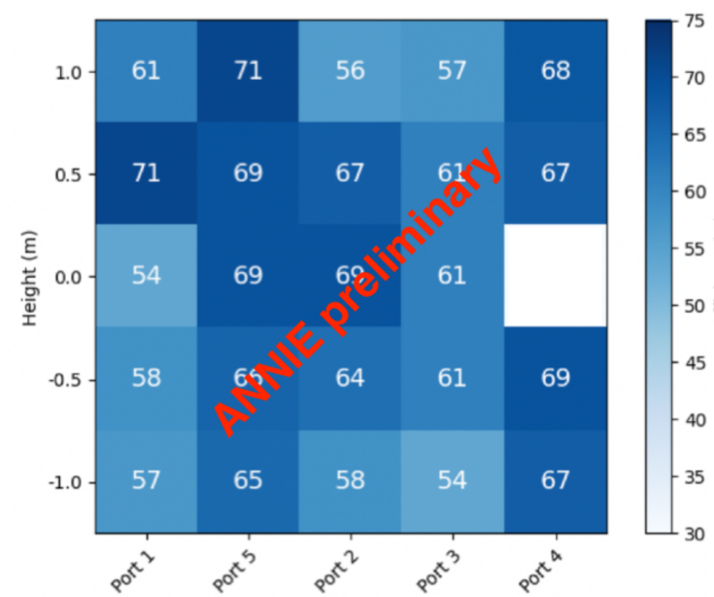


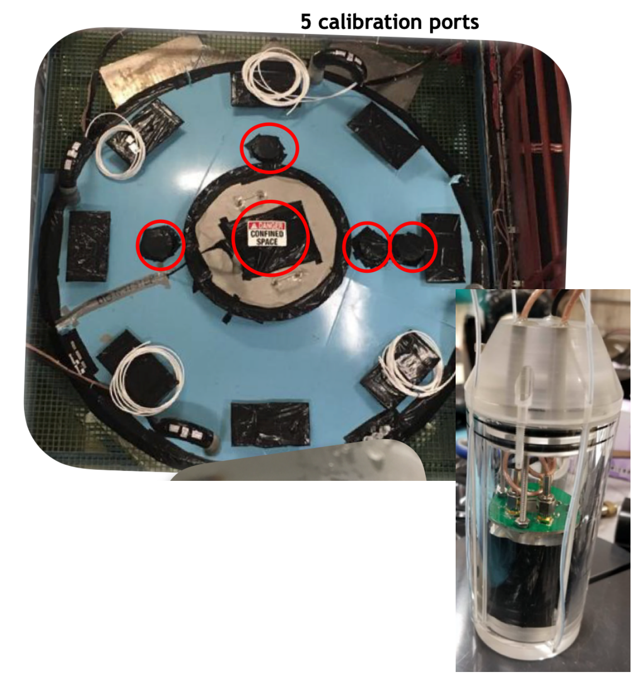


M. Nieslony, PhD thesis (2022)

First neutrons from ν observed with Gd-loaded water

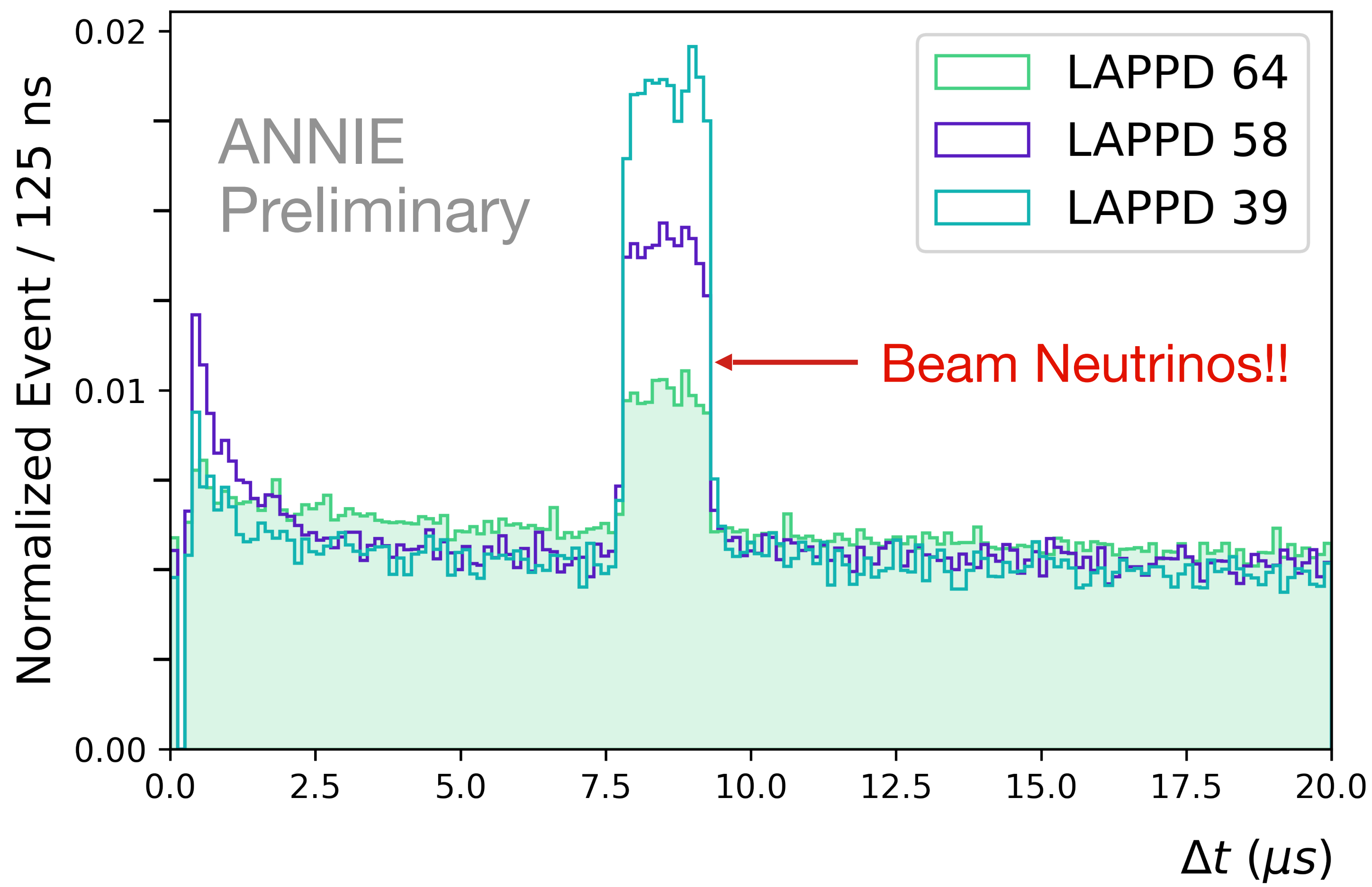
- Tank PMTs used to detect neutrons
- Neutron capture time profile from beam data agrees well with prediction for nominal 0.1% Gd concentration.
- Position dependent neutron capture efficiency has been measured to be consistent with expectations: ~55-70%.

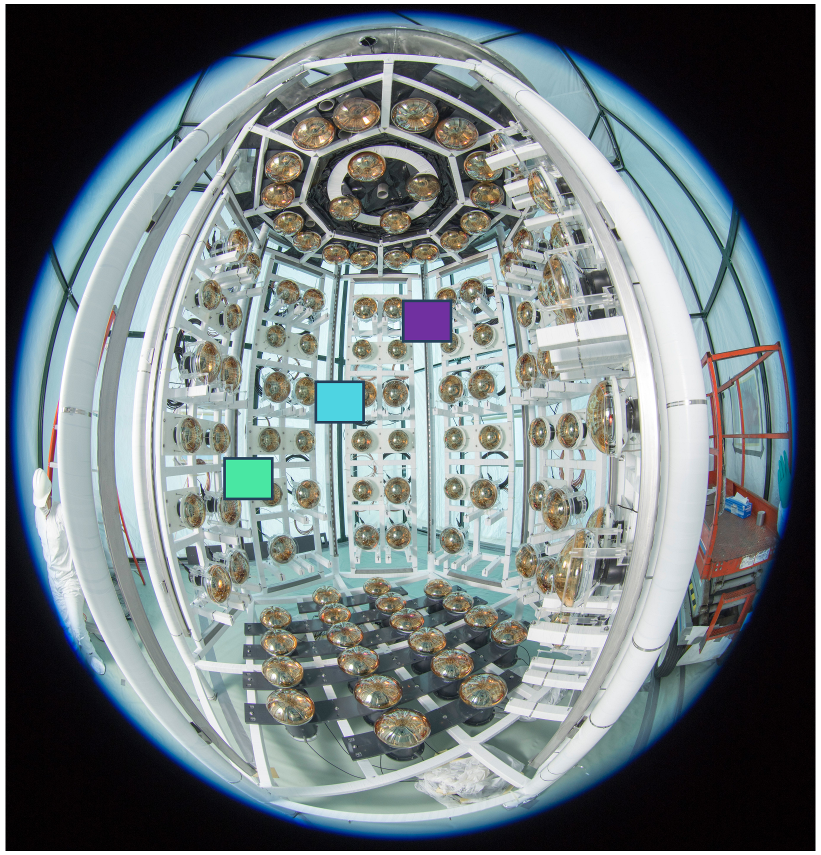




Scaffolding of neutron multiplicity measurement in place

First Neutrinos on (multiple) LAPPDs

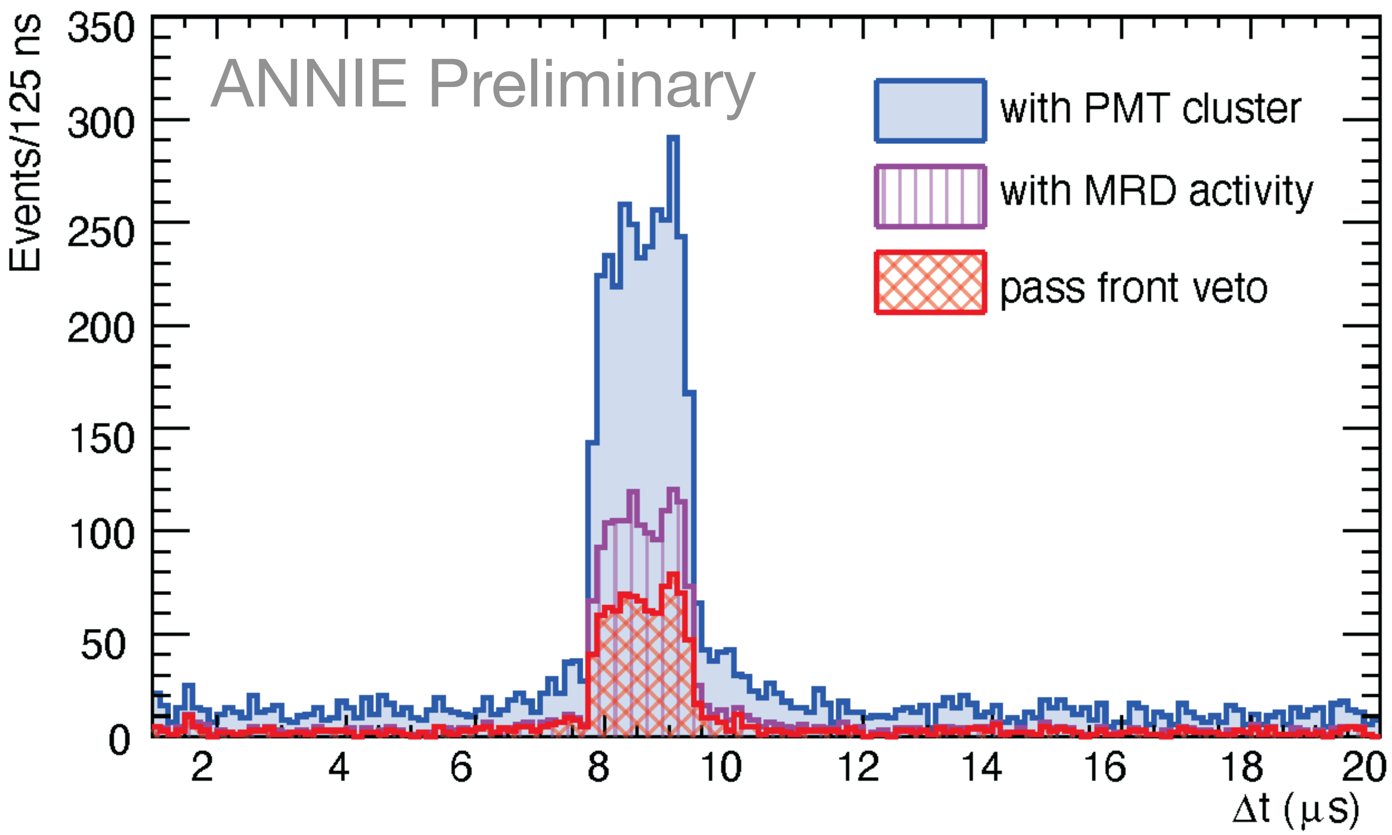


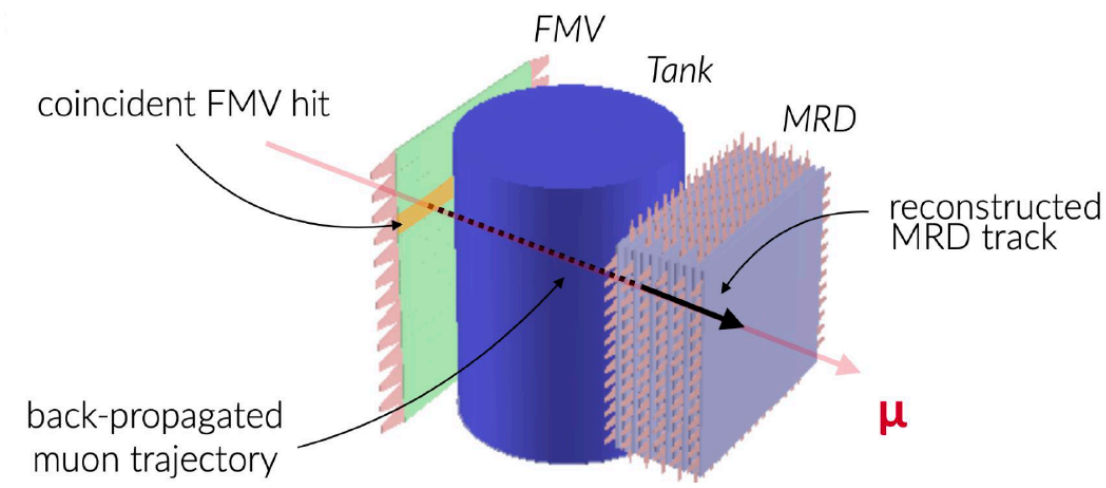


- Neutrinos seen concurrently by the 3 LAPPDs currently operating in ANNIE (a first!)
  - 1.6 μsec wide excess = LAPPD-triggered events in-time with the BNB spill.

World's first: neutrinos observed with an LAPPD!

Single-LAPPD ν Reconstruction

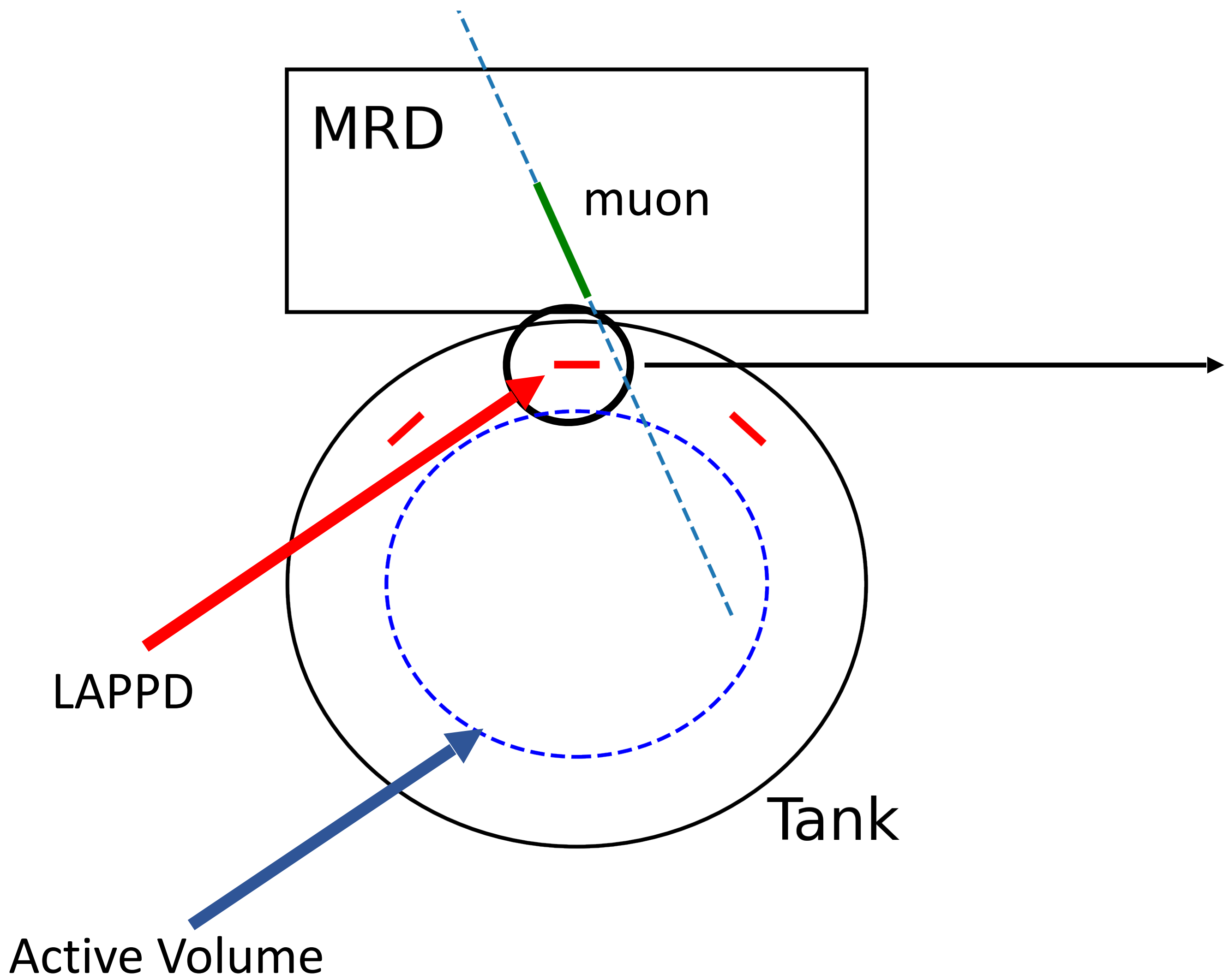


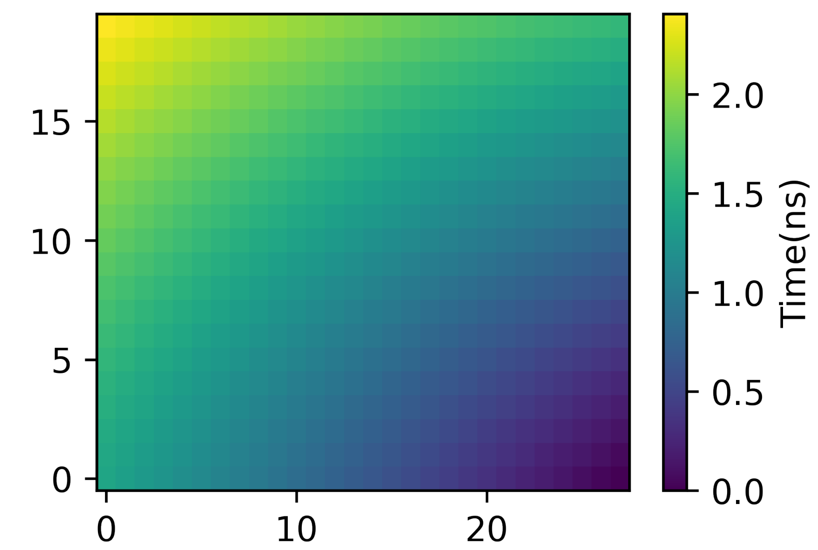


- 2022-23 single-LAPPD data at central position
- Dark noise accidentals reduced by requiring coincidence with tank PMTs
- Require MRD coincidence (muon) [CC ν_μ]
- CC neutrino interactions in tank selected by removing events that interact in the forward veto

Golden sample for imaging/reco studies

LAPPDs are Imaging Photosensors

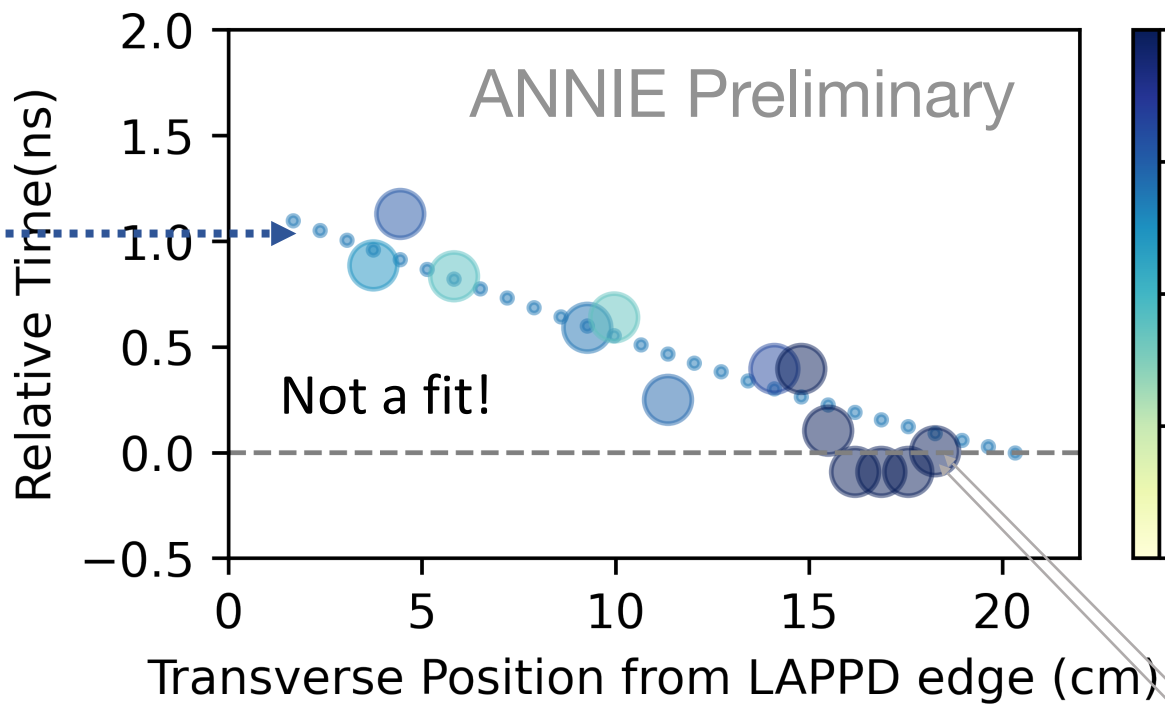


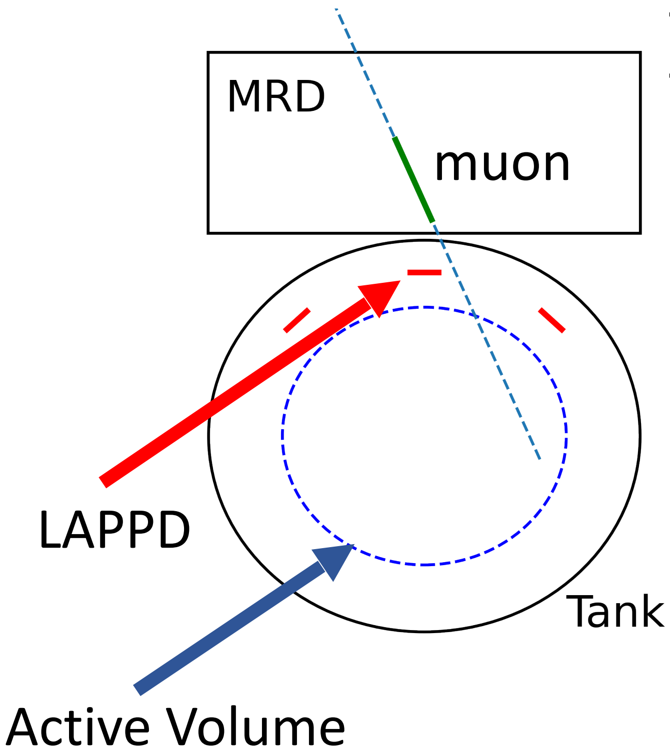


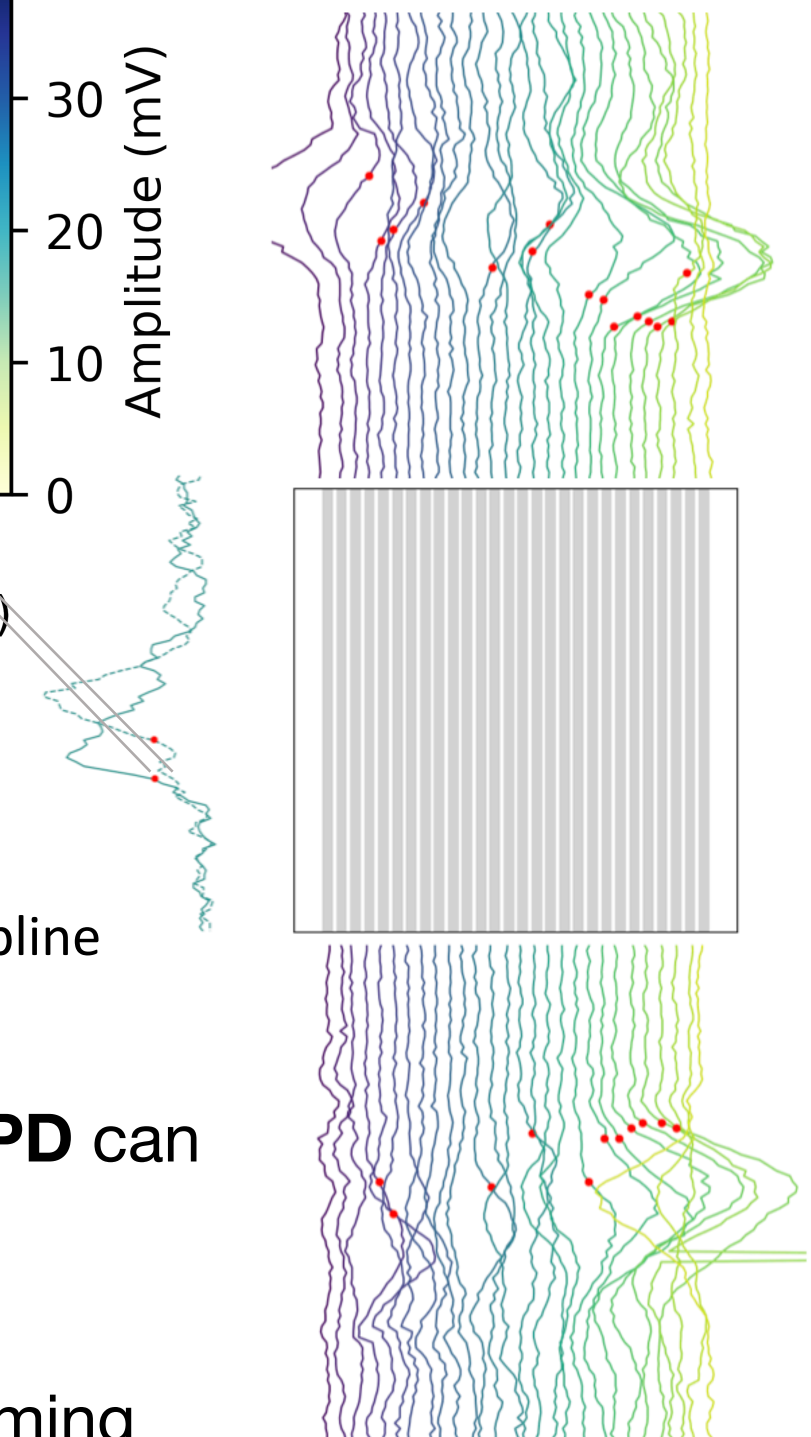
- LAPPDs can reconstruct simultaneous time and spatial gradient of light on their surface

LAPPDs are Imaging Photosensors!

Predicted avg. arrival time vs strip from independently reconstructed muon track (MRD)







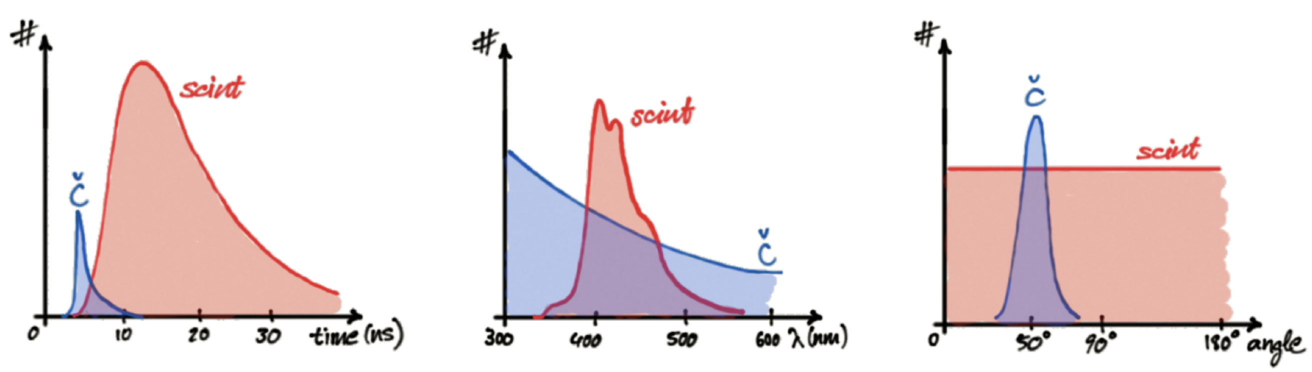
Transverse reconstruction:
Avg. arrival time at both sides of stripline

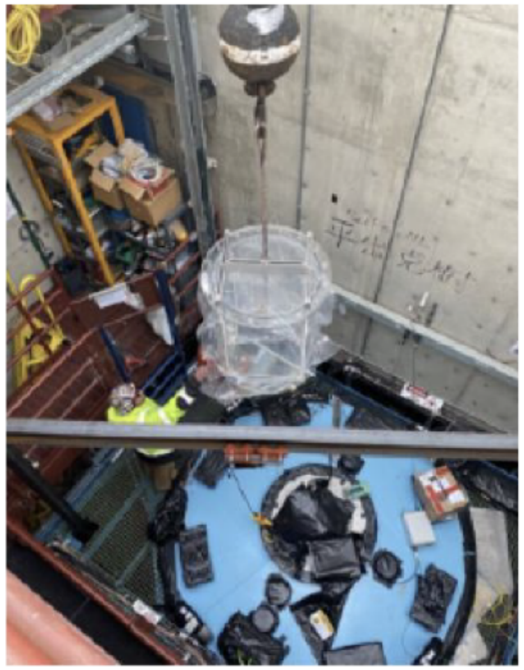
- Time evolution of Cherenkov ring across a **single LAPPD** can reconstruct track direction
  - Sub-ns gradient resolved
- First step toward full 3D reconstruction and absolute timing benchmarks. (Paper in prep.).

First Water-based LS Deployment in a ν beam

- Hybrid detection of scintillation and (unabsorbed) Cherenkov signals
  - Enhanced neutrino energy reconstruction
  - Enhanced background rejection, particle ID
  - Enhanced neutron signals

- SANDI
  - ~3’×3’ acrylic vessel containing 356 kg of 0.5% LS water-based liquid scintillator (WbLS)
  - Deployed March 2023





Exploring the Quantum Universe

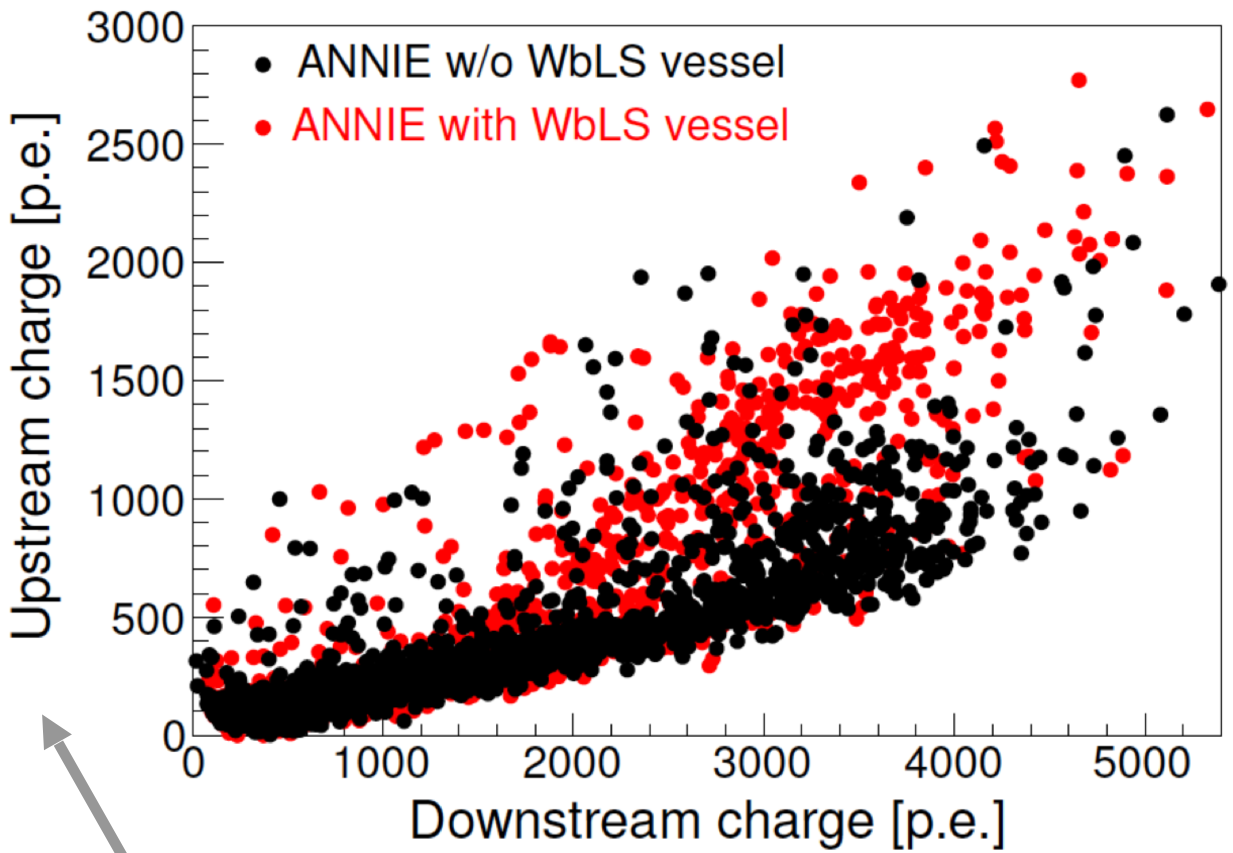
Candidate technology for DUNE FD4

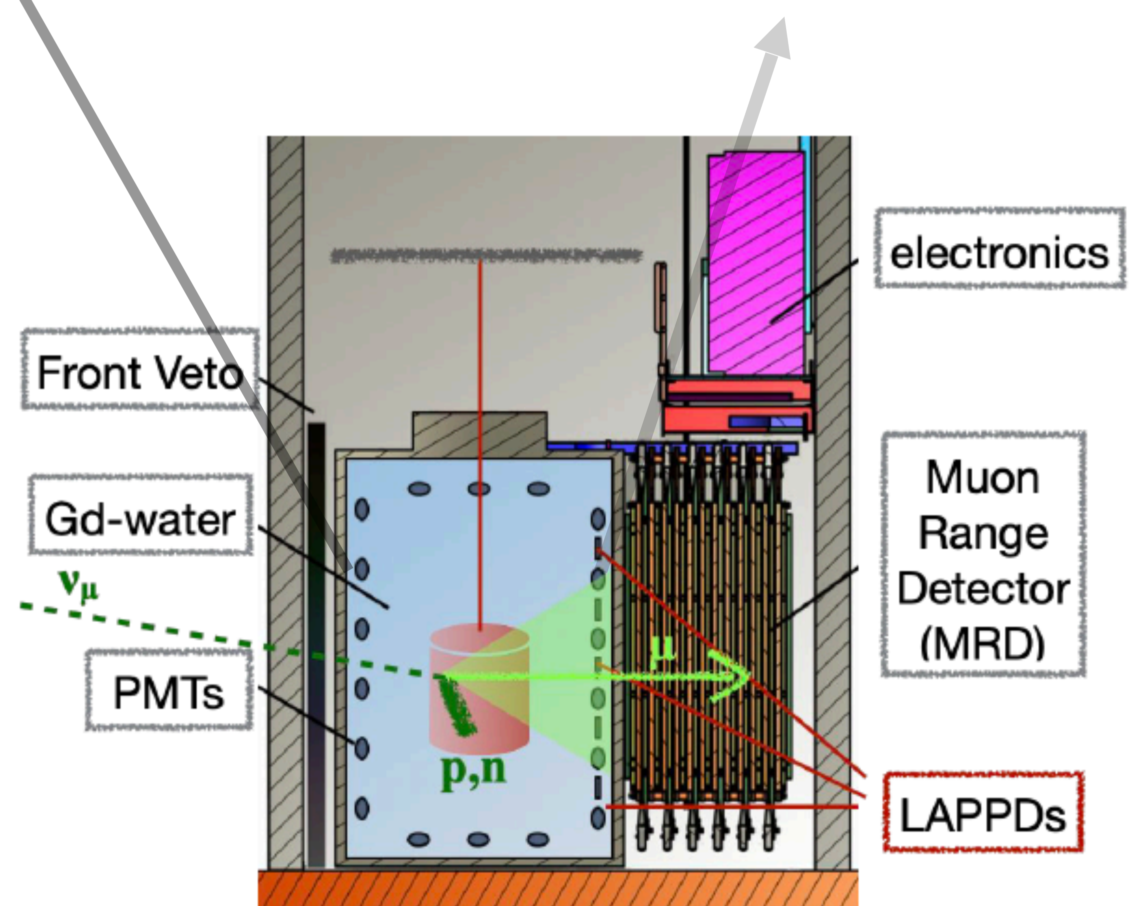
First Water-based LS Deployment in a ν beam

- March -May 2023 (2 months) = few thousand events
- Candidate neutrino events with WbLS vessel show substantially more light in upstream PMTs
    - Now published in JINST →

M. Ascencio-Sosa *et al* 2024 *JINST* **19** P05070

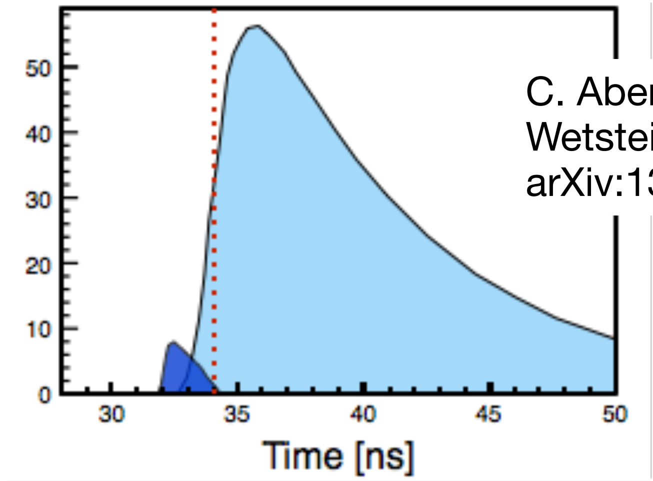
First beam ν observed in WbLS!





Upcoming Fast-Timing Applications

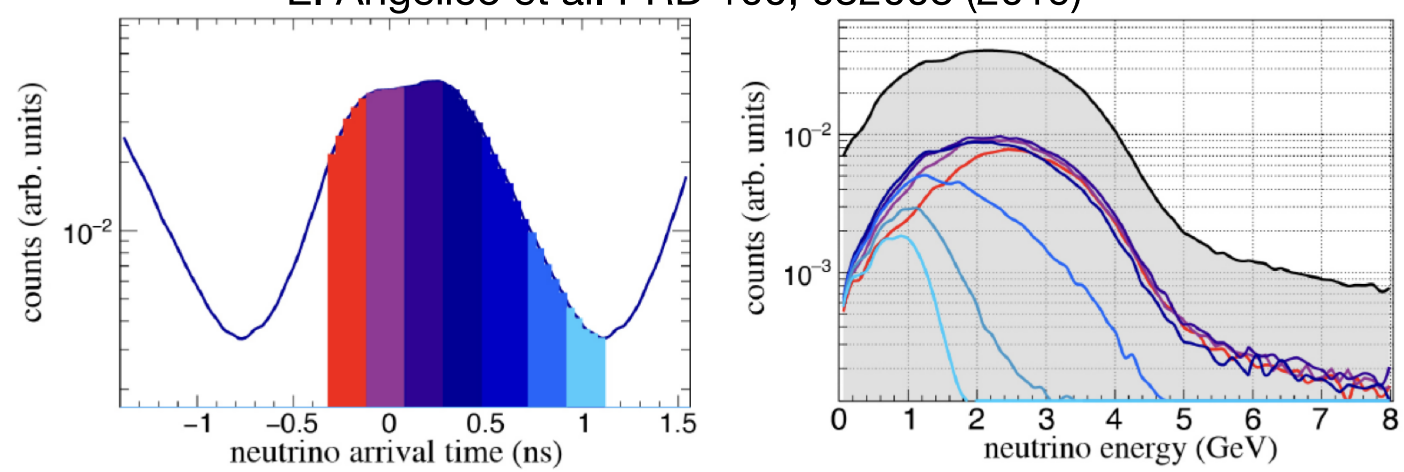
- Timing-based separation of Cherenkov and scintillation light in WbLS using LAPPDs.



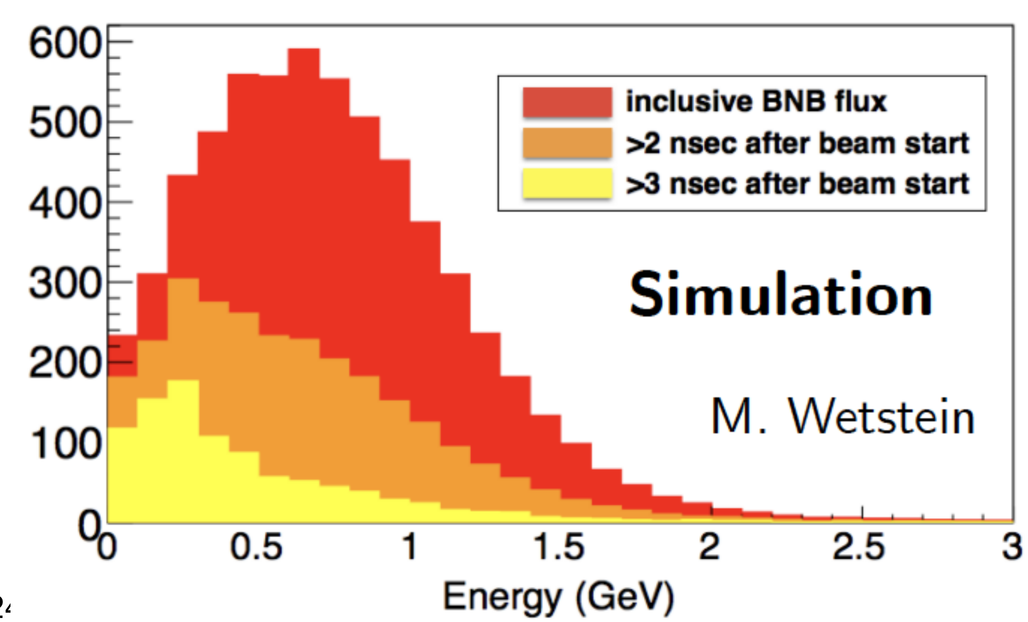
C. Aberle, A.Elagin, H.J Frisch, M. Wetstein, L. Winslow. arXiv:1307.5813

- Fast timing could provide a complementary approach to off-axis "prism" approaches
  - Lower-energy hadrons →lower β→later ν
  - ANNIE with LAPPDs could demonstrate this stroboscopic technique with ns-scale binning and BNB beam.

E. Angelico et al. PRD 100, 032008 (2019)



250 ps bunches, 100 ps detector ("LBNF" with rebunching)



Summary

- ANNIE is the very **first** experiment to use Gd-loaded water, water-based scintillator and LAPPDs for the detection of neutrinos.
  - Significant operational experience gained with these technologies.
  - Neutrino reconstruction and neutron capture demonstrated in Gd-water data.
  - First data with single LAPPD demonstrates LAPPDs as powerful imaging photosensors.

- ANNIE is in a unique position to measure neutrino-nucleus-cross sections in water
  - Complementary sensitivity to LAr-TPCs (neutron vs. proton yield!)
  - Directly comparable due to MicroBooNE/SBND argon data in the same beam.

- With 3+ LAPPD modules installed and commissioned, ANNIE is set for two years of high-quality data taking to leverage the excellent event reconstruction enabled by multiple LAPPDs.

Looking Ahead

- ANNIE is an ideal testing ground for WbLS for hybrid Cherenkov/scintillation reconstruction of neutrino events in future long-baseline experiments.
  - Larger data sample with multi-LAPPD read-out
  - Demonstrate C/S separation based on LAPPD data
  - Look for scintillation-only hadronic neutral current events
  - Plans for Gadolinium-loaded WbLS → enhanced neutron detection

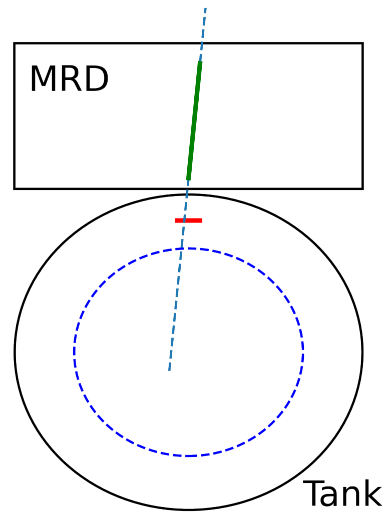
- Plans for R&D program with an **enlarged WbLS volume** and **new upstream LAPPDs with updated electronics**.
  - Received positive feedback from the Fermilab PAC.
  - **A high-statistics measurement is a key step in demonstrating these technologies for long-baseline neutrino experiments.**

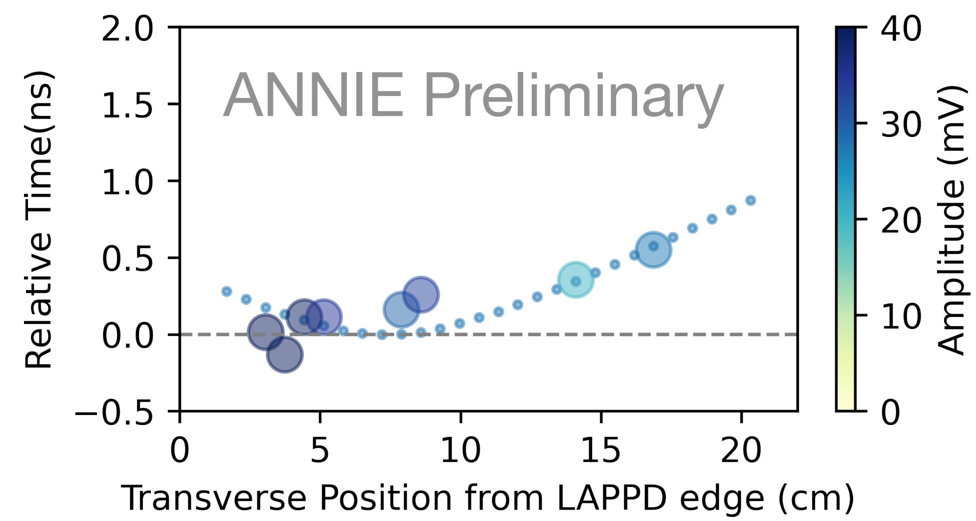
Exciting times ahead for ANNIE!

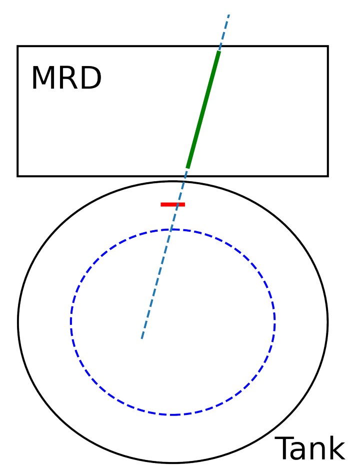
Additional Slides

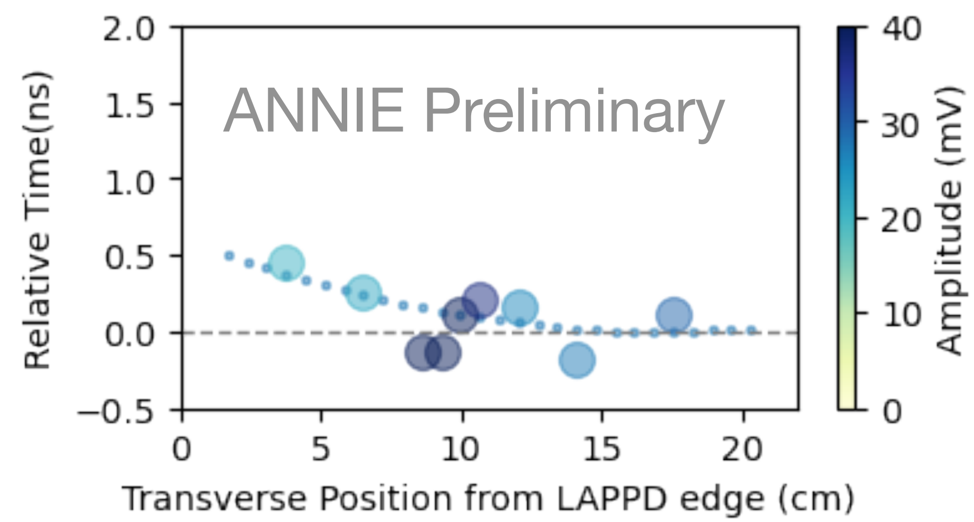
LAPPDs are Imaging Photosensors

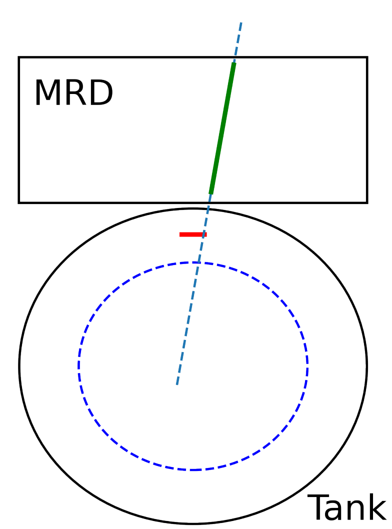
- Qualitative difference between
  - Tracks to left and right of LAPPD
  - Tracks intersecting LAPPD

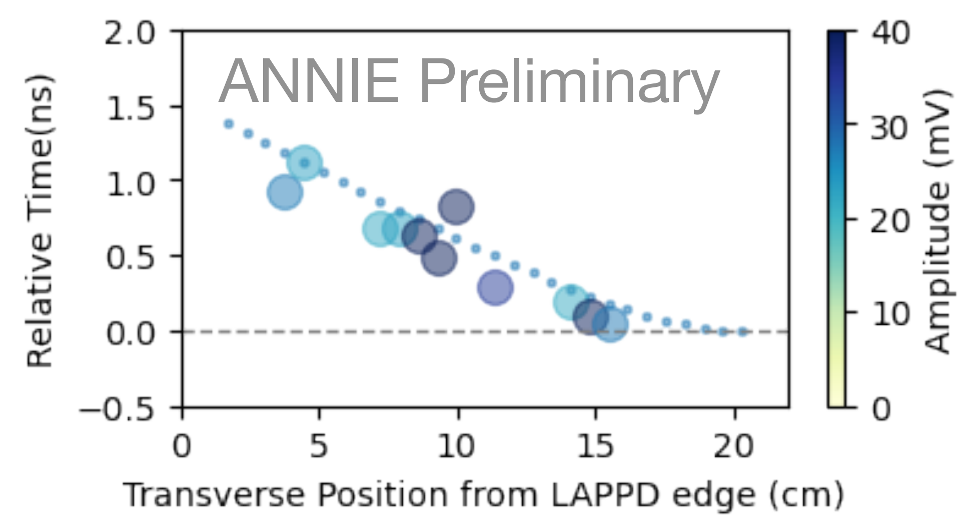




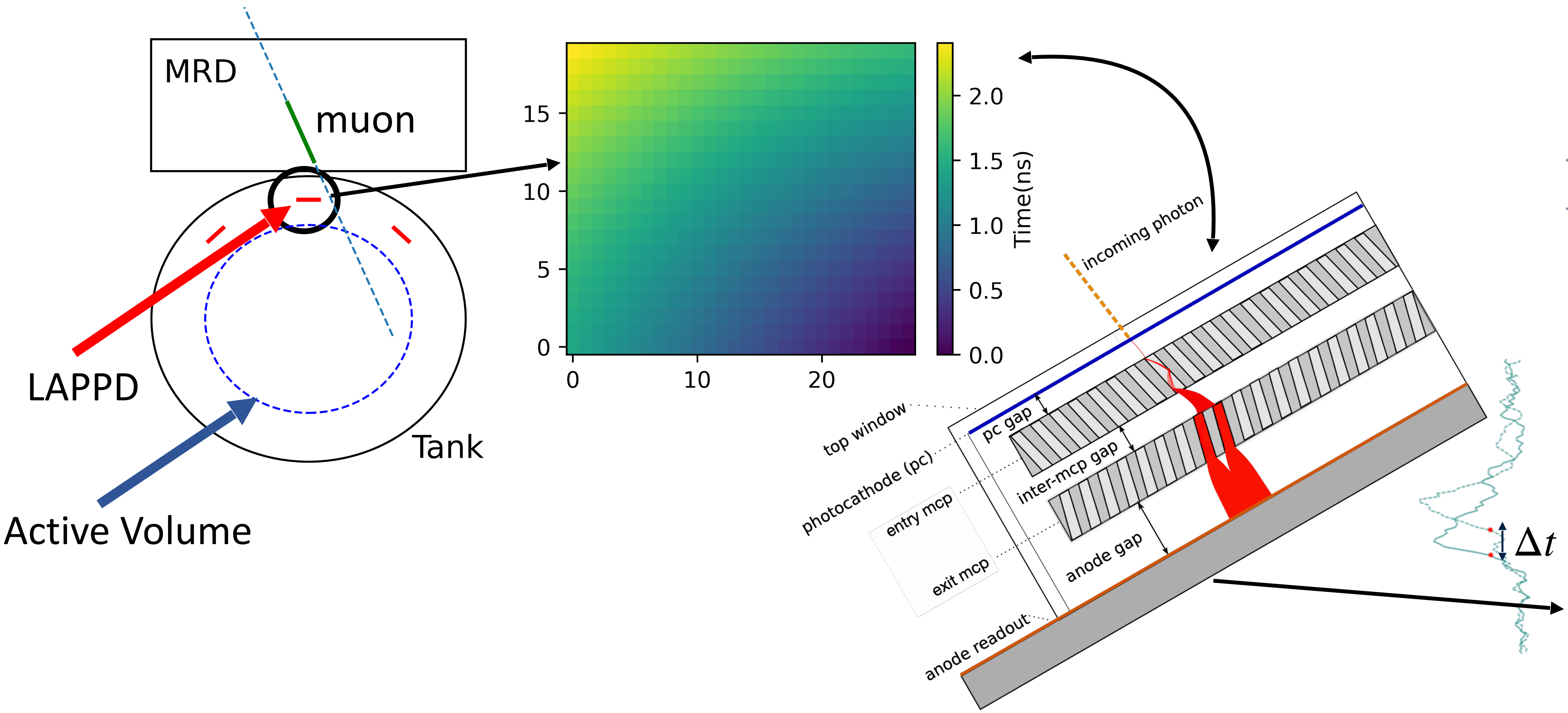


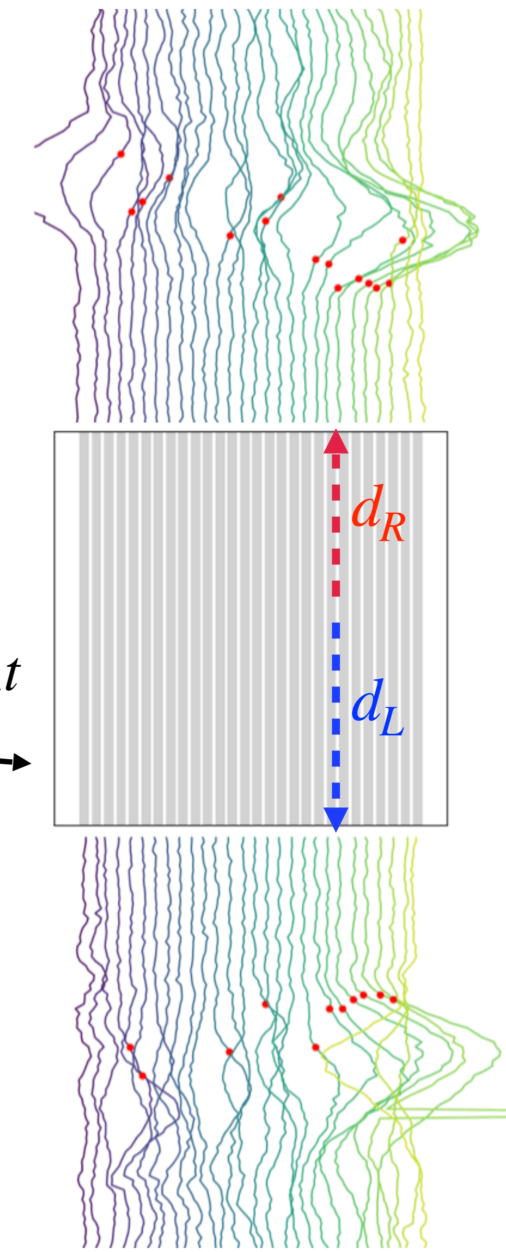






LAPPD Event Reconstruction

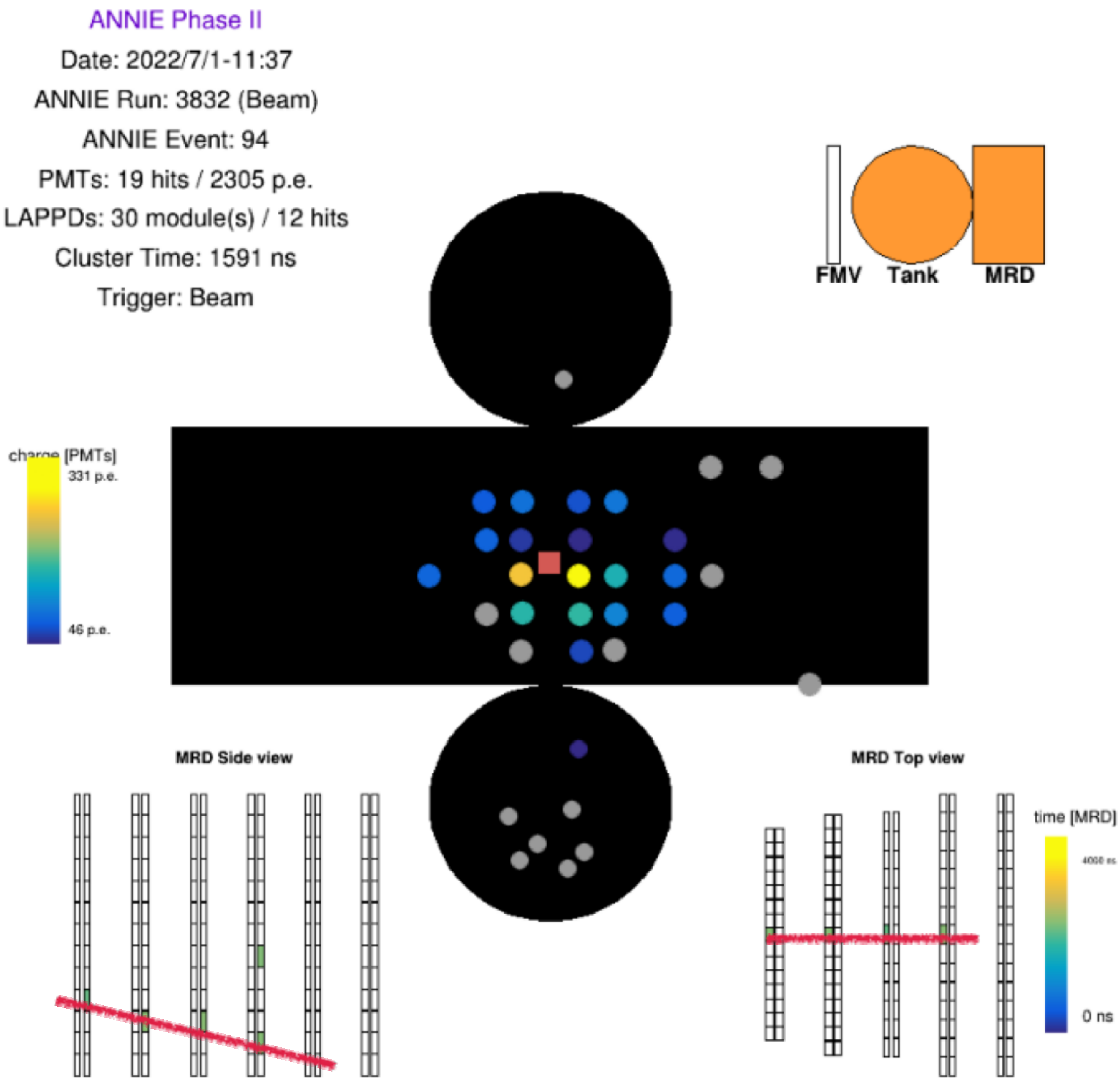




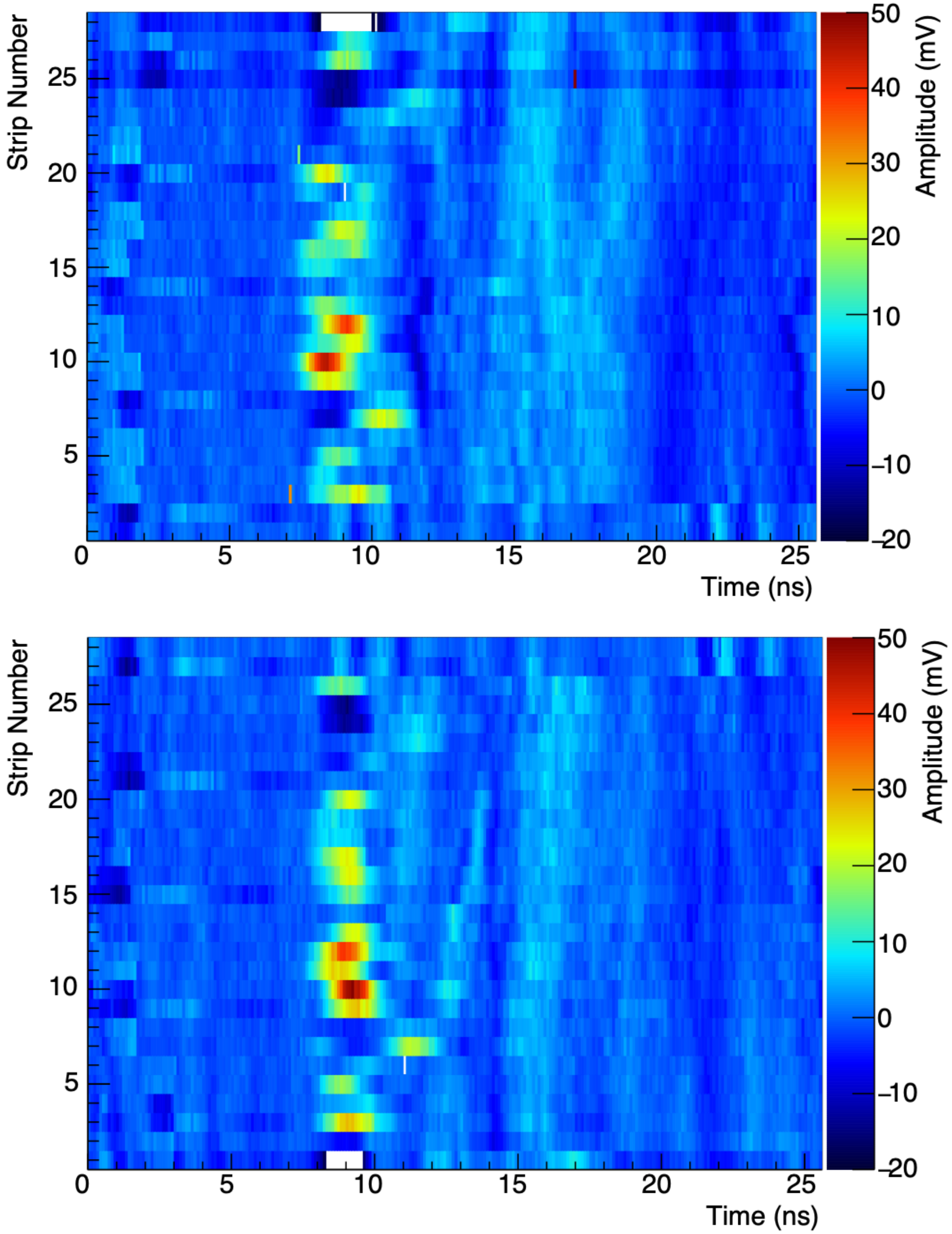
$$\Delta t = \frac{d_L - d_R}{v}$$

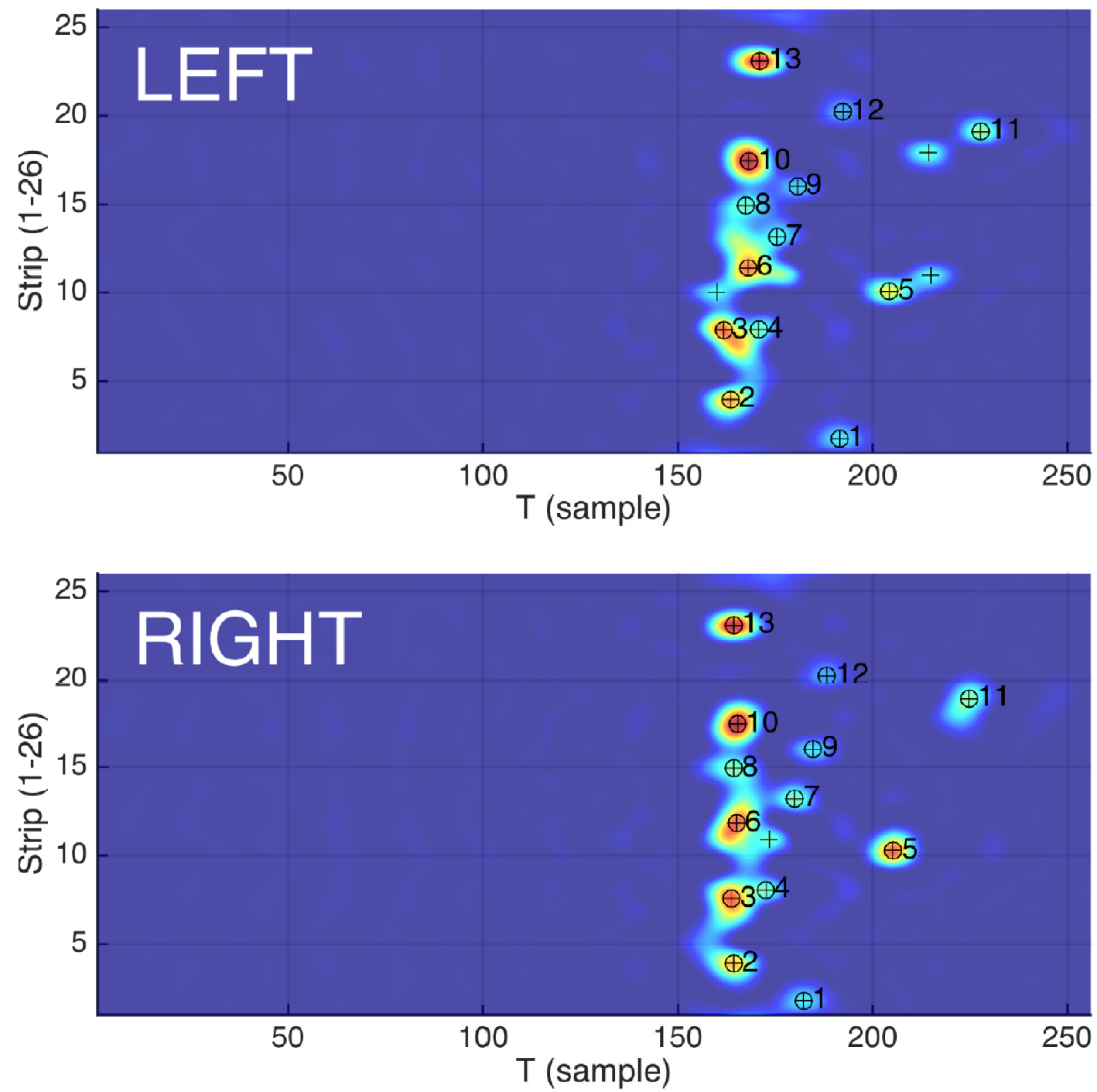
- LAPPDs can reconstruct simultaneous time and spatial gradient of light on their surface
- Silver stripline anode (read out both sides)
    - Horizontal position coarsely (~7 mm) resolved by strips, refined by charge-sharing
    - Vertical position from difference in (single PE) pulse arrival time

ANNIE neutrino candidate



LAPPD "Event Display"

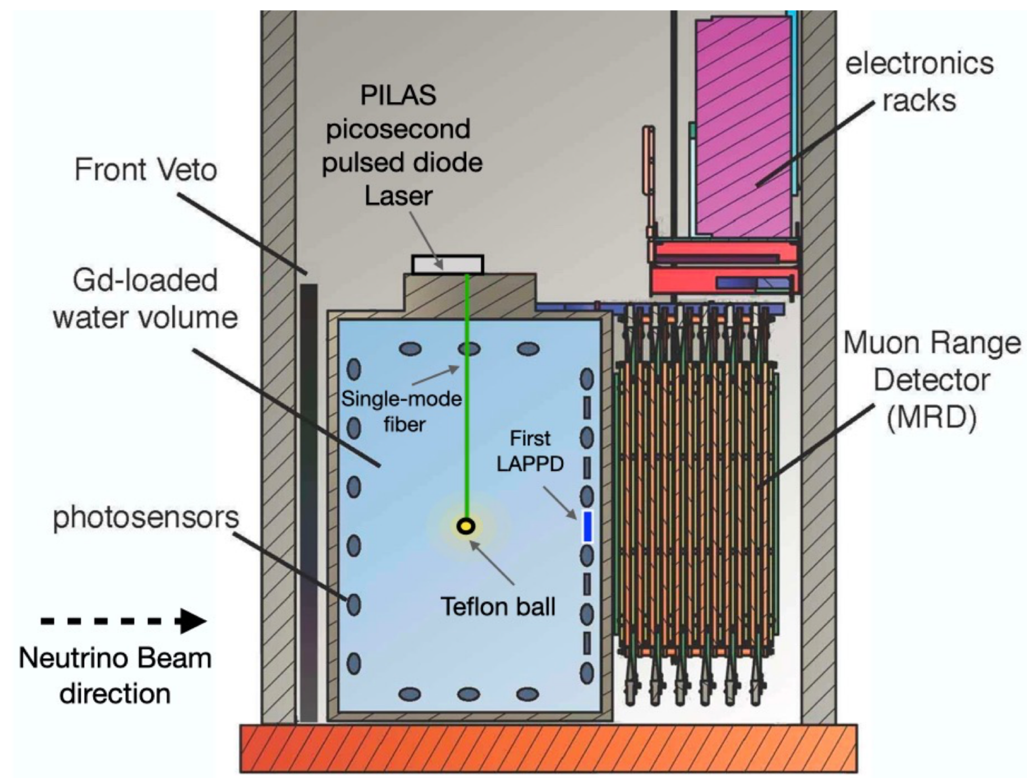




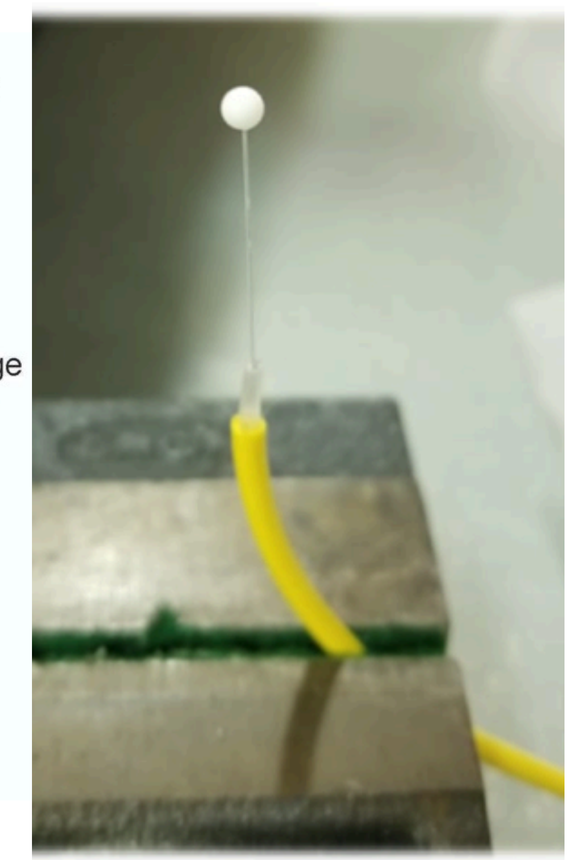
Neutrino event consistent with expectations

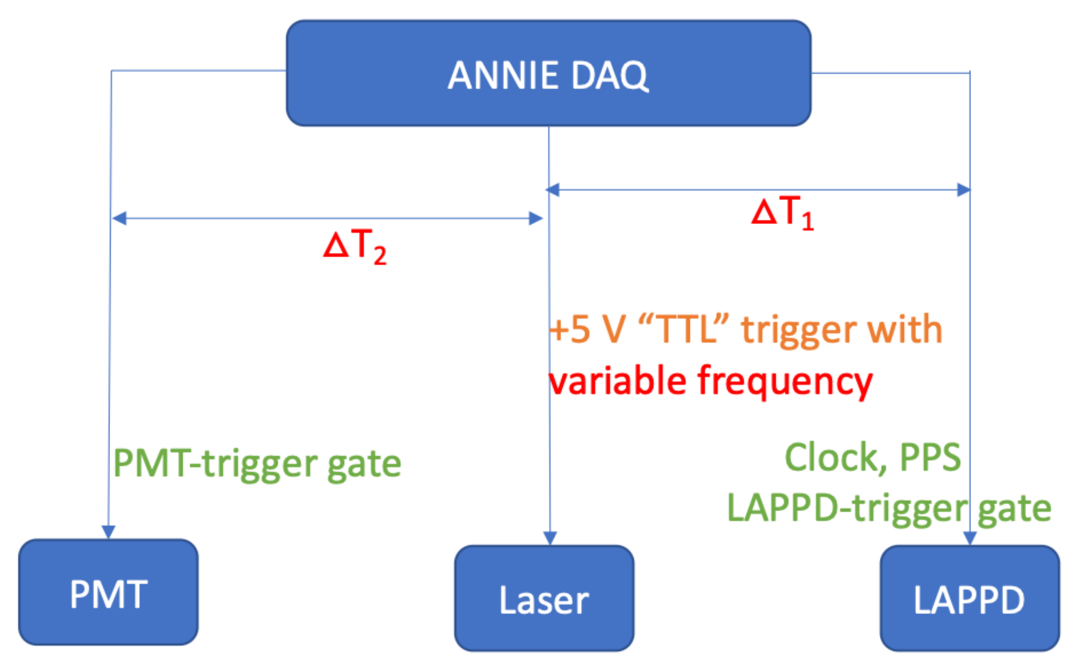
ANNIE LAPPD/PMT Calibration: Laser system

- 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.



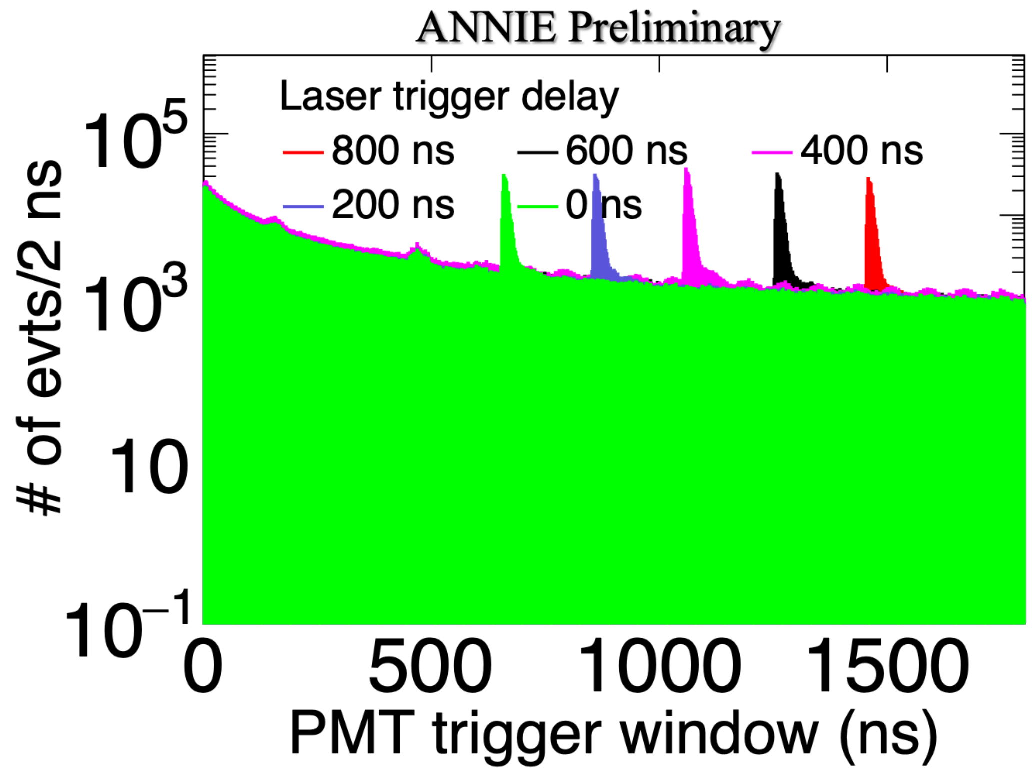
Laser setup in ANNIE Phase II detector

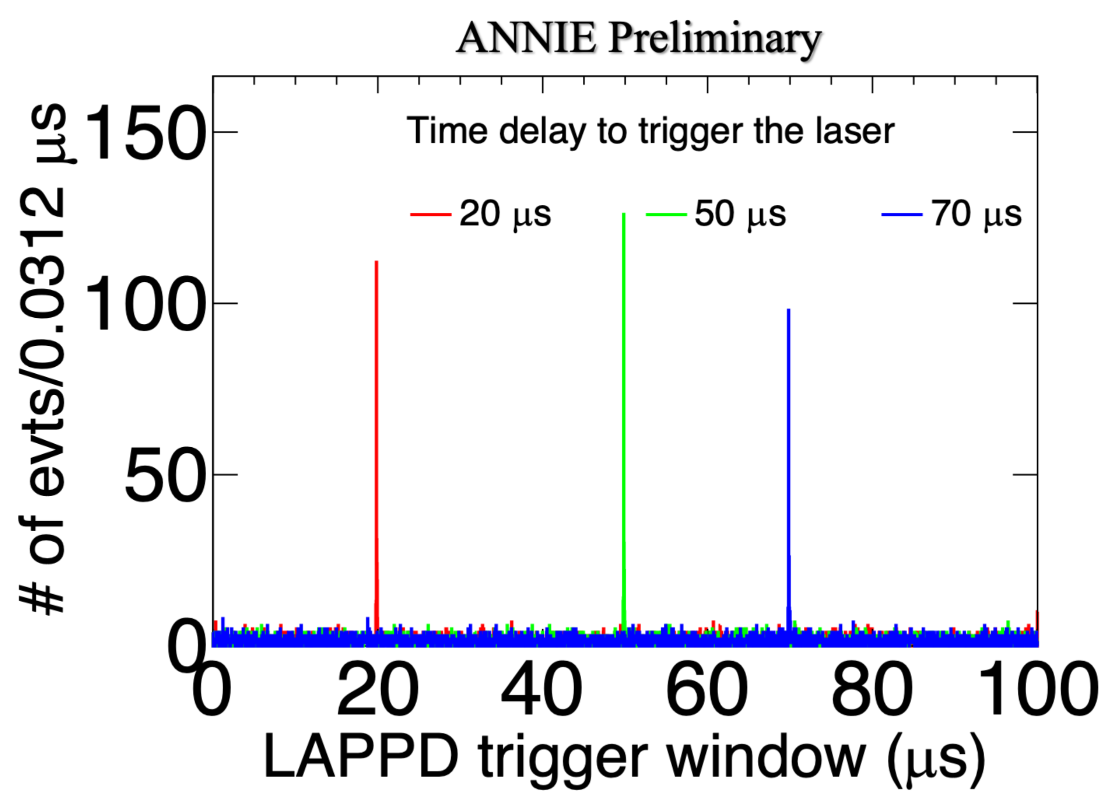




ANNIE LAPPD/PMT Calibration: Laser system

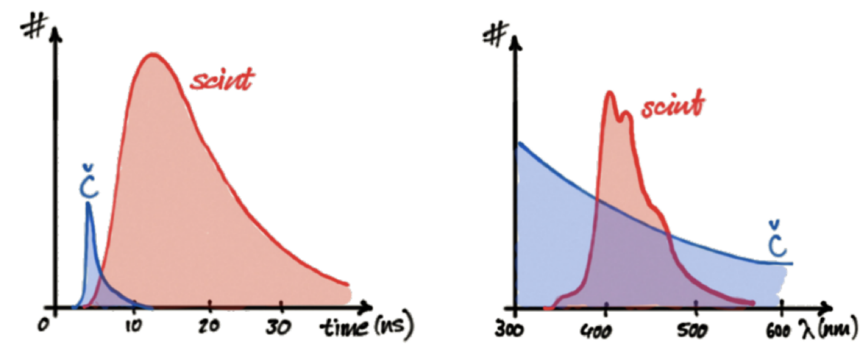
- The arrival time of PMT pulses as a function of time since the beginning of the trigger window initiated by the laser.
- The time-stamps of LAPPD self-trigger events relative to the trigger window initiated by the laser.
- The peaks correspond to laser induced signals above background for different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



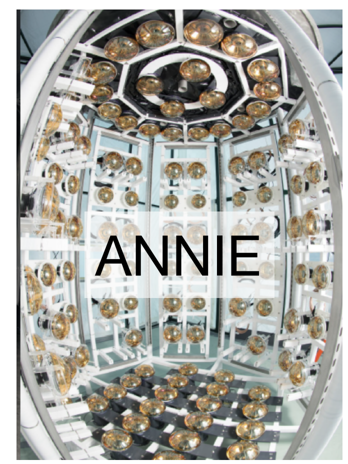


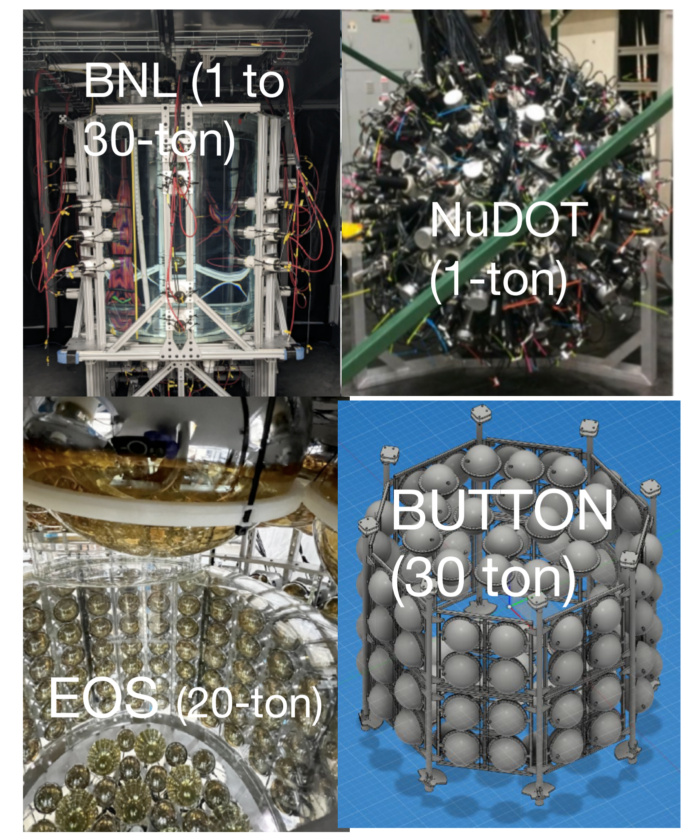
Testing water-based scintillator

- Water-based liquid scintillator (WbLS)
  - hybrid detection of scintillation and (unabsorbed) Cherenkov signals (separate based on timing, wavelength, angle)
  - Tunable ratio
- Enhanced neutrino energy reconstruction: WbLS adds scintillation signal for sub-Cherenkov recoil protons etc.
- Enhanced background rejection, particle ID: C/S ratio
- Enhanced neutron signals: improved light output (3×), detection efficiency (~90%) and spatial reconstruction (40→20 cm)
- Candidate technology for DUNE FD4



Courtesy M. Wurm, THEIA





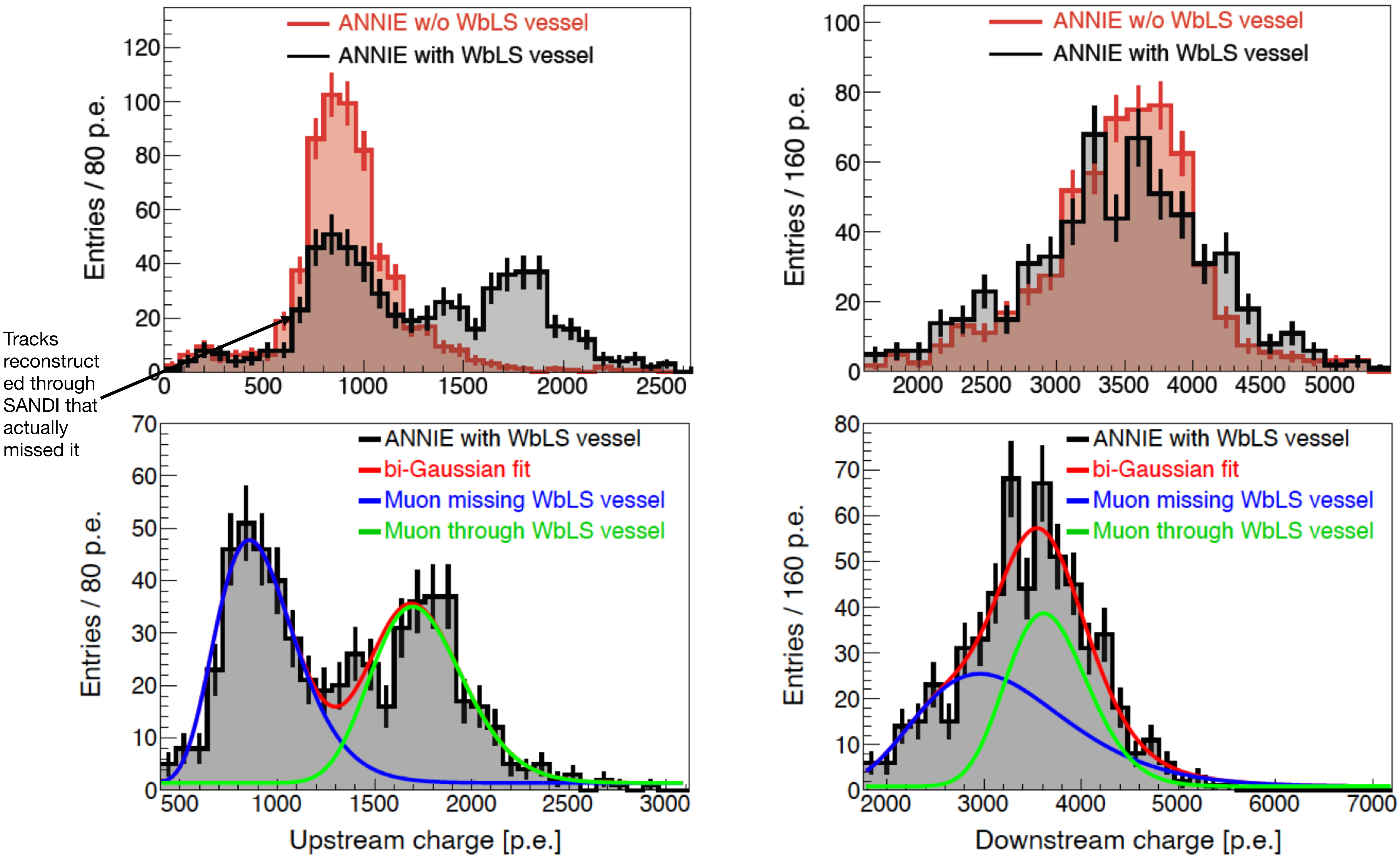
WbLS Demonstrators

Exploring the Quantum Universe

3.1.4 –Future Opportunities: DUNE FD4, the Module of Opportunity

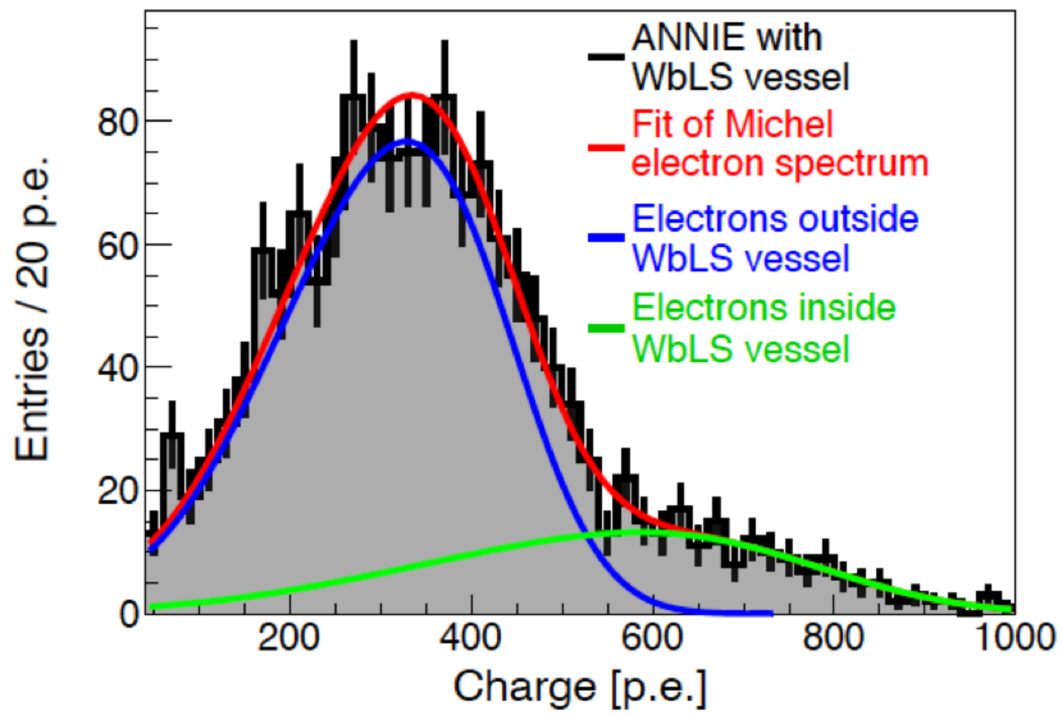
A range of alternative targets, including low radioactivity argon, xenon-doped argon, and **novel organic or water-based liquid scintillators**, should be considered to maximize the science reach, particularly in the low-energy regime.

SANDI: Throughgoing muons



$$\frac{q_{\mathrm{SANDI}}}{q_{\mathrm{Water}}} = 1.42 \pm 0.23(\mathrm{stat.} + \mathrm{syst.})$$

SANDI: Michel Electron Cross-Check



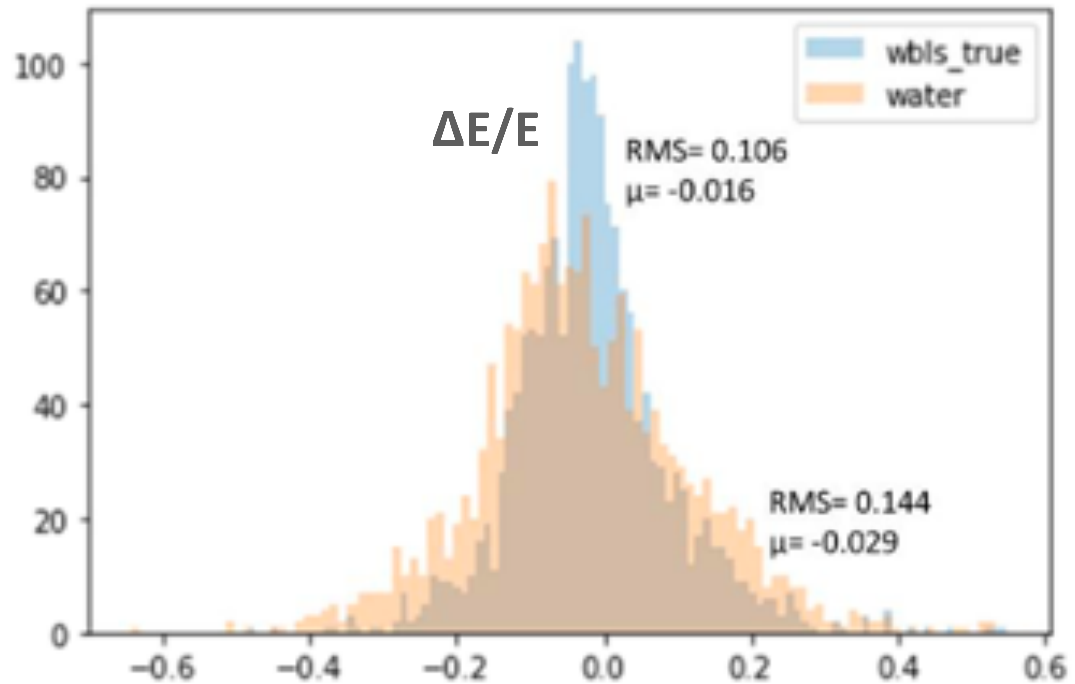
$$g(Q) = \int_0^{E_m} A \cdot f(E) \cdot G(Q, \mu(E), \sigma) dE$$

$$\frac{k_{\mathrm{SANDI}}}{k_{\mathrm{Water}}} = 1.77 \pm 0.08(\mathrm{stat.} + \mathrm{syst.})$$

- Shift in photoelectron mean value per MeV (k) with WbLS present indicates substantial increase due to WbLS-filled SANDI vessel.
- Full MC and reco study needed to estimate intrinsic WbLS light yield.

WbLS Calorimetry

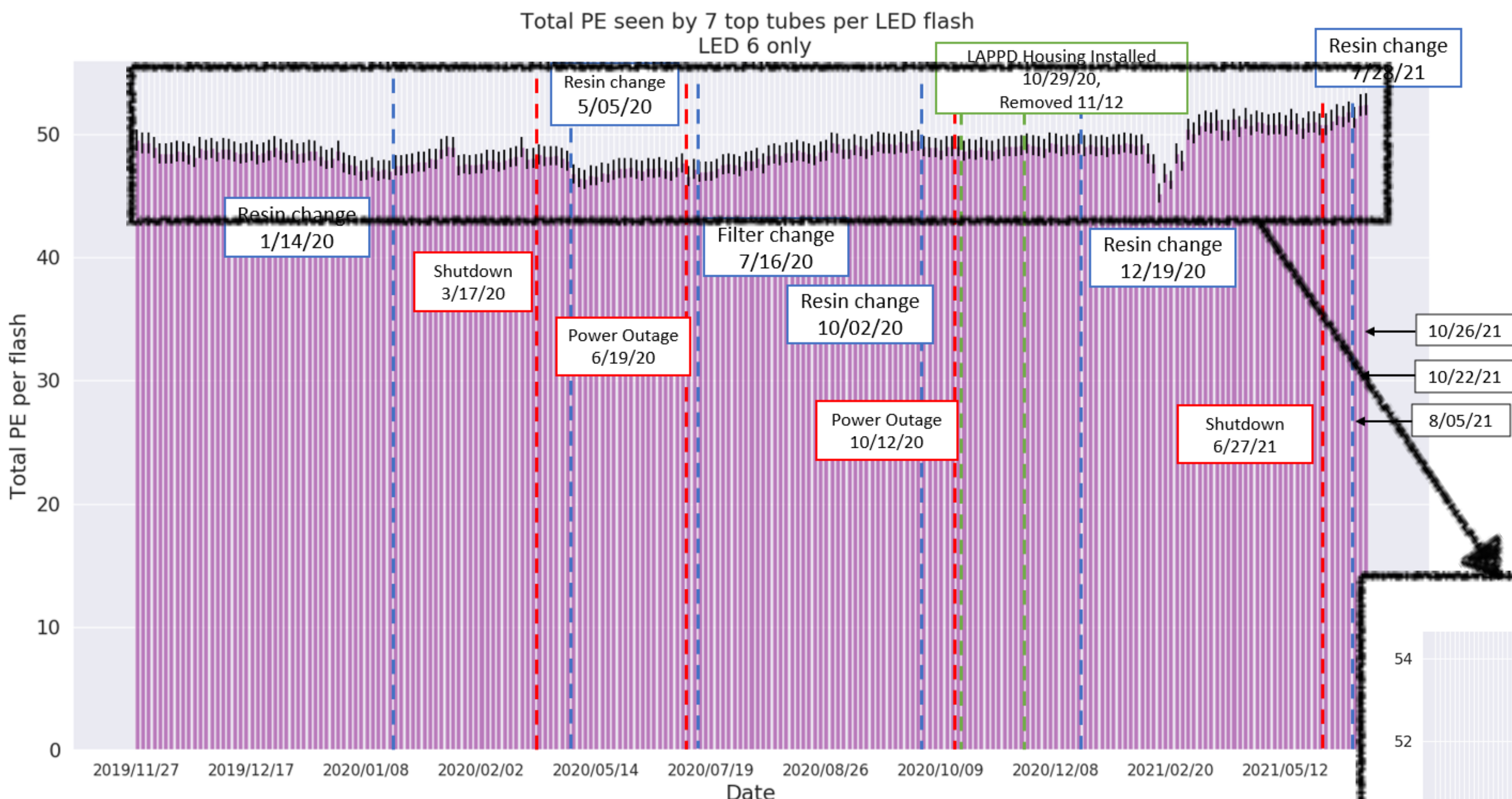
Expected improvement in neutrino energy resolution

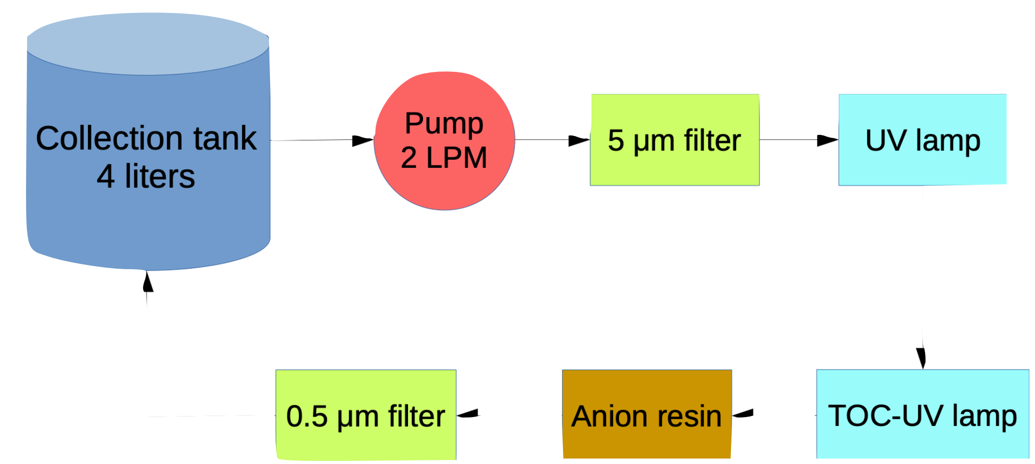


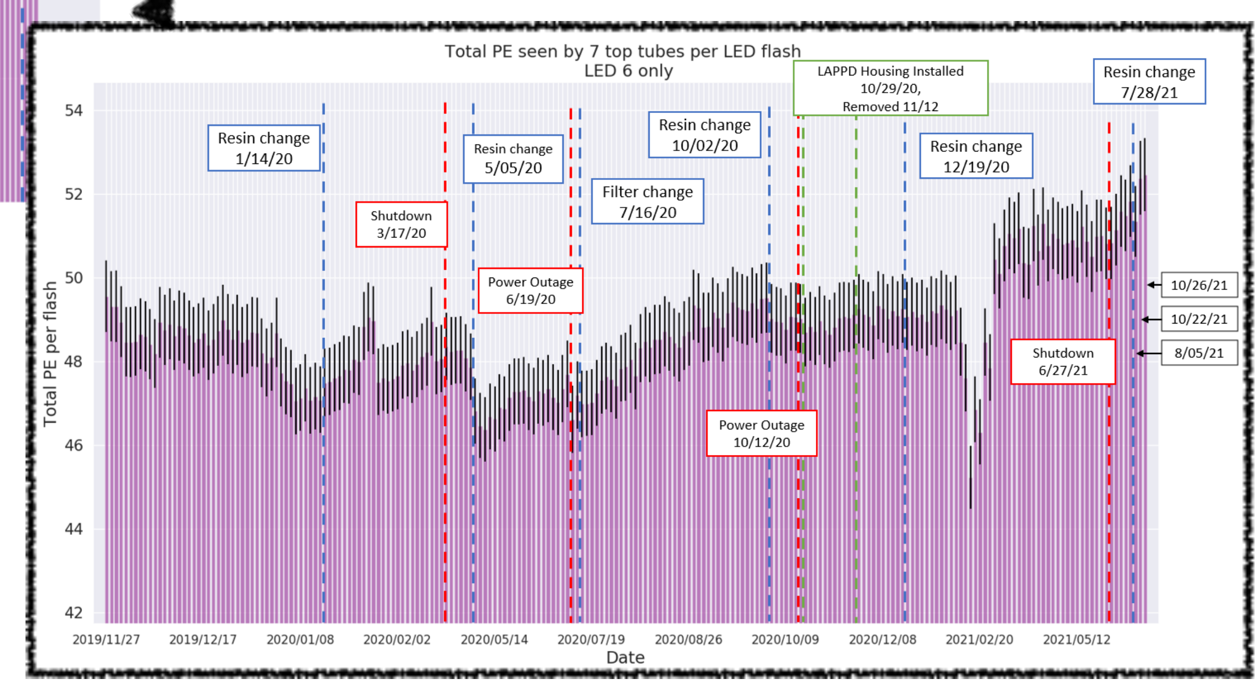
water: 14.4%

→**WbLS: 10.6%**

Enabling Technology: Gd-loaded Water



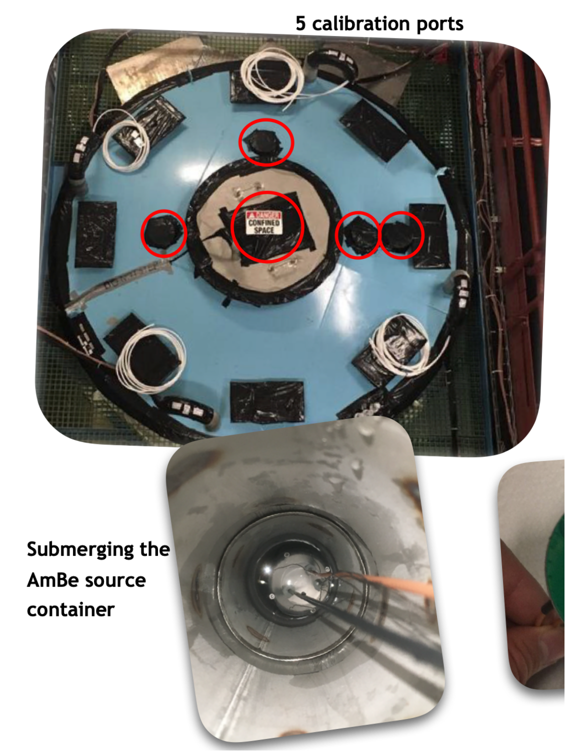




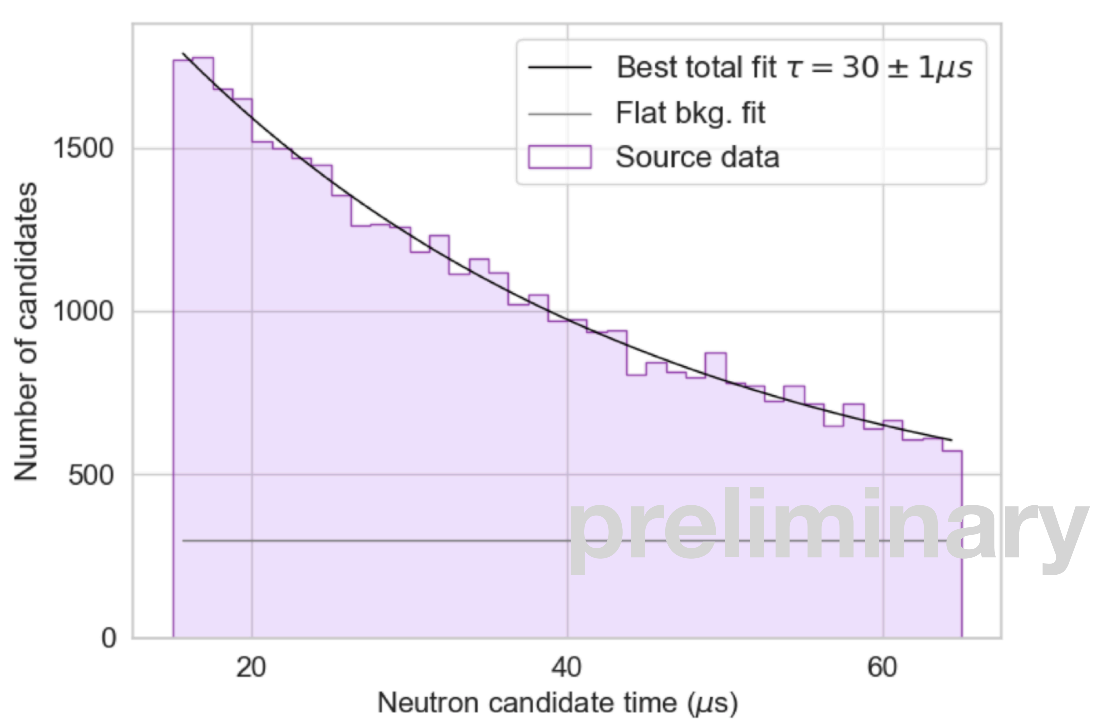
- ANNIE is the most gadiated neutrino detector in the world.
- ANNIE monitors water transparency by measuring intensity of LED flashes with PMTs across the water volume.
- **ANNIE's custom-designed purification & circulation system** maintains high water transparency level (~2 years now).

ANNIE Neutron Capture Calibration

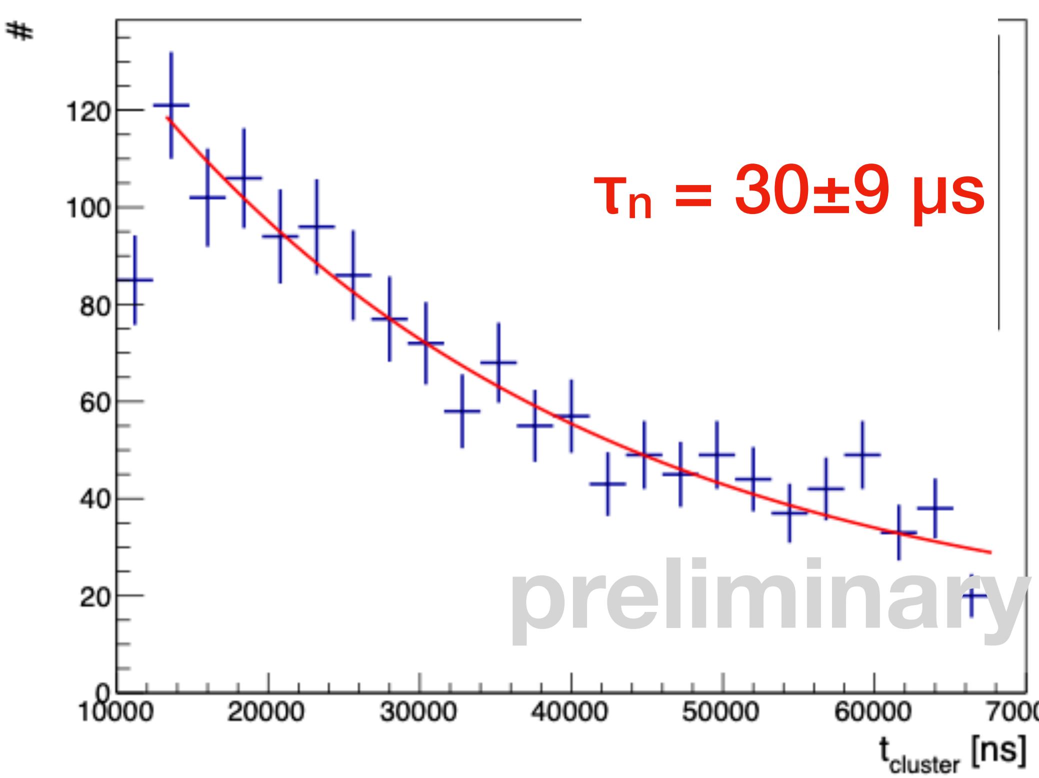
- A tagged AmBe neutron source was deployed inside the water volume to map neutron capture efficiency.
    - Neutron capture time profile from source and beam runs matches expectation for a Gd concentration 0.1% by mass.
    - Position dependent neutron capture efficiency has been measured to be consistent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

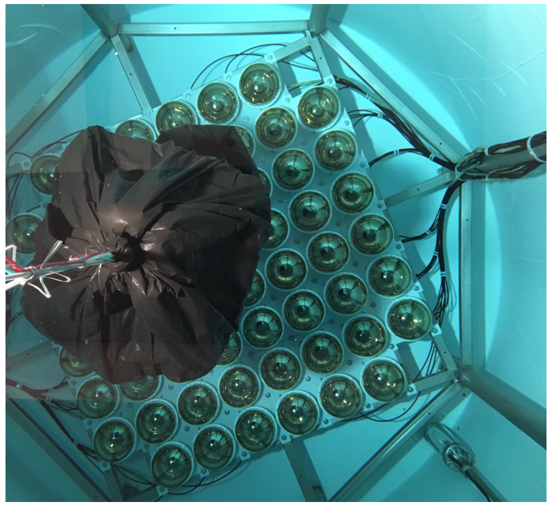


Neutron capture times (source)



Neutron capture times (beam)





ANNIE Phase I (2016-17)

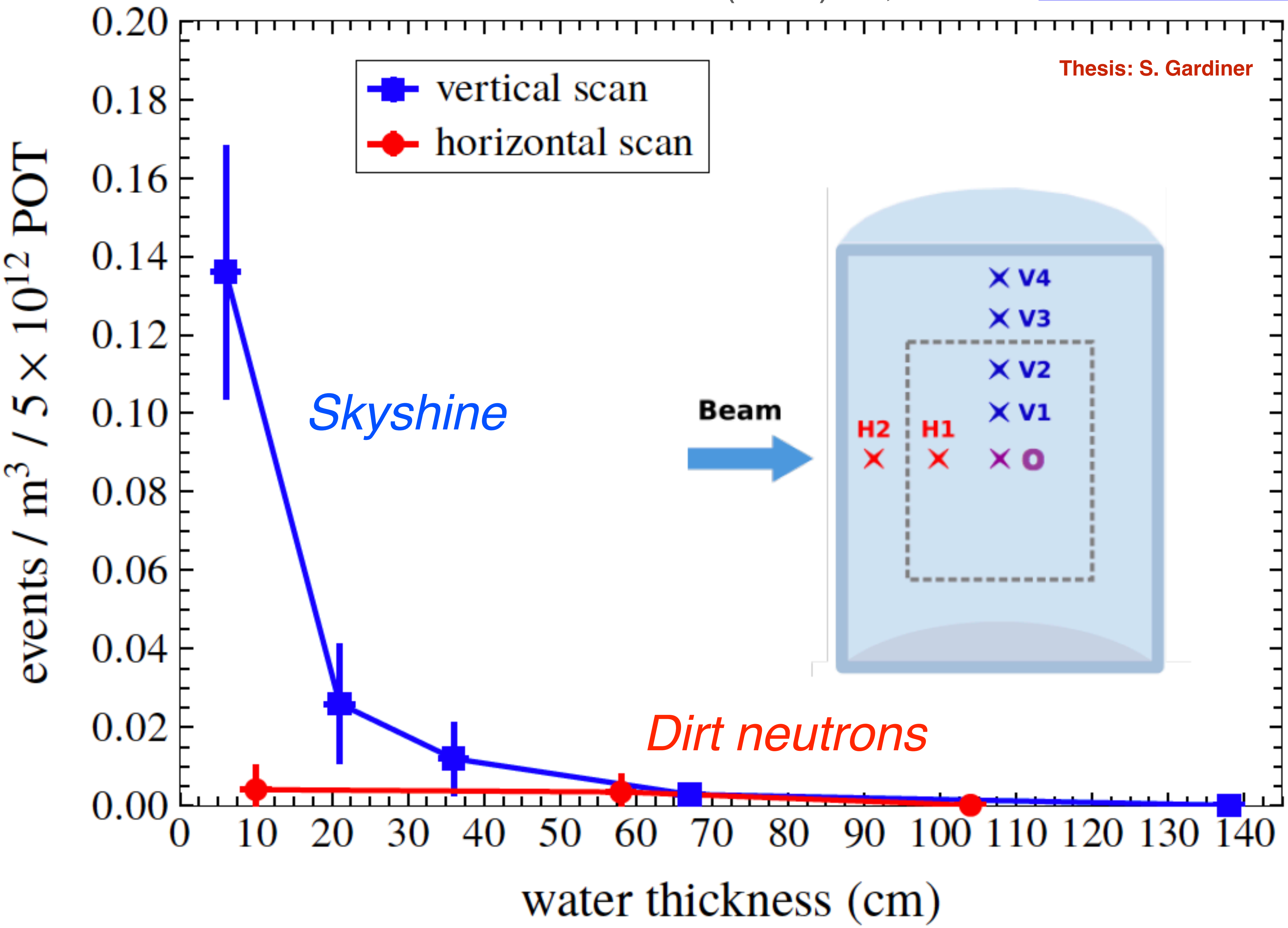
- Partially-instrumented detector
- Engineering, beam-correlated background neutron characterization

JINST 15 (2020) 03, P03011 arXiv:1912.0318

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

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

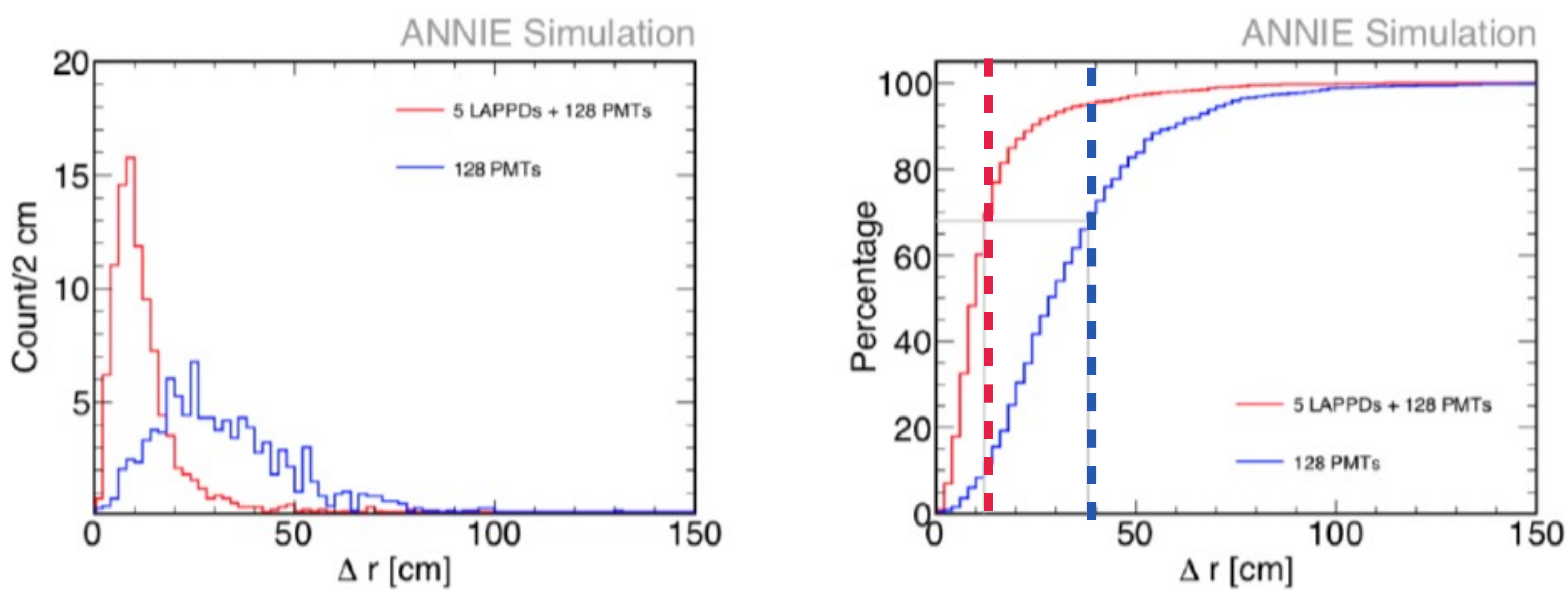
Backgrounds small, mitigated by the buffer layer of water above detector. .



How well can we do?

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

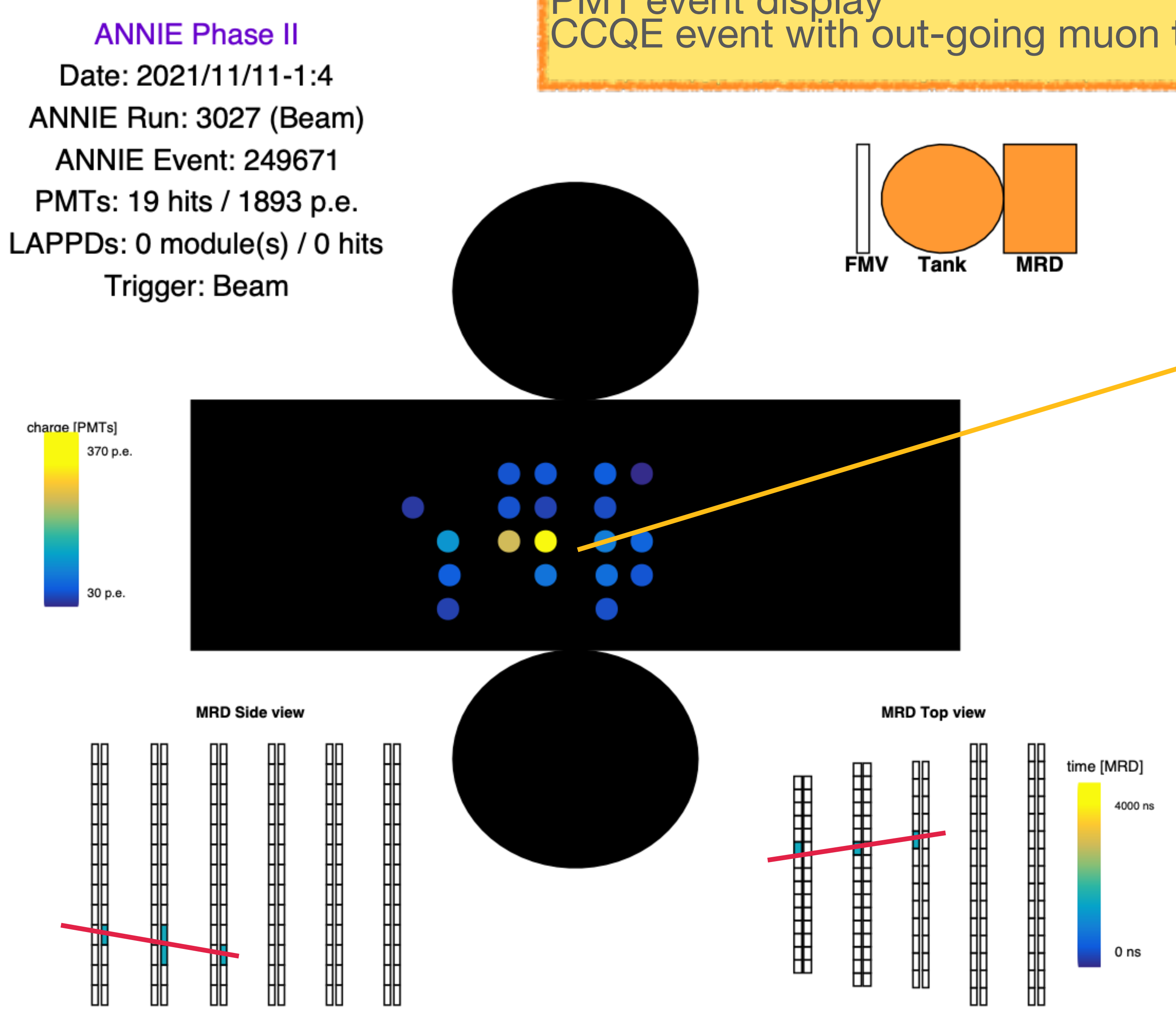
Vertex Radial Displacement: Δr

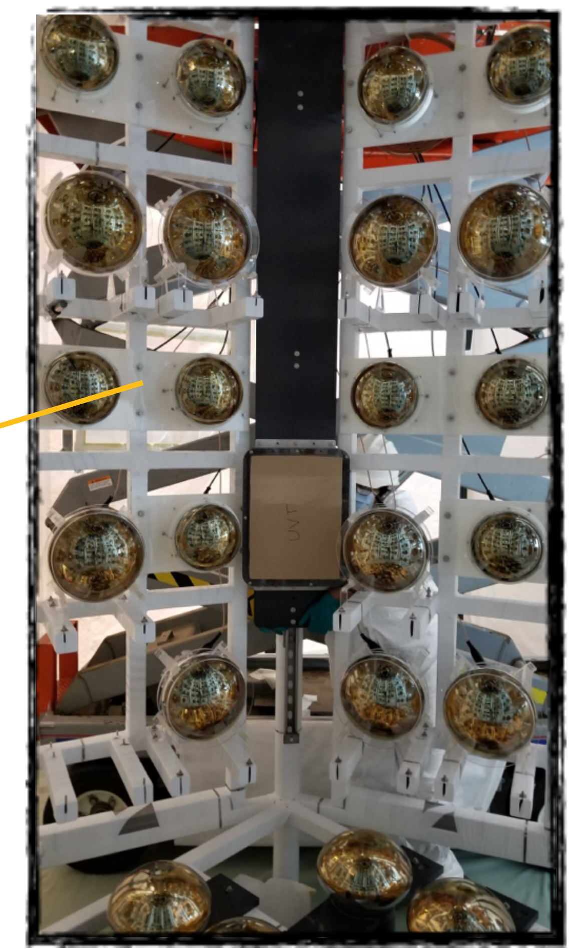


ANNIE Neutrino Beam Data

- All "conventional" ANNIE systems up to specs and running on high duty factors. Beam data taking in the Booster beam since January 2021.

PMT event display
CCQE event with out-going muon track

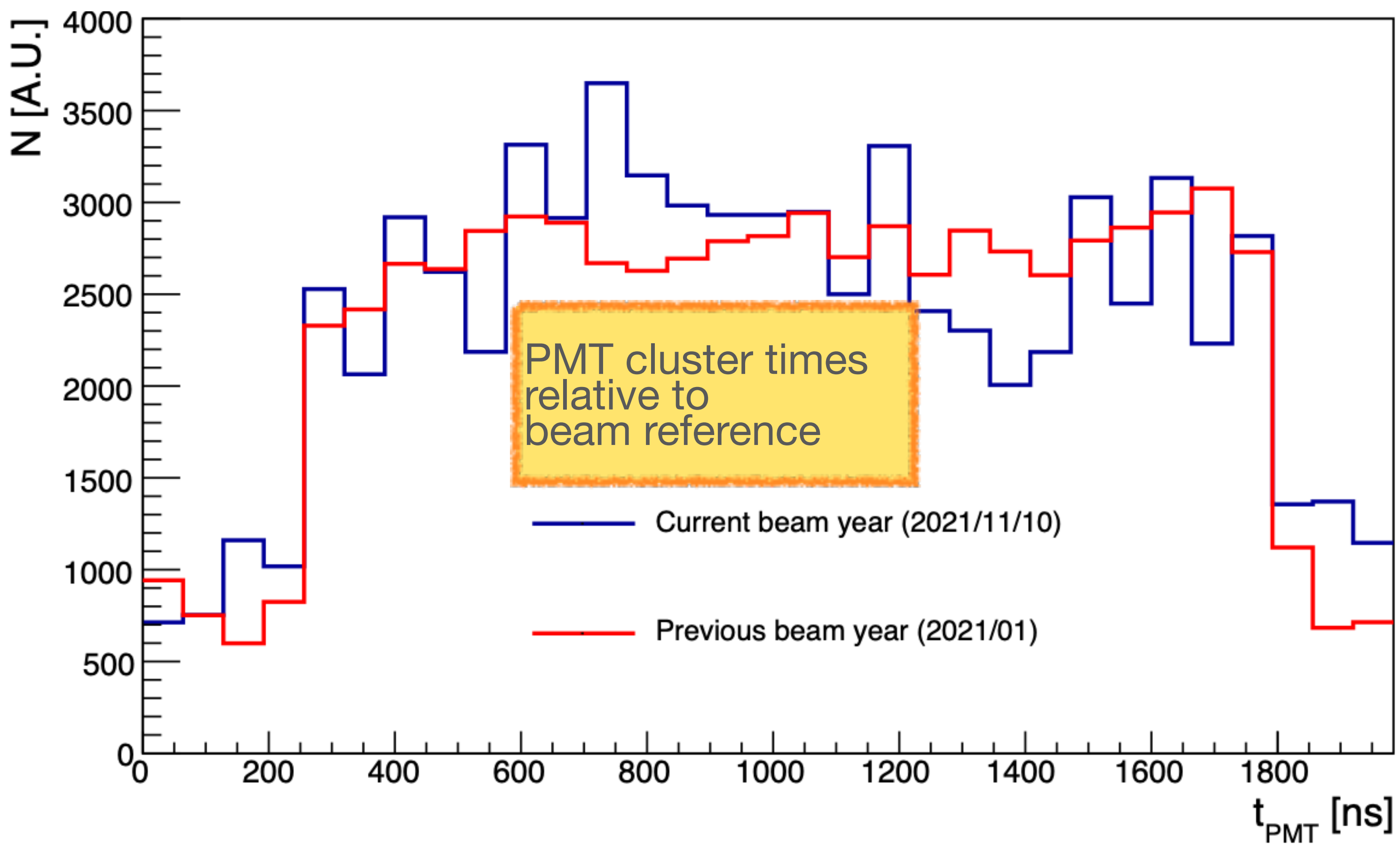


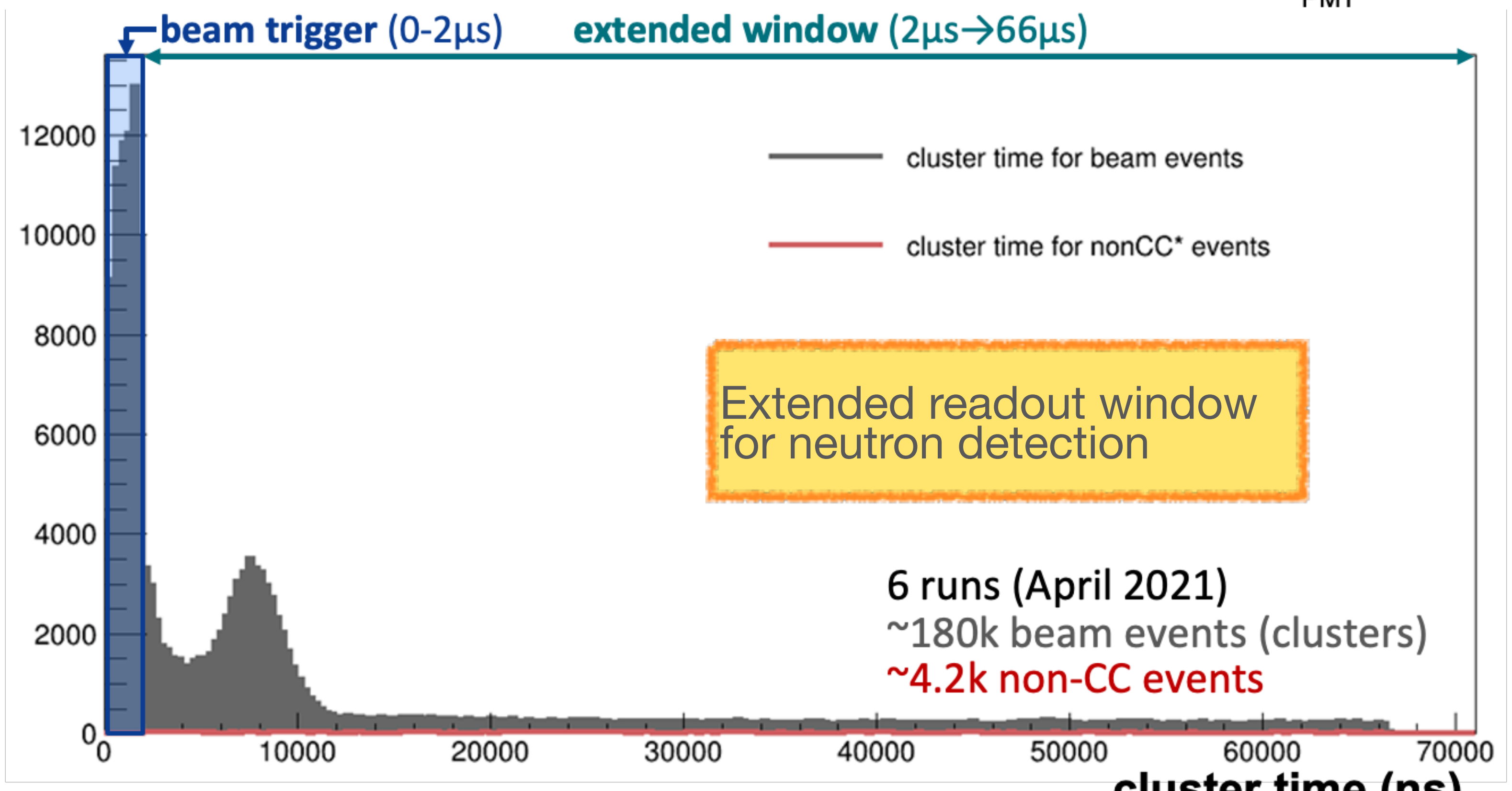


LAPPDs are inserted on slide rails between PMTs

ANNIE Neutrino Beam Data

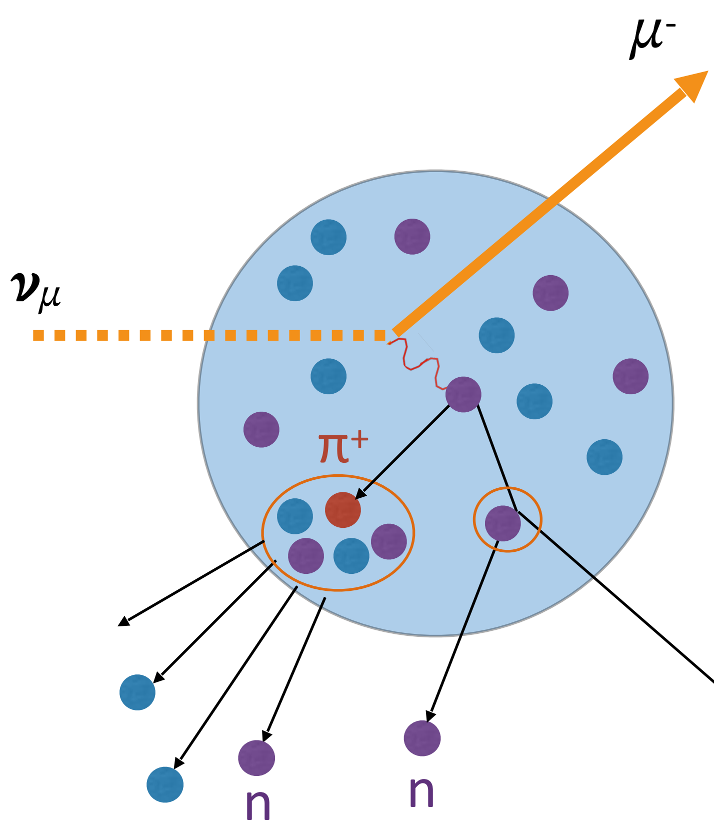
- Selecting PMT cluster times relative to the beam shows an excess in-time with the expected timing of the BNB.
- For beam triggers (<2 μsec) an extended window (2-66 μsec) is recorded to enable neutron detection.





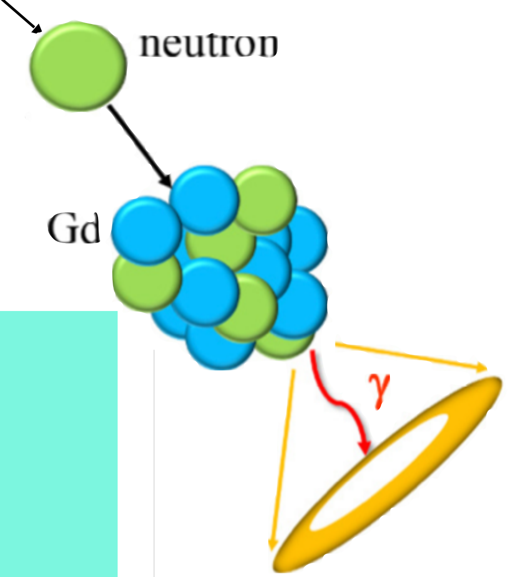
Technology ⟺ Physics

- ANNIE is a flexible test-bed for next-generation detector technologies (novel photosensors/fast timing and novel detection media)



- Adding LAPPDs to PMTs enhances interaction vertex resolution, fiducialization.

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



Deployable volume of water-based liquid scintillator (WbLS)

(elements of interaction below Cherenkov threshold)

- Measuring multiplicity of final state neutrons as a function of the outgoing lepton momentum and direction