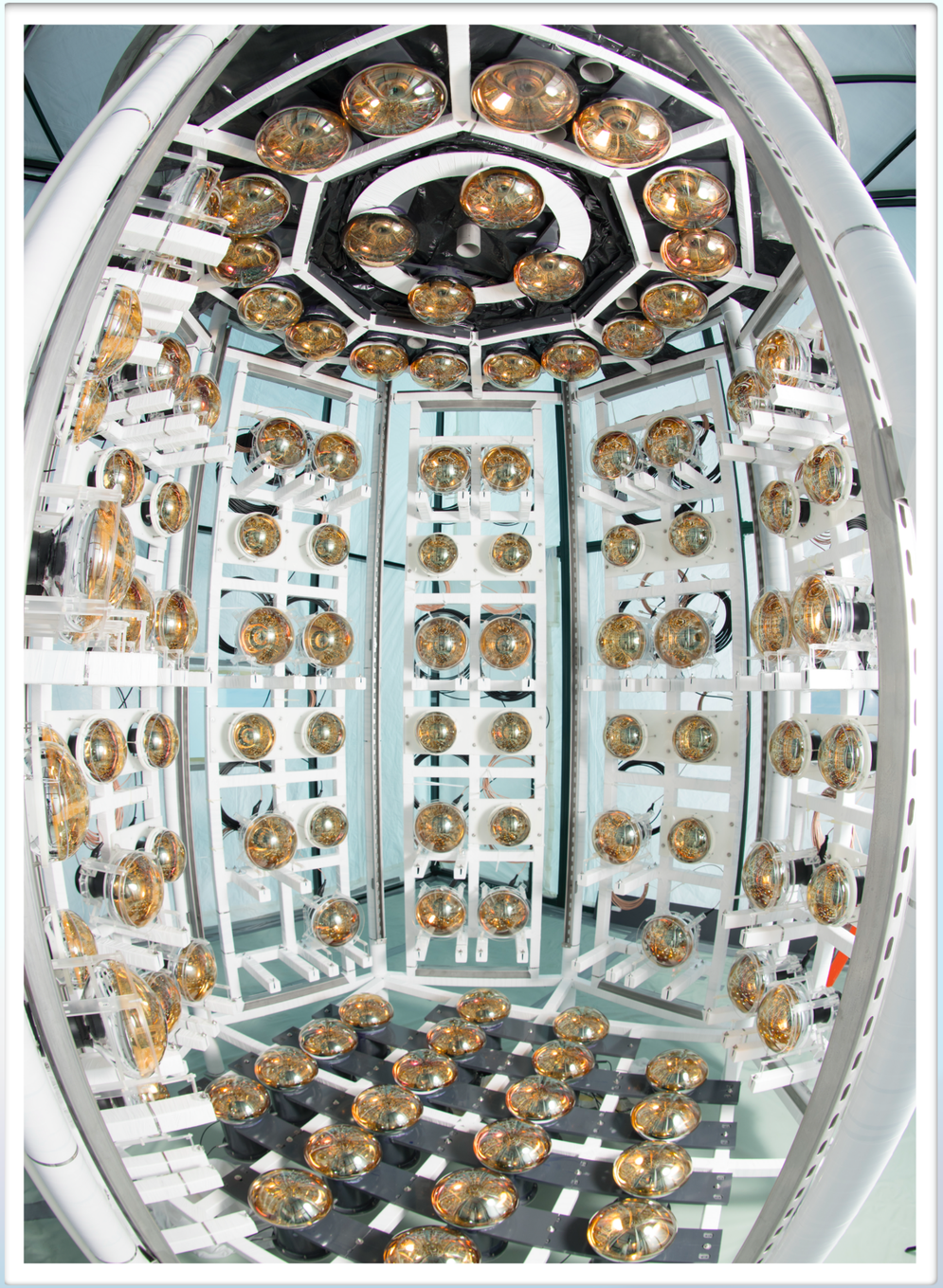
Mayly Sanchez - Florida State University

XXXII International Conference on Neutrino Physics and Astrophysics, University of California, Irvine, June 21-26, 2026

ANNIE in a nutshell

ANNIE : Accelerator Neutrino Nucleus Interaction Experiment

- **Setup:** 26-ton Water Cherenkov detector with 132 PMTs in the Fermilab Booster Neutrino Beam (BNB).
- **Physics goal:** Study neutrino interactions in water (on oxygen), especially the neutron yield.
- **Detector R&D goals:**
  Demonstrate novel neutrino detector technologies:
  - Gadolinium loaded water target
    → enhanced neutron tagging
  - Water-based liquid scintillator
    → detection of sub-Cherenkov particles
  - LAPPDs
    → sub-nanosecond timing, sub-cm spatial resolution photosensors to improve event reconstruction



The ANNIE Collaboration

circa 2026

- Institutions: 18
- Collaborators: 52
  - PIs: 20
  - Postdocs: 8
  - PhDs: 16
  - Undergrads: 8
- Over 15 PhD theses.
- 10+ PostDocs/PhD students now university faculty or national laboratory staff.

US partners:
– Iowa State
– UC Davis
– Florida State
– UC Irvine
– Ohio State
– Rutgers
– SDSMT
– LBNL/UC Berkeley
– BNL
– *Associate:* Livermore

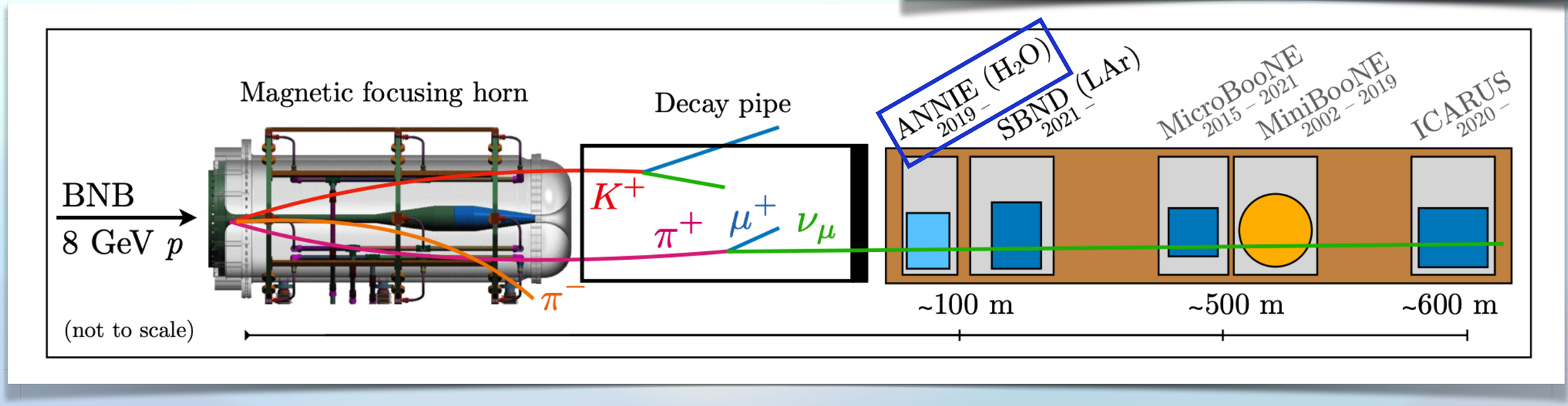
International partners:
– Hamburg + Mainz + Munich + Tübingen (Germany)
– Demokritos (Greece)
– Kanpur (India)
– Erciyes (Turkey)
– Warwick (United Kingdom)

ANNIE Posters at Neutrino 2026

- Jingbo Wang - session-1, #497
  The Physics Program and Recent Results from the ANNIE Experiment
- Adil Aman - session-1, #385
  Neutrino Interactions observed with Large Area Picosecond Photodetectors in ANNIE
- Bruno Gelli - session-1, #453
  Hybrid Light Detection in ANNIE: In-Beam Studies of Water-based Liquid Scintillator
- Christian Nguyen - session-2, #285
  Single and double differential charged current νμ–Argon cross section without pions in the final state at MicroBooNE, and current status of simultaneous cross-section extraction with ANNIE
- Dylon Fleming - session-2, #332
  Continuing Analysis of Charge Current Interactions in ANNIE
- Dhaval Ajana - session-2, #398
  Neutron Yield for Neutrino-Nucleus Interactions Measurement from ANNIE

The Physics of ANNIE

- ANNIE shares the BNB with several liquid-argon experiments:
  - → competitive statistics for oxygen x-sections;
  - → direct comparison of oxygen & argon cross-sections (MicroBooNE, SBND) for combination of future oscillation analyses.



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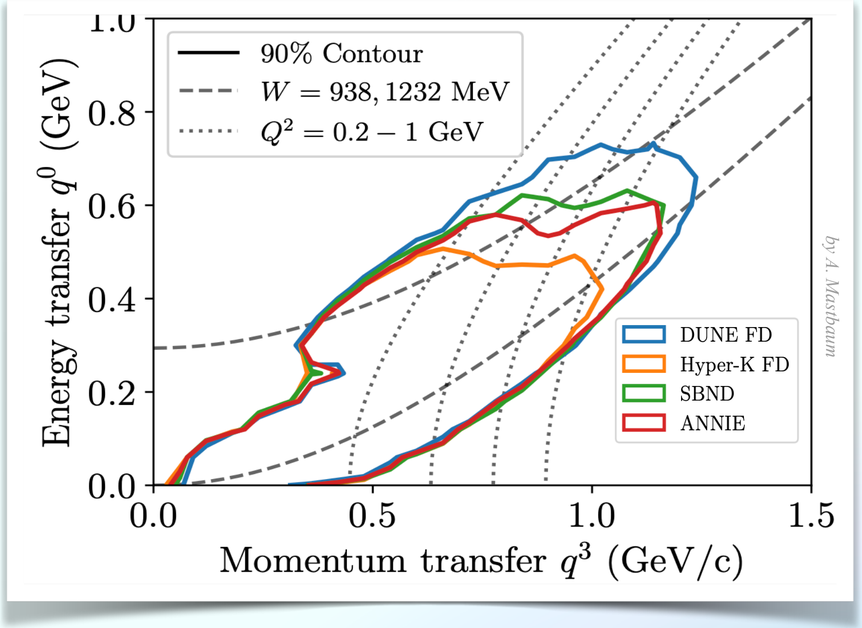
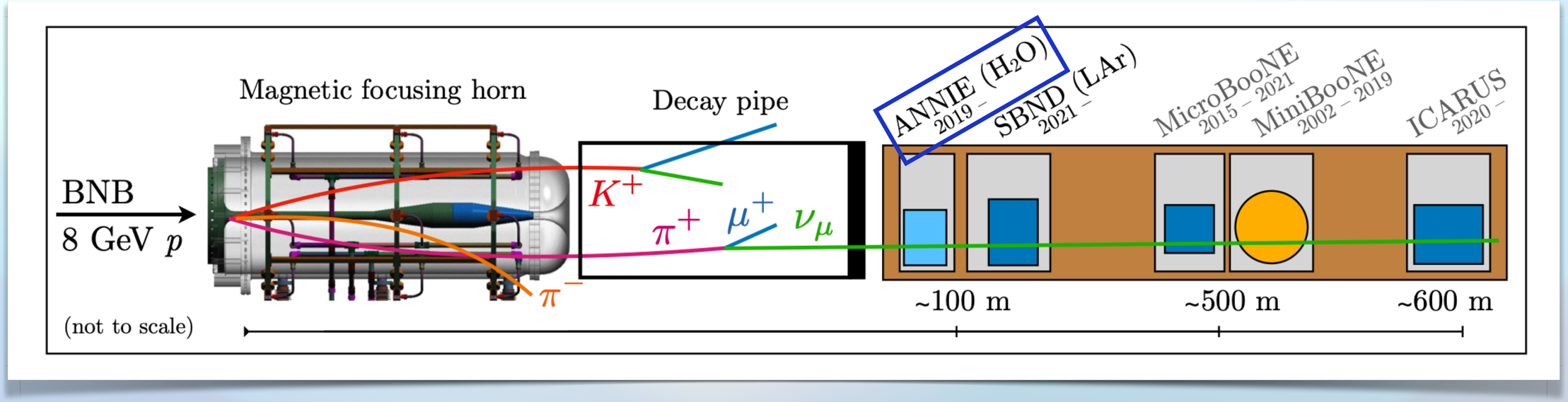
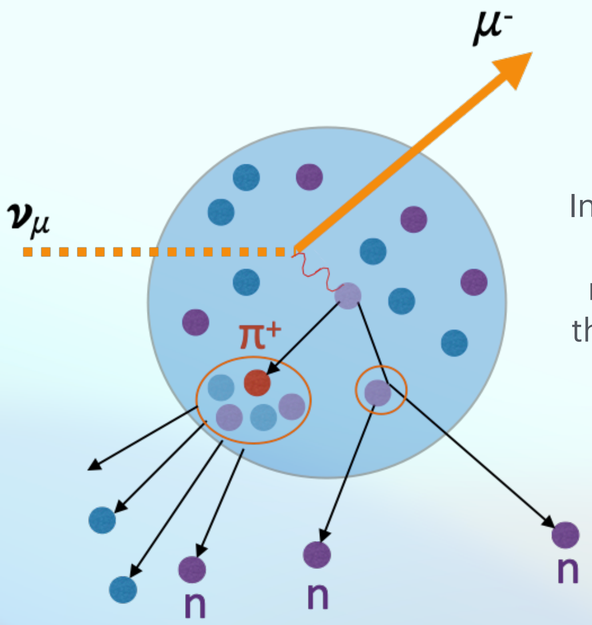
Momentum and energy transfer of neutrino interactions in the BNB largely overlap with those of DUNE and HK Far Detectors.



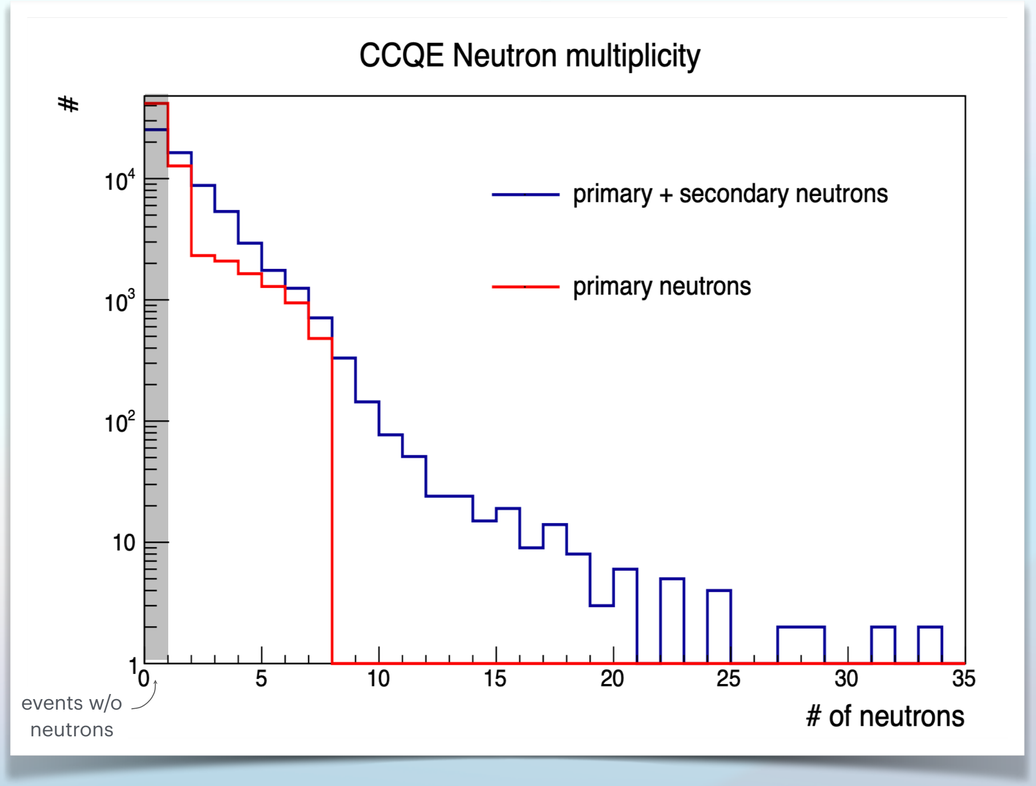


The Physics of ANNIE

- Differential cross-sections on oxygen and neutron multiplicity from neutrino interactions → important input for neutrino event generators and reducing the neutron yield uncertainties of current and future oscillation experiments.

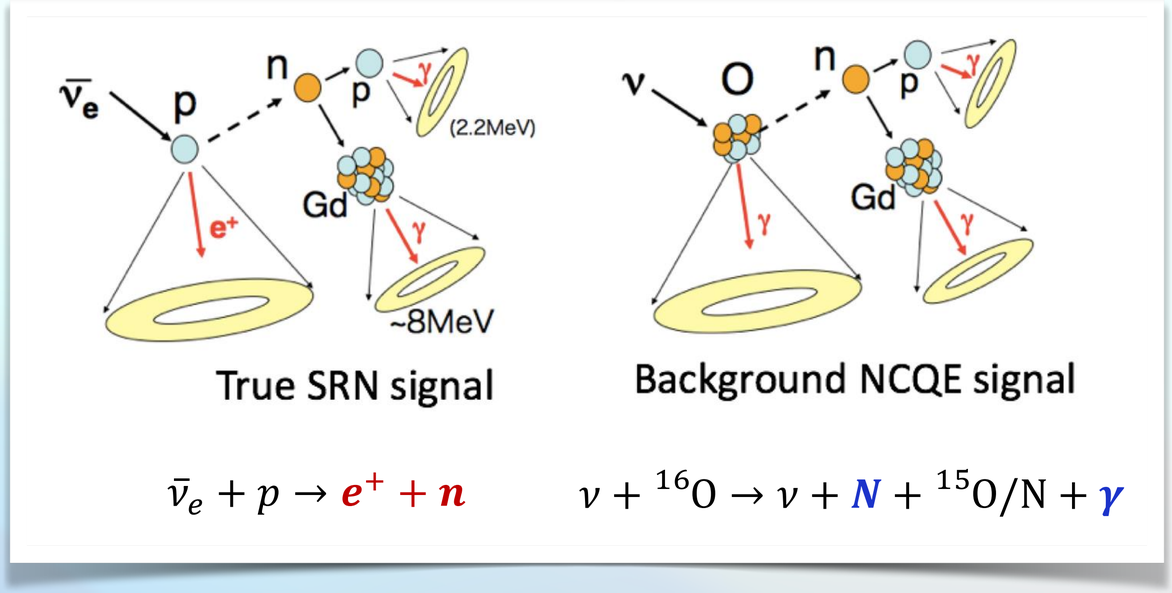


In CCQE interactions, primary neutrons are created by nuclear effects. In addition, there are secondary neutrons caused by reactions on neighboring nuclei.



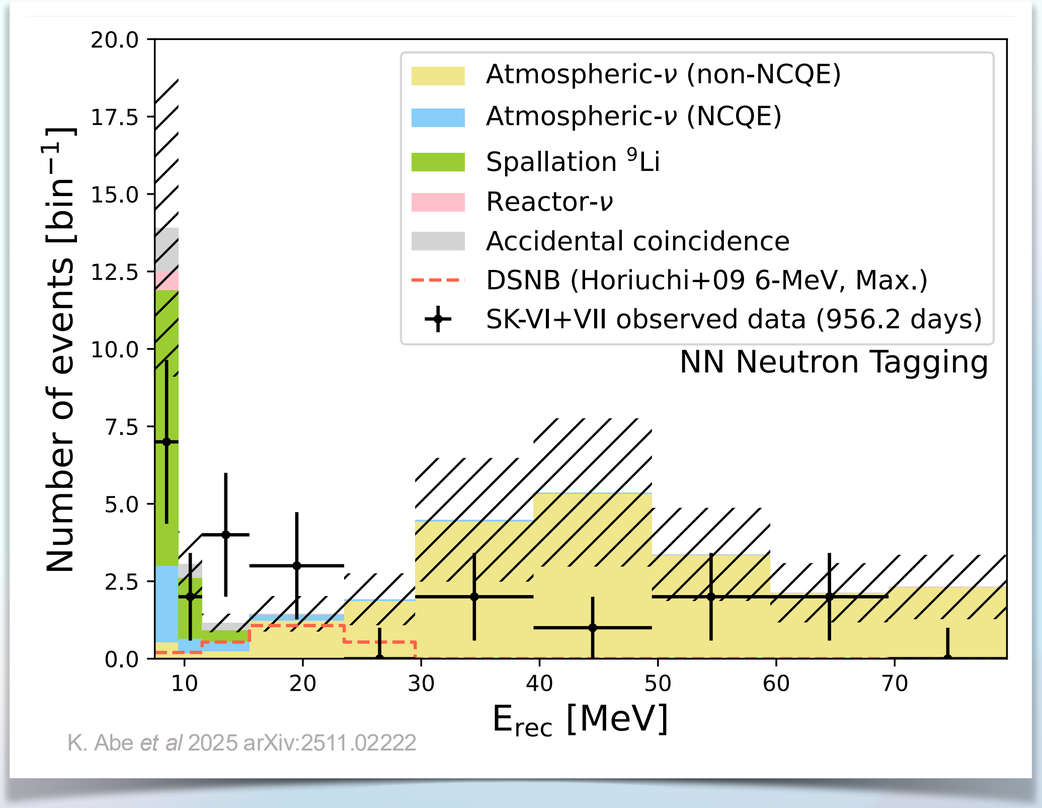
The Physics of ANNIE

- Study of NC interactions, relevant for:
  - → Diffuse Supernova Neutrino searches
  - → Long-baseline oscillation experiments
  - → Proton decay searches



Prominent background below 20 MeV: atmospheric neutrino Neutral Current Quasielastic (NCQE) scattering on oxygen

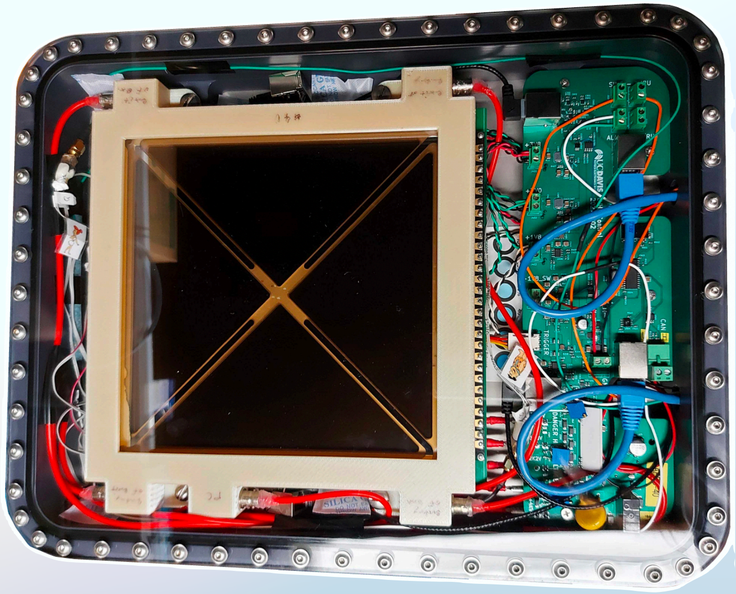
Search for the Diffuse Supernova Neutrino Background (DSNB) in SK-Gd: Atmospheric neutrinos make up the primary background.



K. Abe *et al* 2025 arXiv:2511.02222

The R&D of ANNIE

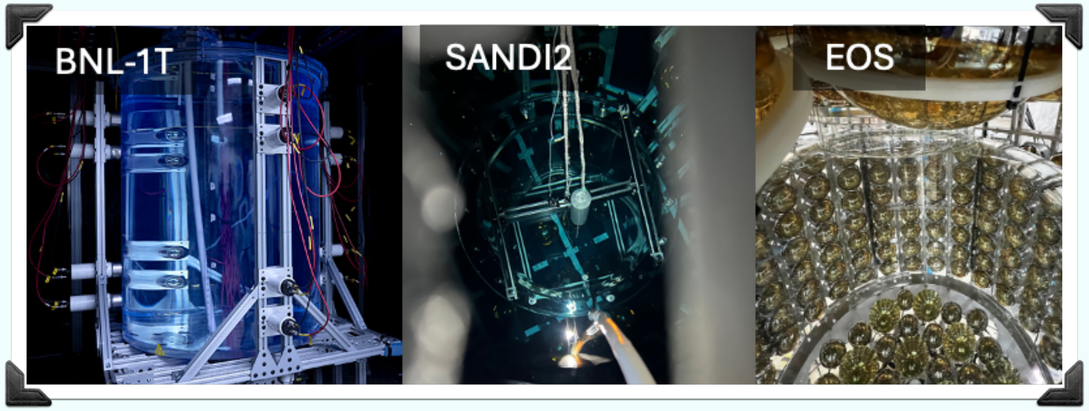
- **Large Area Picosecond Photo-Detectors (LAPPDs)** are 20 x 20 cm tiles based on microchannel plates with resistive and emissive coating and dual-sided anode readout.
  - Fast photodetector capabilities (60-100 psec time resolution) and excellent position resolution (sub-cm scale).
- The ANNIE collaboration has:
  - Developed an LAPPD package, waterproof housing and electronics.
  - Carried out sustained multi-LAPPD operation under realistic detector conditions.
  - Demonstrated LAPPD-based detection of beam neutrino events: JINST 21 (2026) 02, P02002.

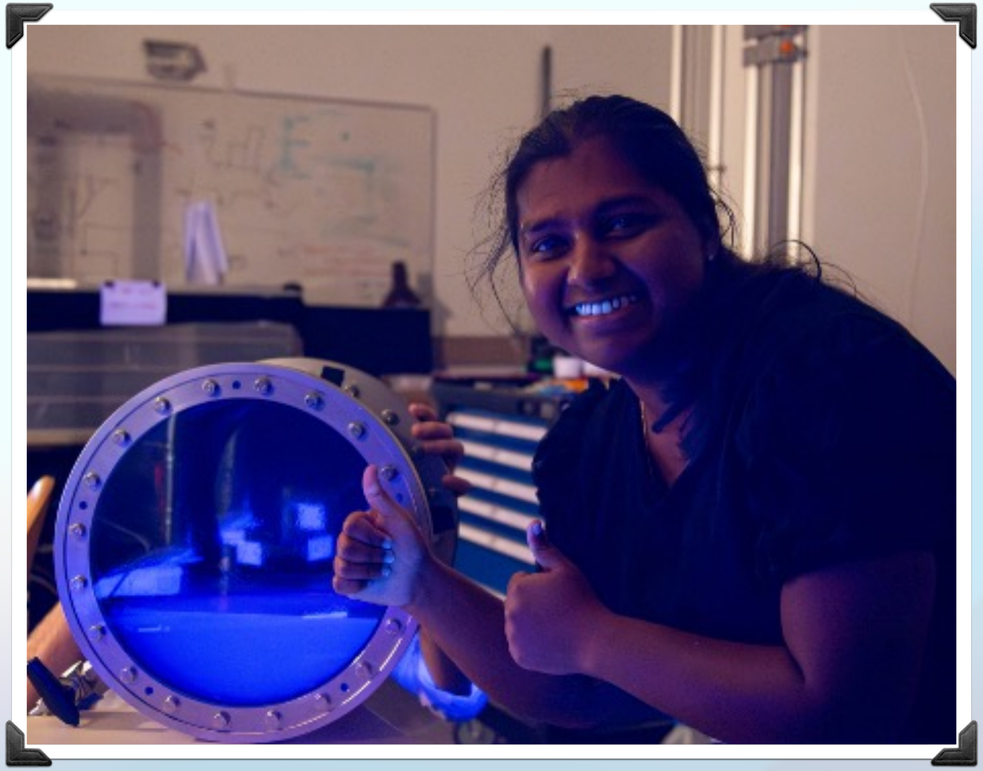


LAPPDs (here in waterproof housing) provide large-area sub-nanosecond timing

The R&D of ANNIE

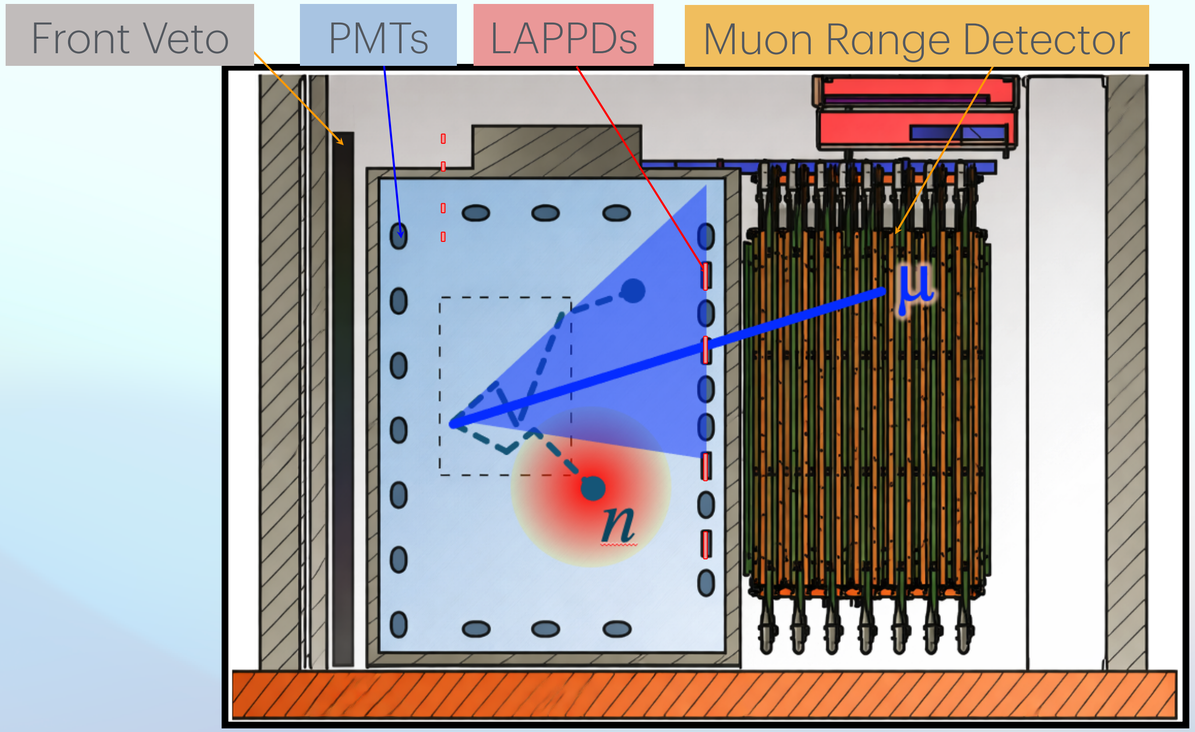
- **Water-based Liquid Scintillator (WbLS)** adds a small amount of scintillation to the Cherenkov signal, enabling hybrid signal reconstruction.
  - R&D is part of larger international effort on hybrid scintillator detectors (see J. Harnell's talk on Friday).
- The ANNIE Collaboration has:
  - Completed two deployments of a small volume of WbLS in the ANNIE detector.
  - Observed neutrinos in WbLS: JINST 19 (2024) 05, P05070.

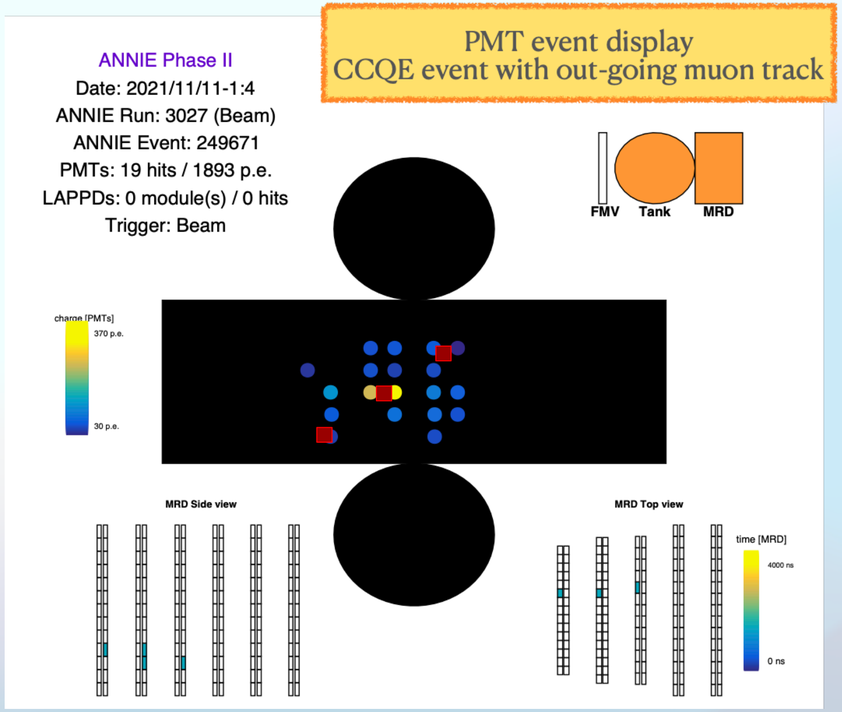




Observing neutrinos in ANNIE

- Basic event selection: PMT/LAPPD activity in water tank on-time with BNB beam trigger.
- Muon neutrino event: requires no signal in Front Veto but out-going track in MRD.
- Depending on analysis: specific Fiducial Volume for vertex, in-time with beam bunch etc.

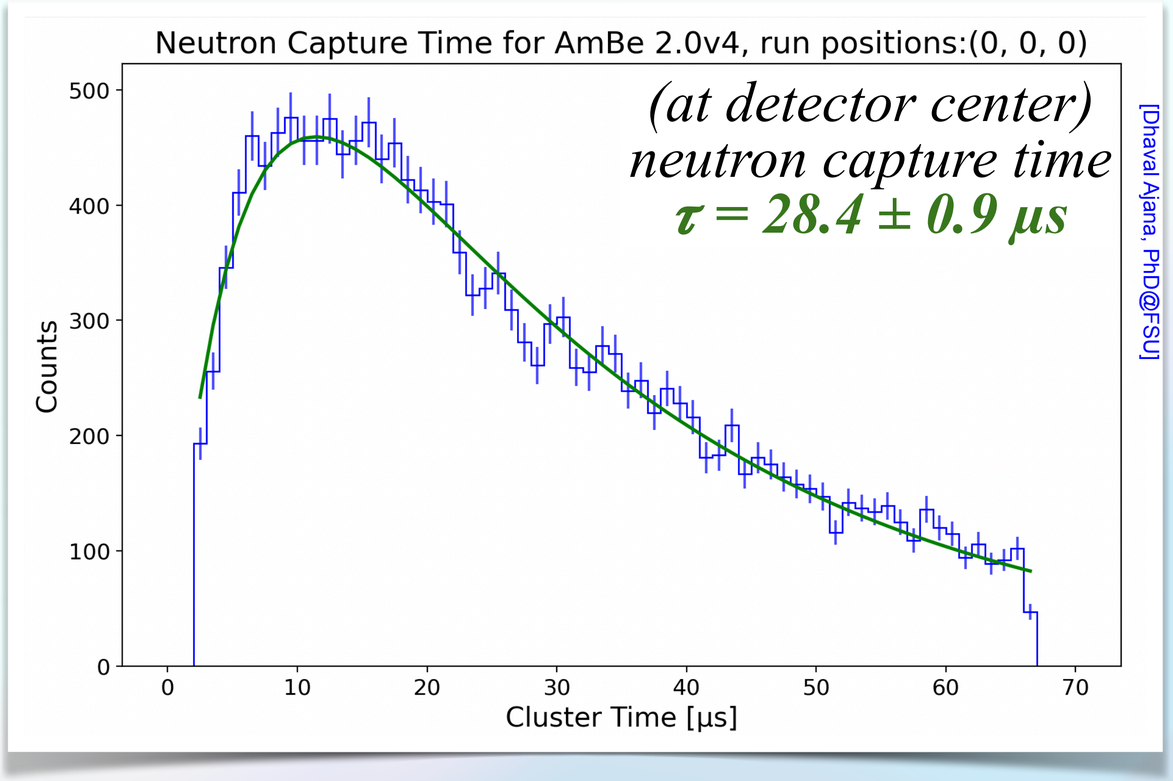




Details of our PMT event reconstruction: [JINST 21 (2026) 03, P03039]

Observing neutrons in ANNIE

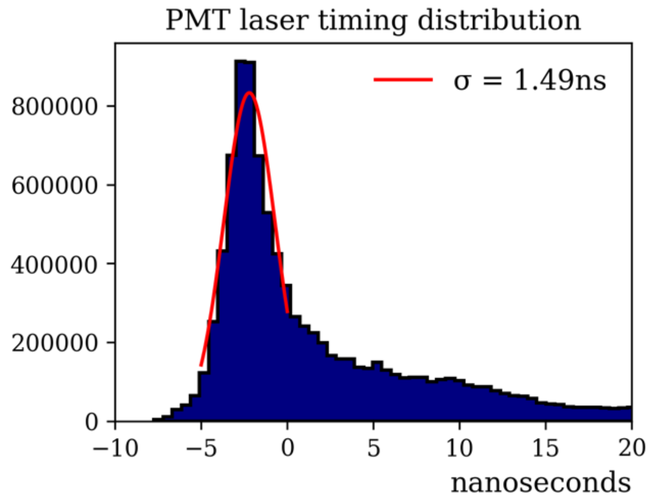
- ANNIE has 26-ton of Gd-doped water.
  - 0.1% Gd-loading results in ~30 μsec neutron capture time
- We use a tagged AmBe neutron source to calibrate both the capture time and the detection efficiency based on the fraction of detected neutrons.
- The measured capture profile fits the 0.1% Gd-loading expected capture time.
  - It matches the neutron captures observed from neutrino interactions.



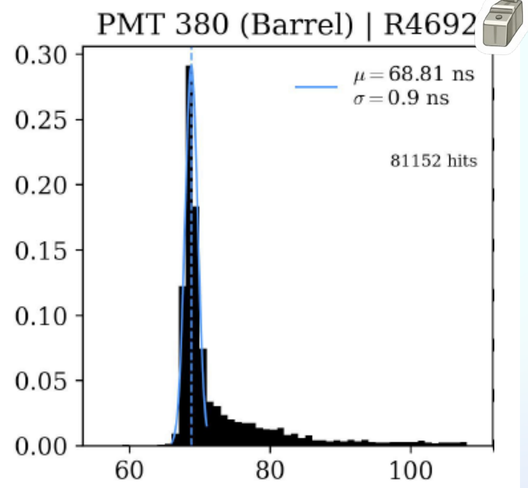
Timing and energy-scale calibration

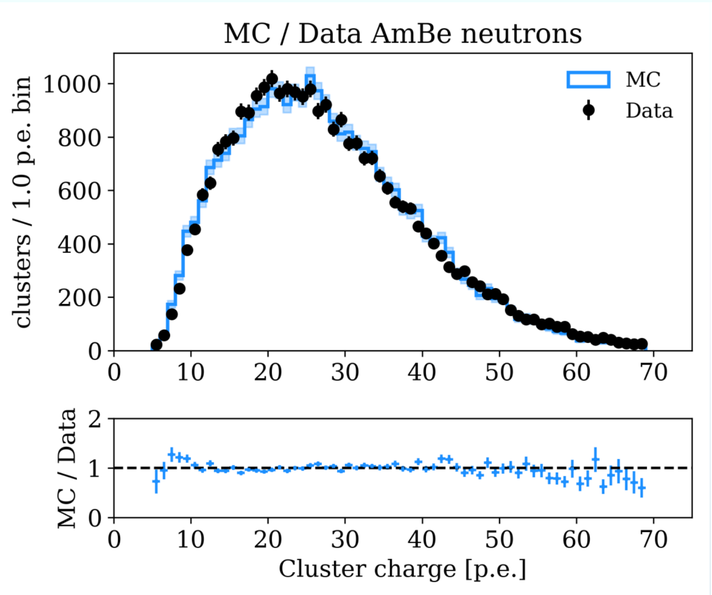
- PMT-based vertex reconstruction requires $\mathcal{O}$ ns timing uncertainties
  - We calibrate median PMT timing uncertainty from ~10 ns spread to ~1.5 ns.
- Data/MC simulation comparisons for AmBe neutrons and Michel electrons validates detector response calibrations.
  - Includes correction for PMT tilting discovered and fixed recently.

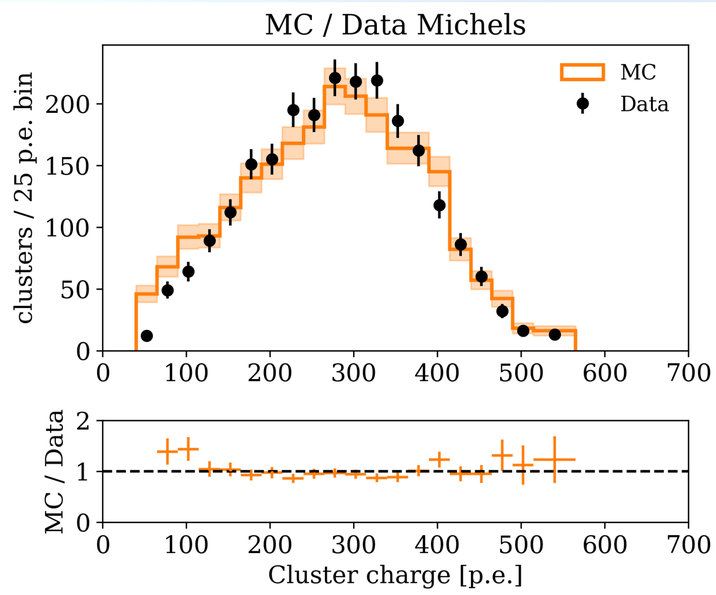
All PMTs



Individual PMT





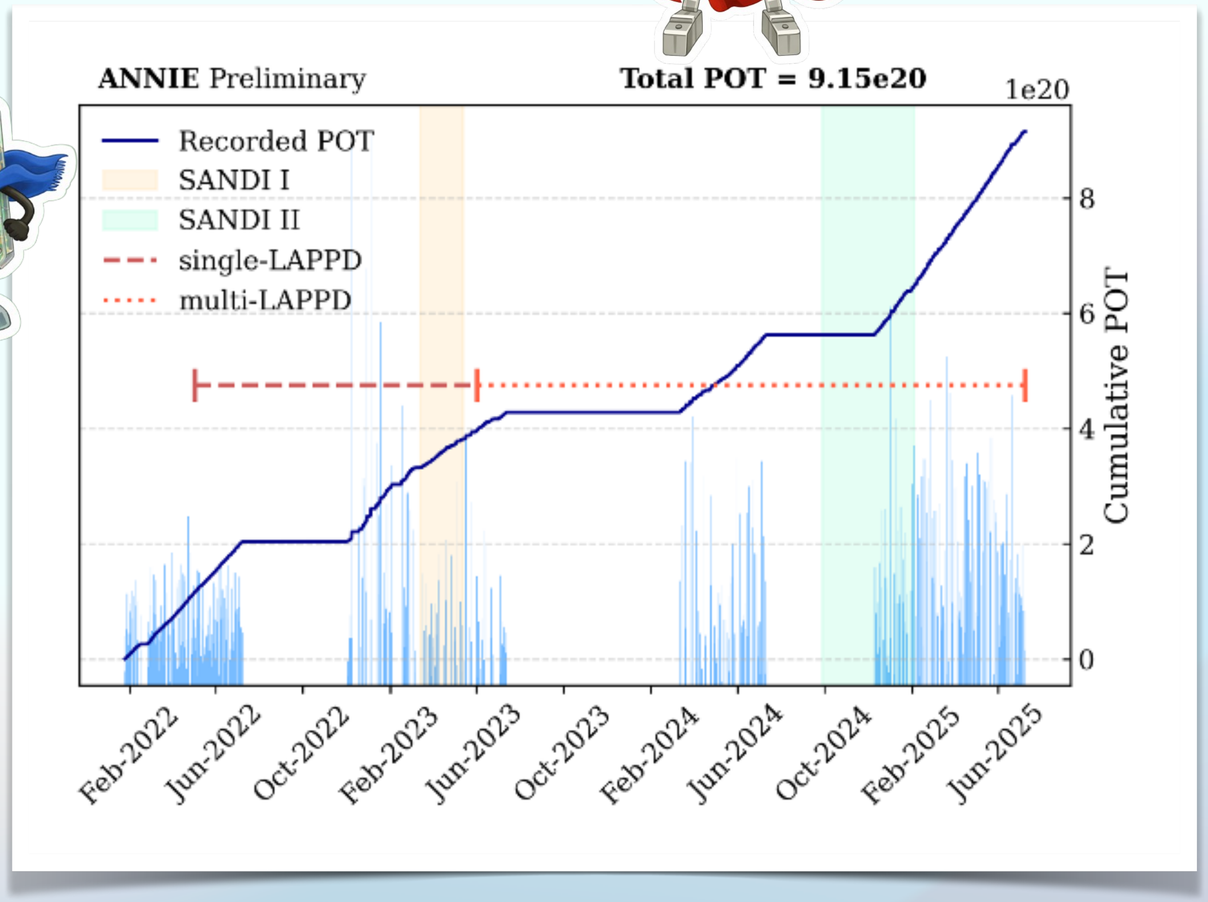


ANNIE data collected since 2022

- Results shown today are based on the PMT+MRD sample collected: CC and NC cross-sections.

- Running multi-LAPPD configuration since early 2023:
  → data set including LAPPD information still to be fully exploited.

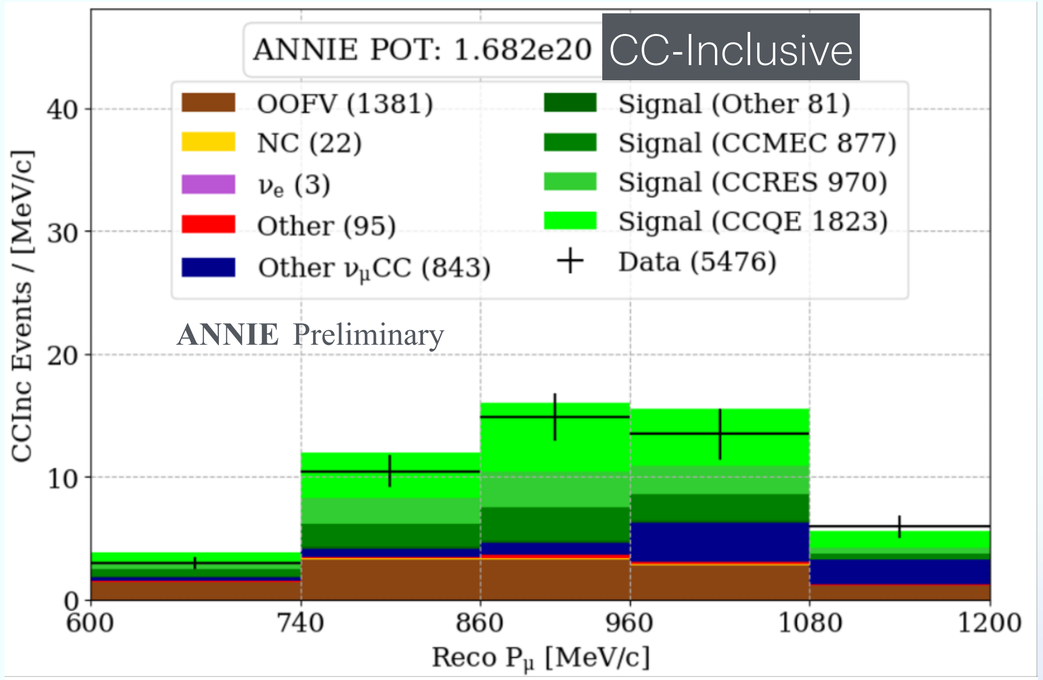
- Two deployments of SANDI/WbLS vessel, total ~4 months of beam data in 2023-24.

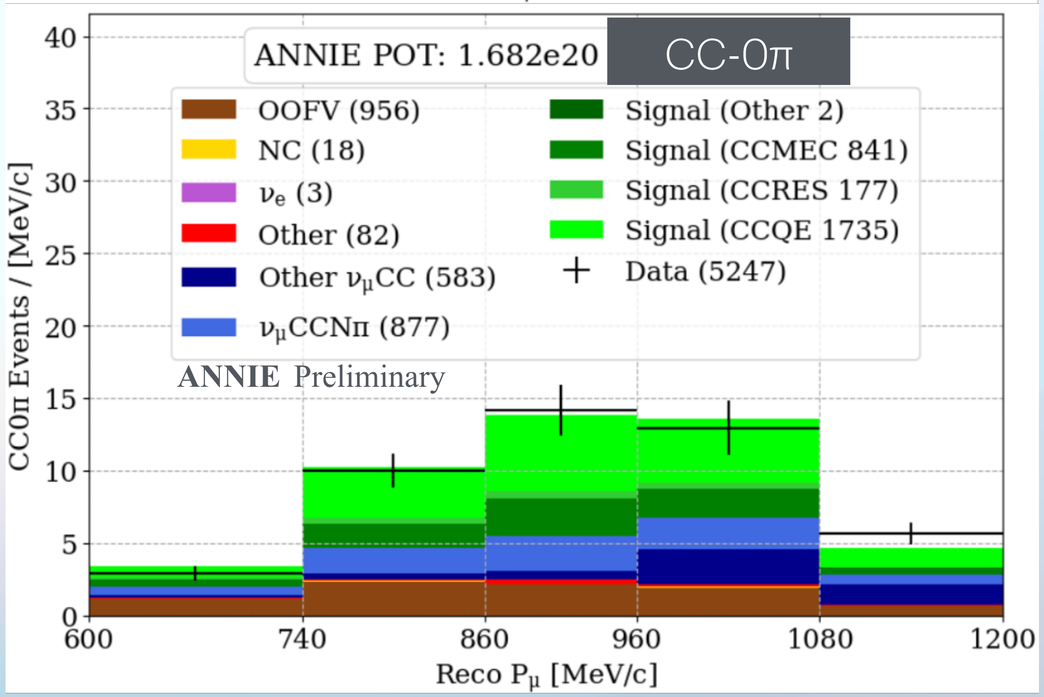


Poster #332

Charged-Current Cross Section

- Cross section analyses for CC-inclusive and CC-0π.
  - Data set from 1.68 x 10^{20} POT
- Samples selected based on standard analysis cuts:
  - Event vertex in fiducial volume
  - No front veto activity but track in MRD
- For CC-inclusive: no hadronic final-state requirement: CCQE, 2p2h, RES and DIS candidates
- For CC-0π: no final state pions: CCQE, 2p2h and pion absorption candidates.





[James Minock, PhD@Rutgers]

Poster #332

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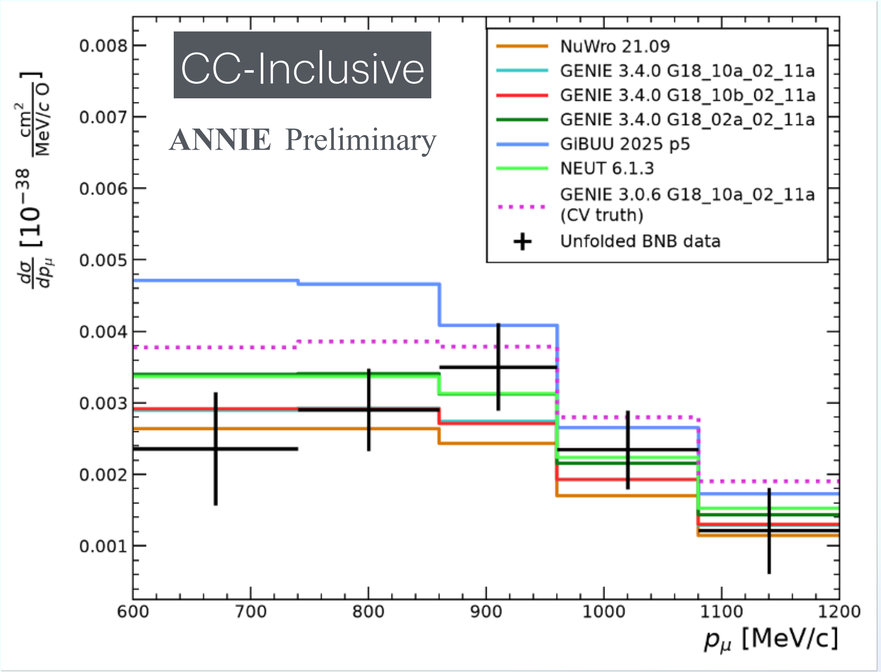
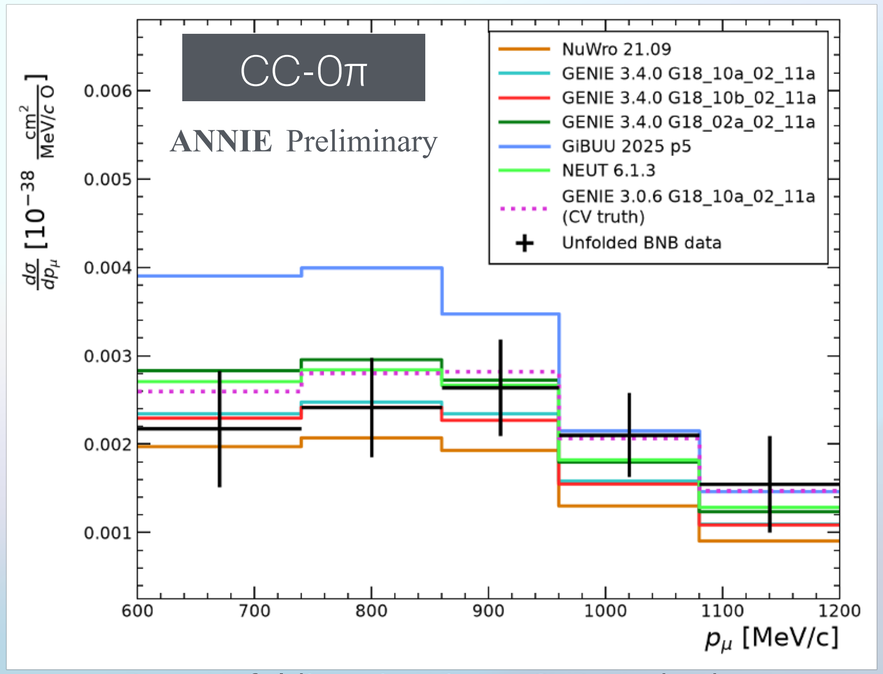
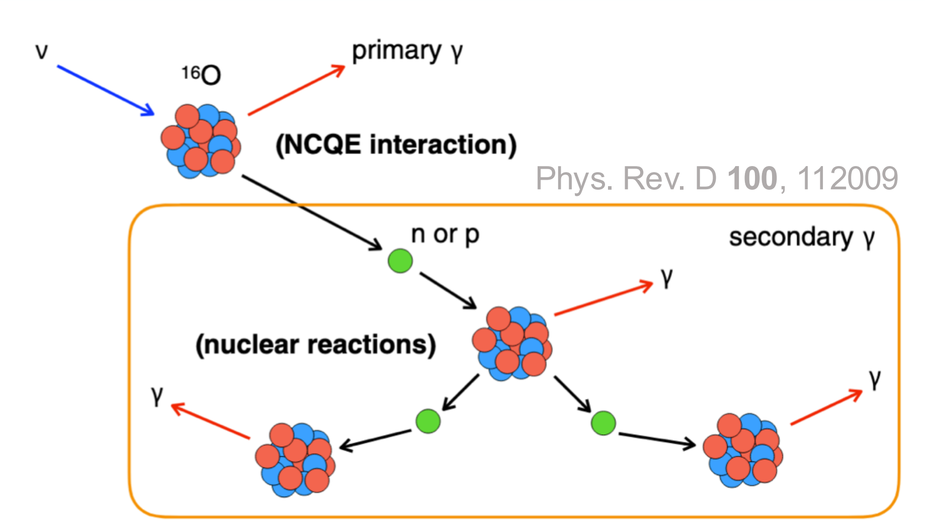




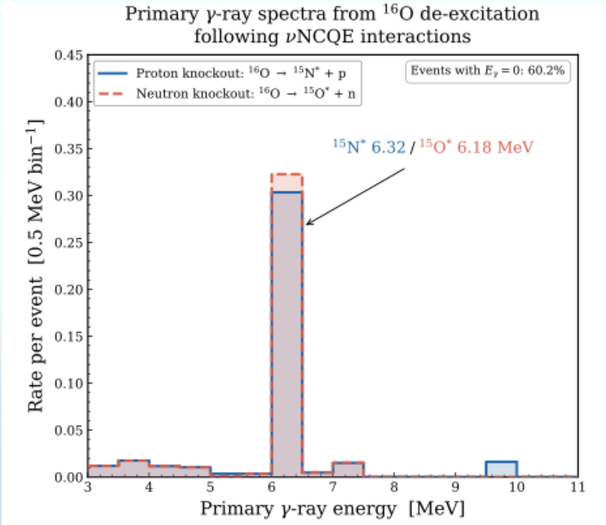
[James Minock, PhD@Rutgers]

Data Unfolding via Wiener-SVD Method

Neutral Current Quasi-Elastic Cross Section



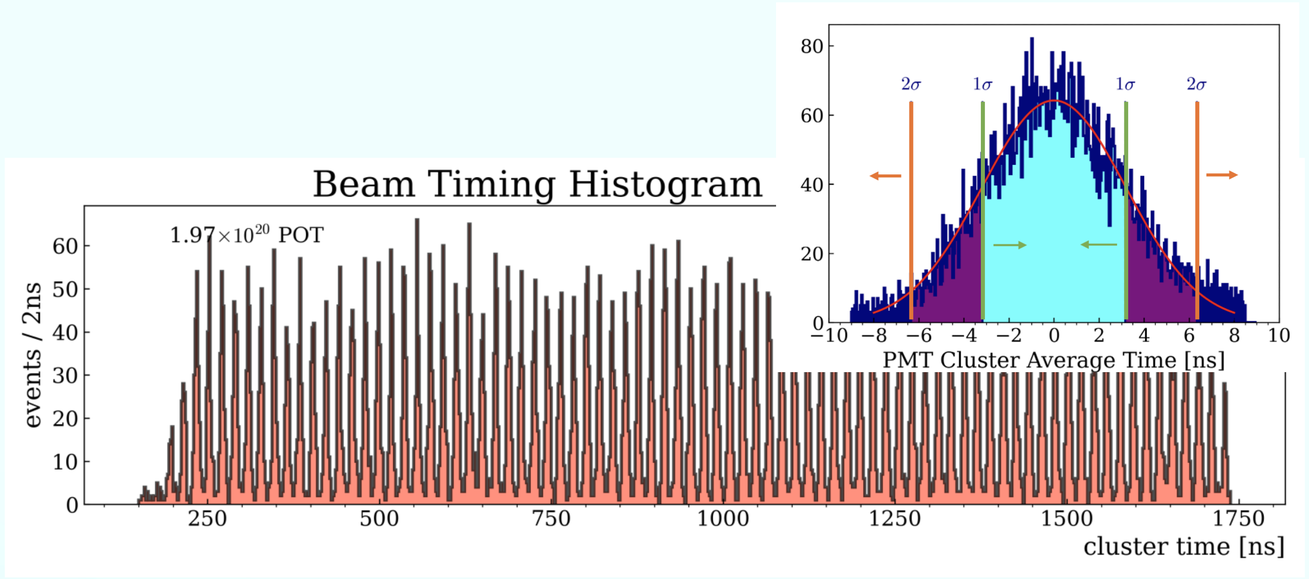
Phys. Rev. D **100**, 112009

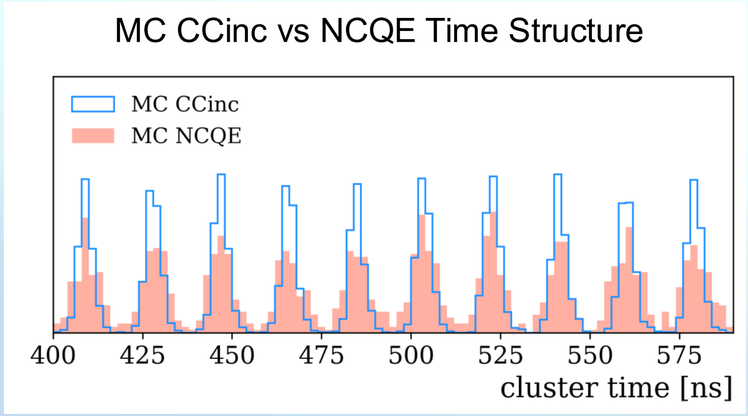


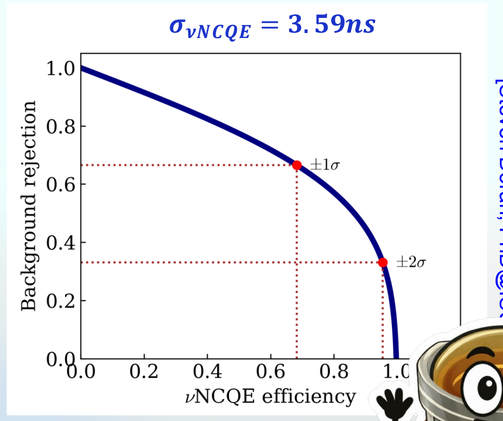
- Neutral current quasi-elastic (NCQE) neutrino interactions is the dominant NC topology at these neutrino energies (100MeV - 1 GeV).

- Interactions can be identified by a prompt gamma of ~6 MeV, and secondary gammas from nucleon-nucleus interactions then potential neutron capture (~μsecs later).

Neutral Current Quasi-Elastic Cross Section





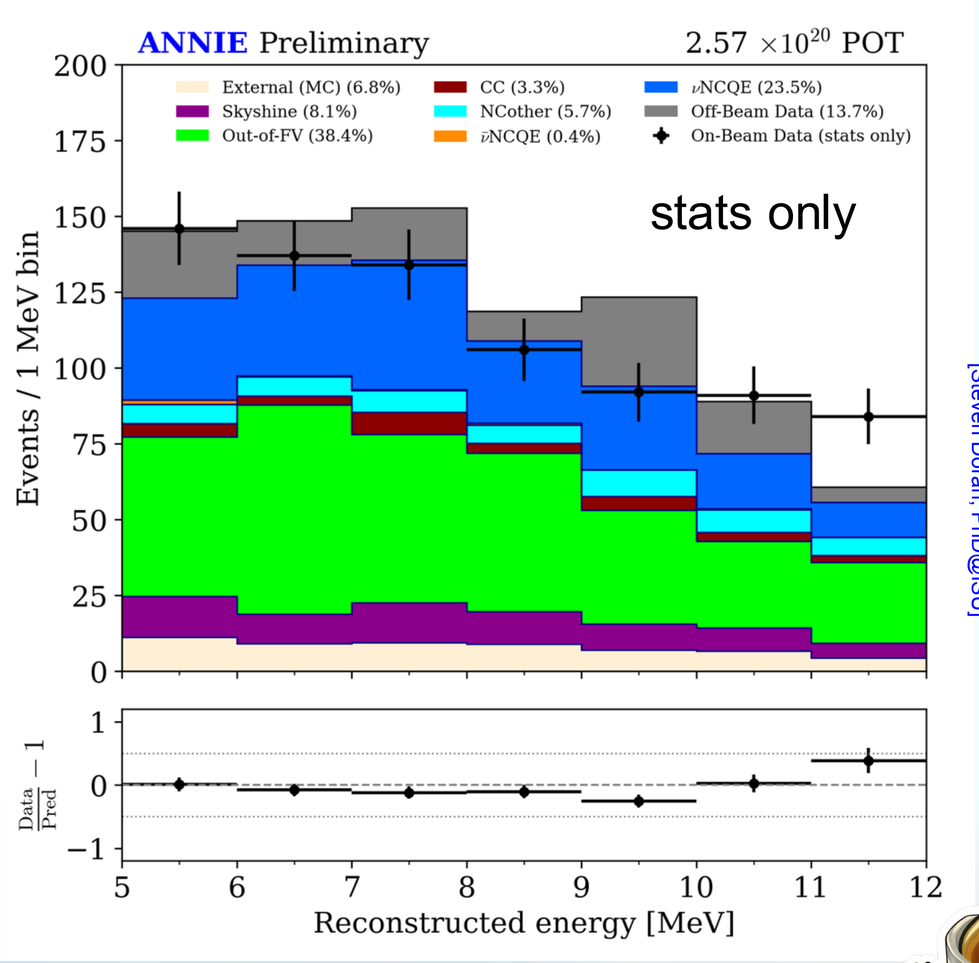


[Steven Doran, PhD@IS

±1σ reduces neutron/CIT background by ~66% (at 68% efficiency)

- NC interactions feature very low visible energy
  → event selection based on energy alone includes large background contributions.
- We exploit beam spill structure to reduce continuous in time (CIT) and diffuse backgrounds (neutrons).
- Selection of events in-time with bunches to improve purity of NC sample.
  - Previously done with CC candidates in MicroBooNE: Phys Rev D 108, 052010 (2023).

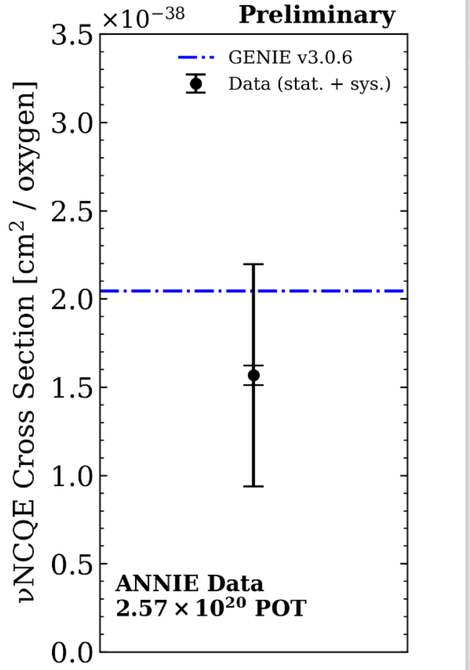
Neutral Current Quasi-Elastic Cross Section

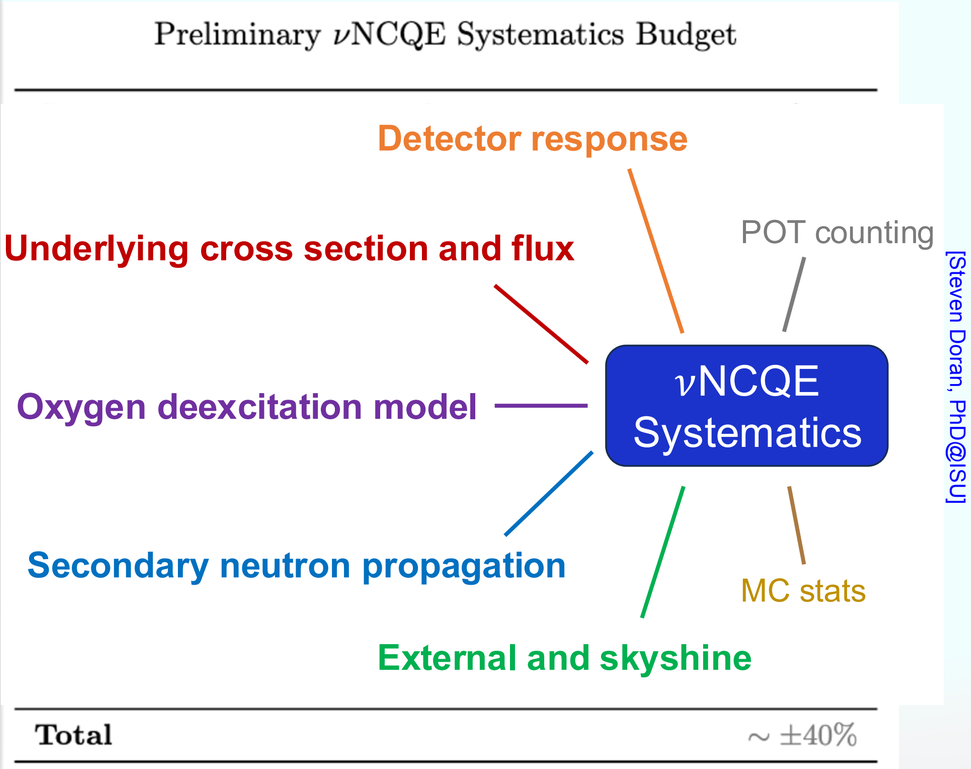


[Steven Doran, PhD@ISU]

- Cross section analysis for neutral current quasi-elastic (NCQE) neutrino interactions.
  - Data set is 790 events from 2.57 x 10^{20} POT.
- Event selection:
  - fully contained events in time with BNB bunch structure.
  - low energy (5-12 MeV) photons without a muon going through the MRD.
- Backgrounds:
  - Largest background category comes from interactions outside the FV.

Neutral Current Quasi-Elastic Cross Section





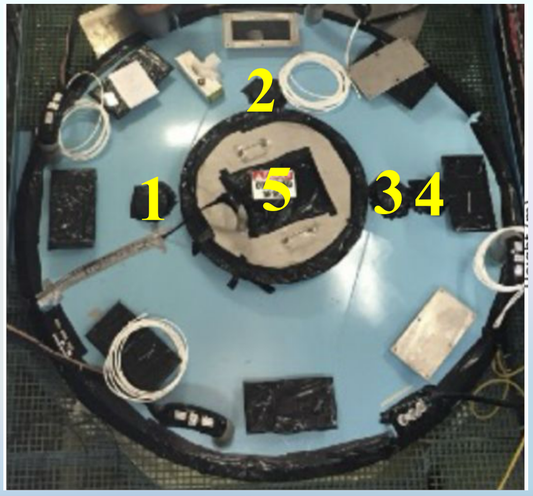
[Steven Doran, PhD@ISU]

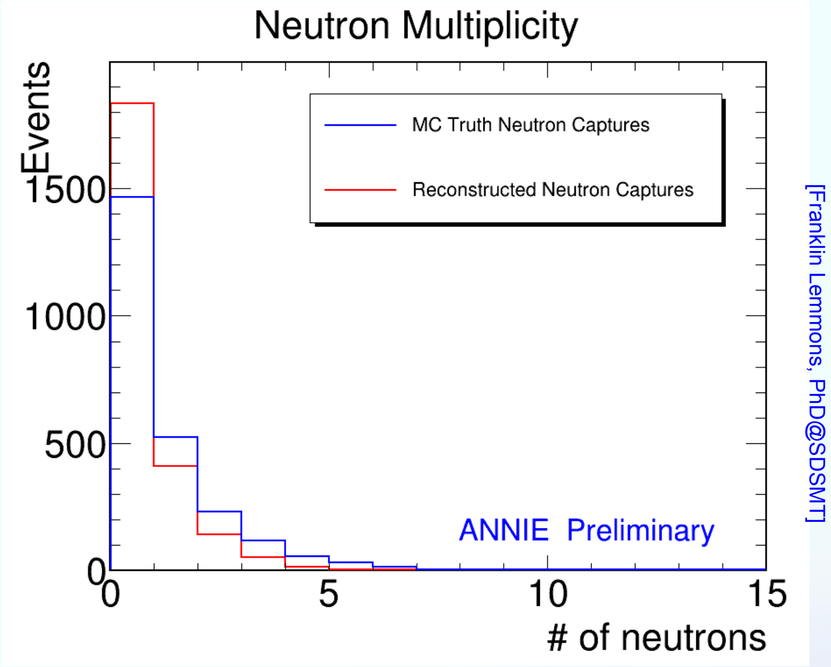
- Cross-section measurement relies on background subtraction.
  - External, skyshine and off-beam background rate estimates are data-driven.
  - All other beam-related background rates based on BNB flux prediction and simulations.
- Cross-section uncertainties dominated by cross-section systematics of background channels.
  - Using an updated data-driven model for oxygen de-excitations instead of standard GENIE implementation.

Poster #398

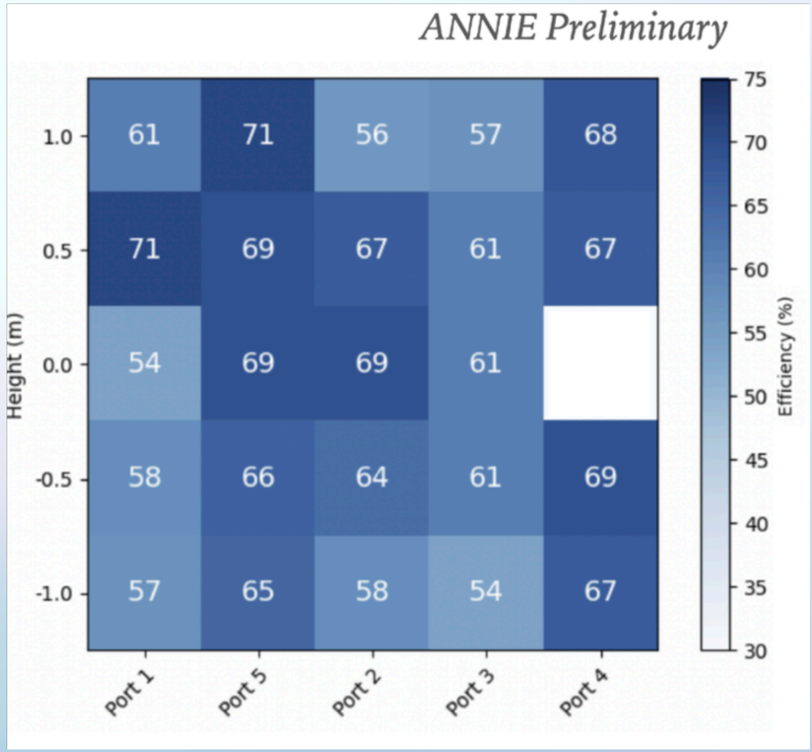
Neutron multiplicity in neutrino interactions

- Signal candidate selection developed:
  - CC muon neutrino in fiducial volume
    → select ~100 CCμ events per year
  - extended (70μs) window for neutrons
    → select neutron capture clusters
- Using the tagged AmBe source calibration we create a data-driven neutron capture efficiency spatial map enabling prediction of true neutron captures.
  - 50-70% efficiency from edge to center.





[Franklin Lemmons, PhD@SDSMT]



[Dhaval Ajana, PhD@FSU]

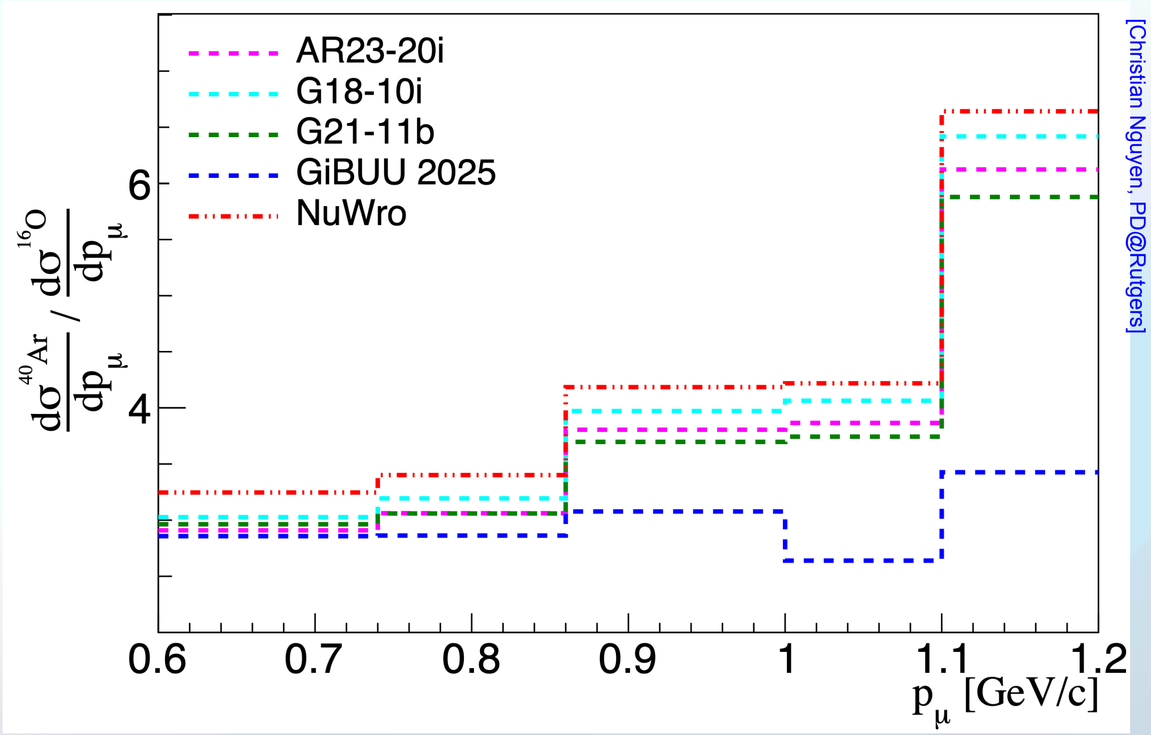
Poster #285

Joint cross section analysis ANNIE - MicroBooNE

- CC0π measurements can constrain the neutrino interaction and nuclear physics uncertainties that limit oscillation measurements..
  - Common handling of BNB flux and cross section systematics for oxygen/argon cross-sections.
- Developed joint signal definition:
  → Using selection for CC events without pions (CC0π) in both experiments
- Comparative analysis framework for MicroBooNE and ANNIE data based on GENIE
  → tests on-going with fake MC data.

CC0π Joint Signal Definition

1. Charged-current ν_μ interaction with ^{40}Ar or ^{16}O
2. $0.60 < p_\mu^{true} < 1.2$ GeV/c
3. $\cos\theta_\mu > 0.8$
4. No final state charged pions ($\pi^\pm$) with $p_\pi^{true} > 160.0$ MeV/c
5. No final state neutral pions (π^0)



[Christian Nguyen, PD@Rutgers]

Cross section ratio with Oxygen (ANNIE) as the denominator and Argon (MicroBooNE) as the numerator with different generators

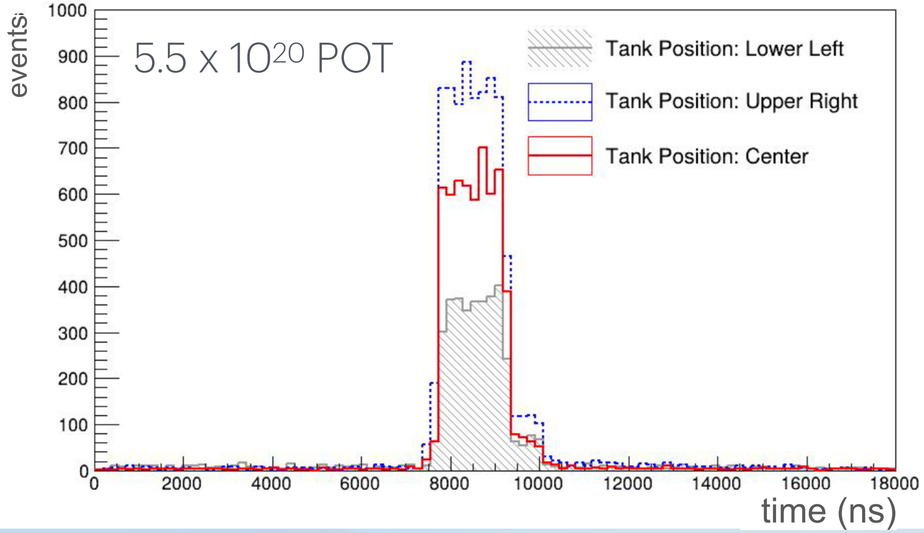
Poster #385

Using LAPPDs in ANNIE

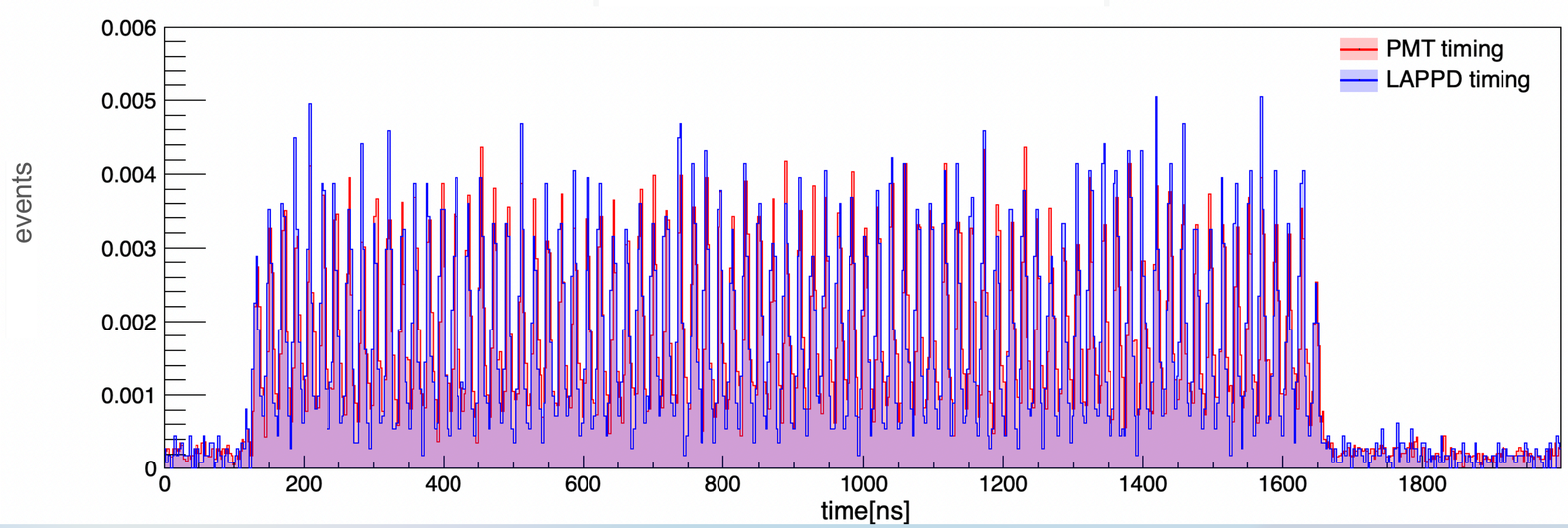
- We have deployed 6 units across the downstream face of the tank at 3 locations
  ↳First demonstration of observed neutrinos using LAPPDs: JINST 21 (2026) 02, P02002.
  ↳We have demonstrated time alignment using multiple LAPPDs event-by-event.
  ↳We have also resolved BNB bunch structure, demonstrating alignment between the PMT and LAPPD array.

- The next step is augmenting track reconstruction with the spatiotemporal information from the LAPPDs.

Relative time alignment of multiple LAPPDs for beam events



Bunch fine structure of spill resolved by a single LAPPD



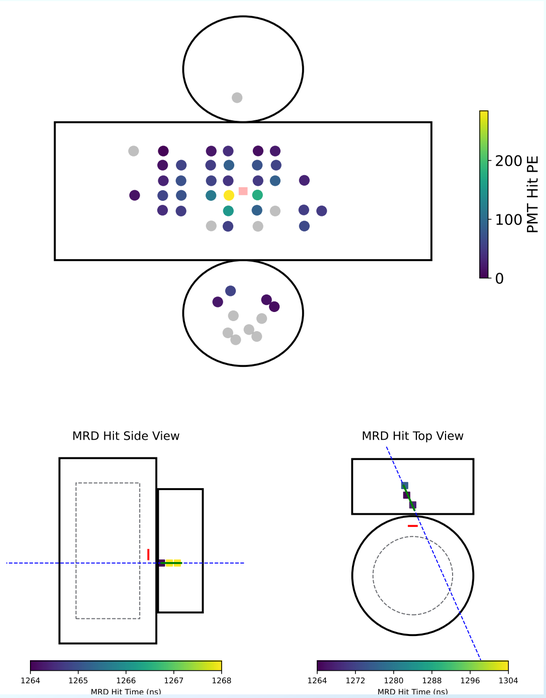
Poster #385

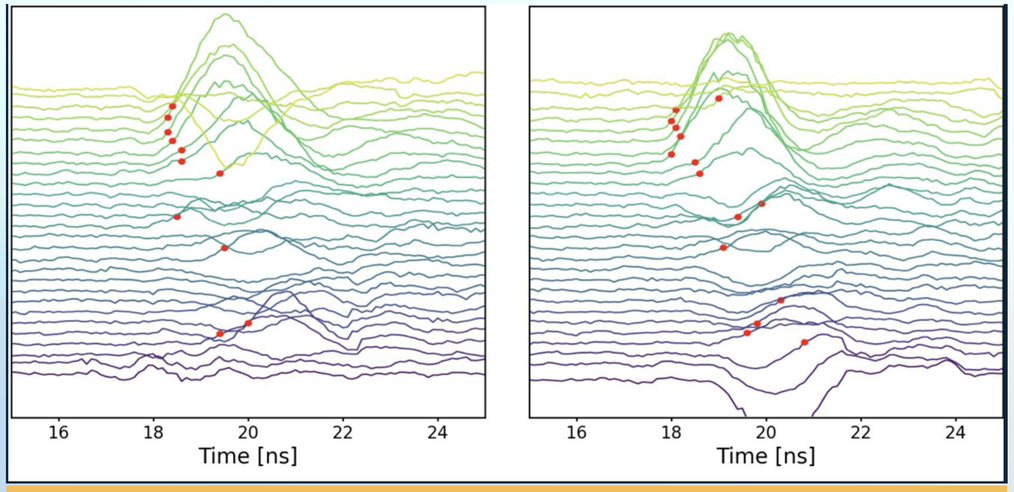
Using LAPPDs in ANNIE

- LAPPDs are imaging photosensors, registering information about the pattern of light arriving at the LAPPD surface in time and space. We can record waveforms from both sides of the LAPPD strip readout, corresponding to a given event.

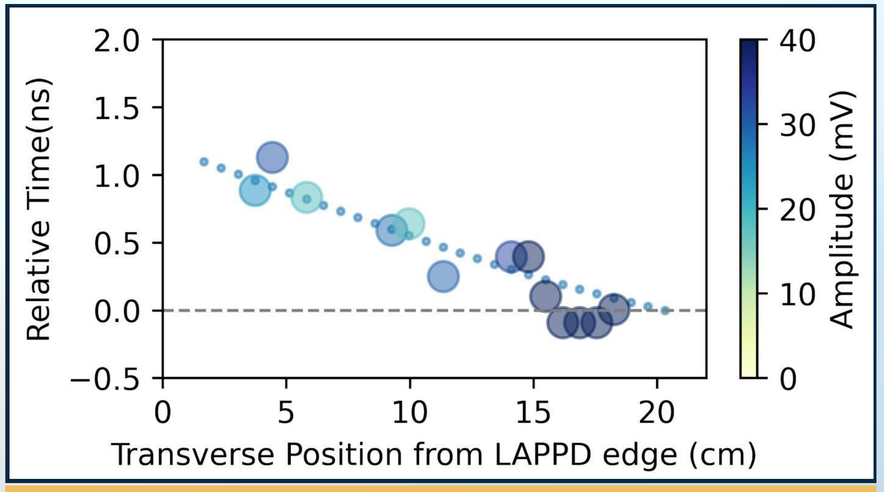
- A single LAPPD can partially constrain the track parameters of a muon; something that is not possible with a single conventional photosensor

  - LAPPD-enhanced reconstruction with multiple LAPPDs is in progress.





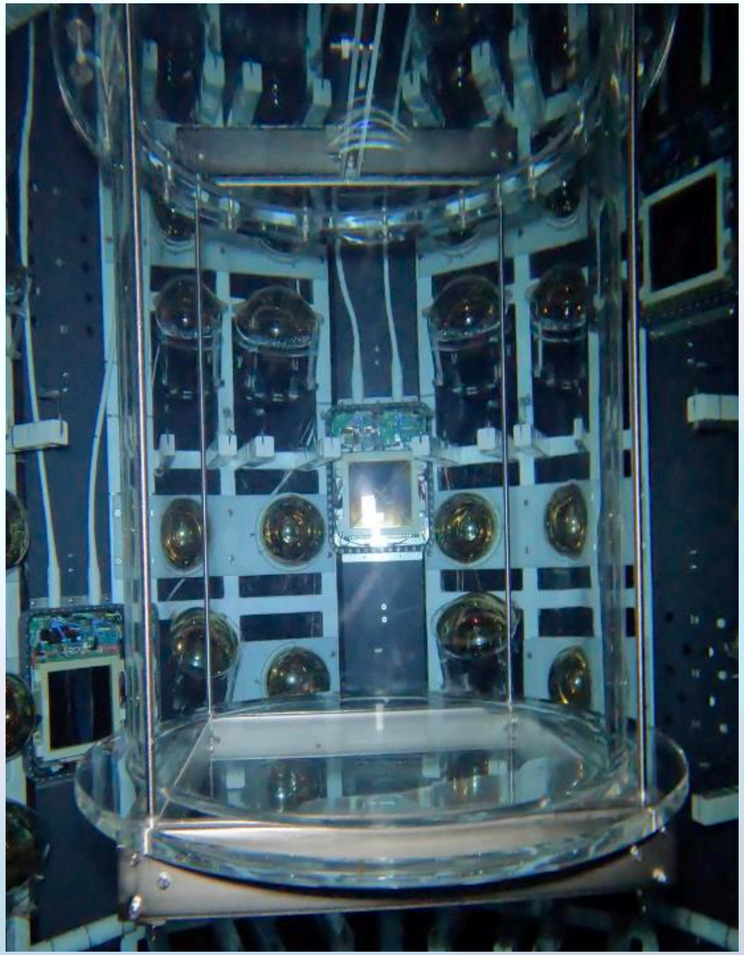
The estimated arrival time for each waveform is shown as a red dot.



Time gradient in the arrival-time of the light across the surface of the LAPPD

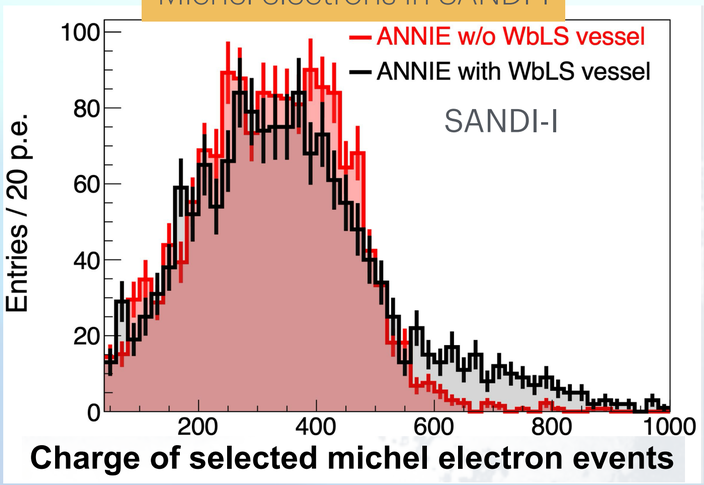
Using WbLS in ANNIE

- We have completed two runs with an acrylic vessel (SANDI) holding 365 liters of WbLS in ANNIE tank.
- Detected forward running Cherenkov and isotropic scintillation emission for beam events (e.g. Michel electrons) using WbLS.
- Deployed Gd-WbLS for first time observing enhanced neutron signal.
- Demonstrated basic hybrid event topology, but larger active volume required to demonstrate full event reconstruction.

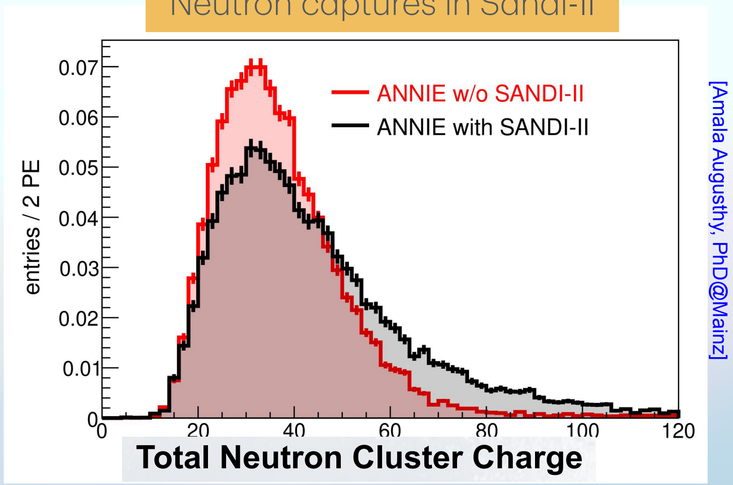


[Amala Augusthy, PhD@Mainz]

Michel electrons in SANDI-I



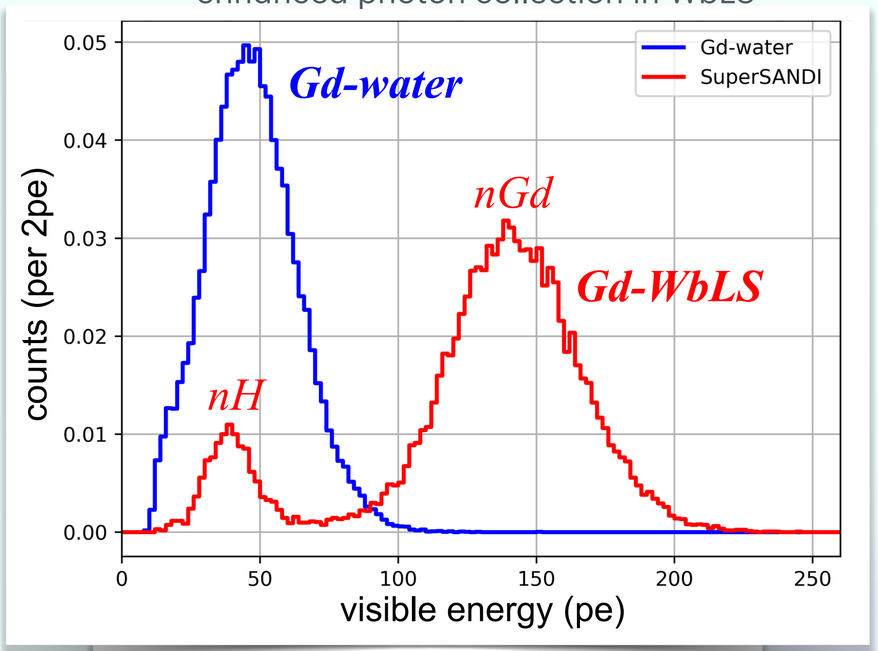
Neutron captures in Sandi-II

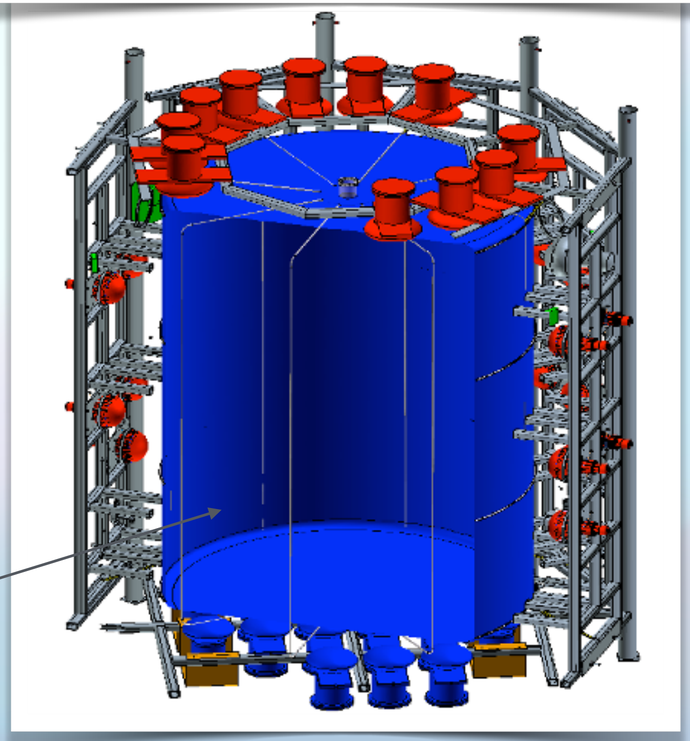


What is next for ANNIE

- We are deploying a larger 7 ton WbLS vessel/balloon filling the entire active volume and add Gen-II LAPPDs.
- By adding scintillation we are able to detect and demonstrate reconstruction of recoil hadrons as well as more neutron captures:
  → neutron detection efficiency: 80%
- In addition, LAPPDs in ANNIE have the potential to demonstrate enhanced Cherenkov/scintillation separation based on sub-nanosecond timing.

enhanced photon collection in WbLS





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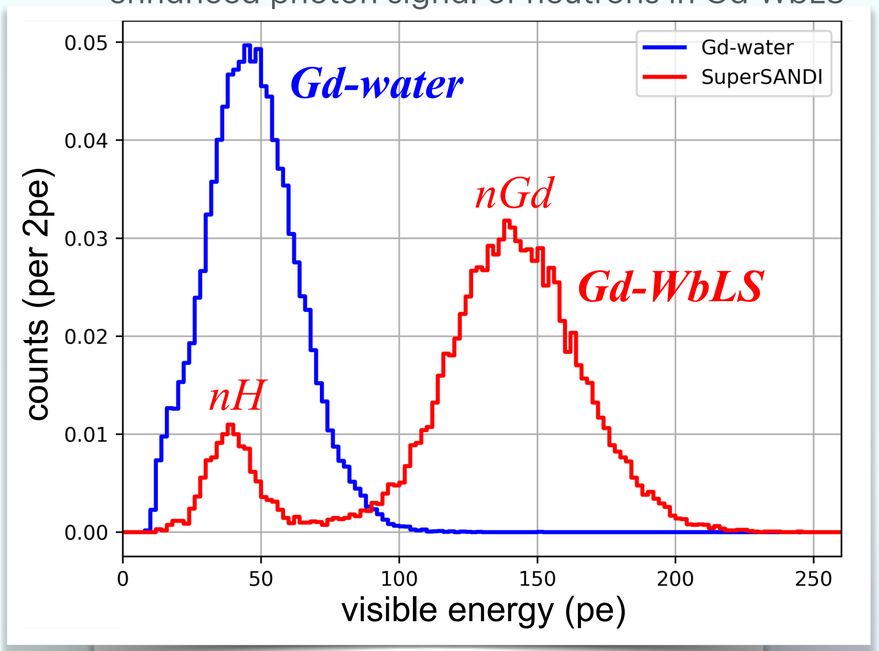
enhanced photon signal of neutrons in Gd-WbLS



SuperSANDI

Summary

- ANNIE is in a unique position to **measure neutrino-nucleus-cross sections in water** (first results shown today!), with complementary sensitivity to LAr-TPCs (neutron vs. proton yield!) and directly comparable due to **MicroBooNE/SBND argon data in the same beam**.

- ANNIE is a **testbed for novel technologies**: Detector operation of past years has established **Gd-loaded water, WbLS and LAPPDs** for the detection of neutrinos.

- ANNIE continues to collect a **substantial multi-LAPPD data set** (10x data from first paper). Work on advanced event reconstruction is on-going and will lead to a second series of analysis papers.

- **Deploying a large WbLS vessel and new LAPPDs in 2026-2027**, harvesting the return on substantial R&D efforts over the past years.