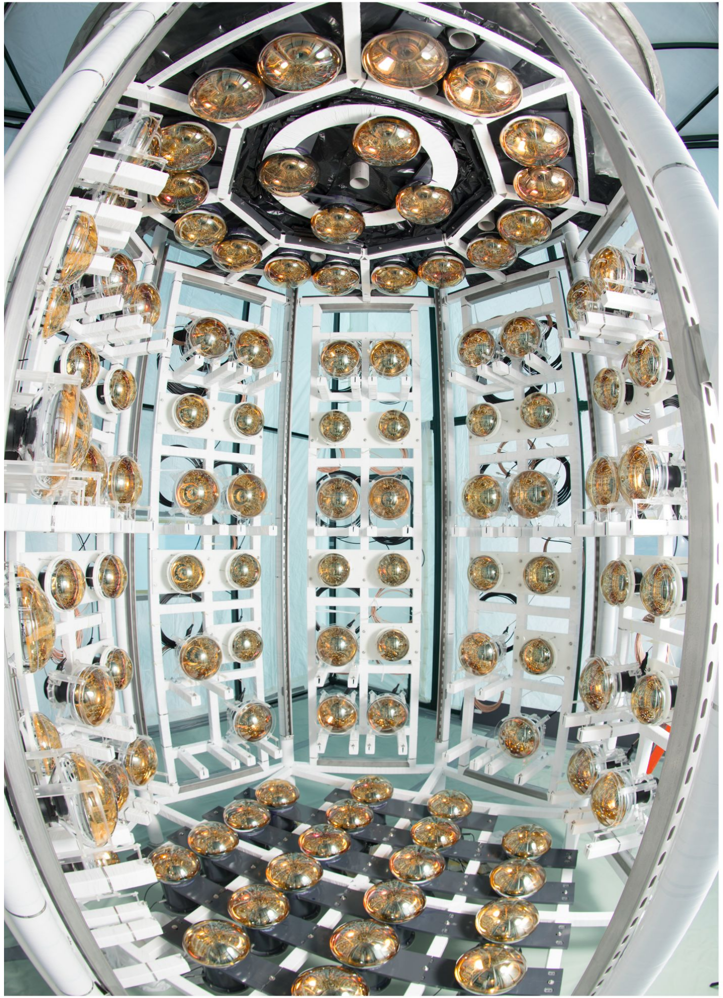
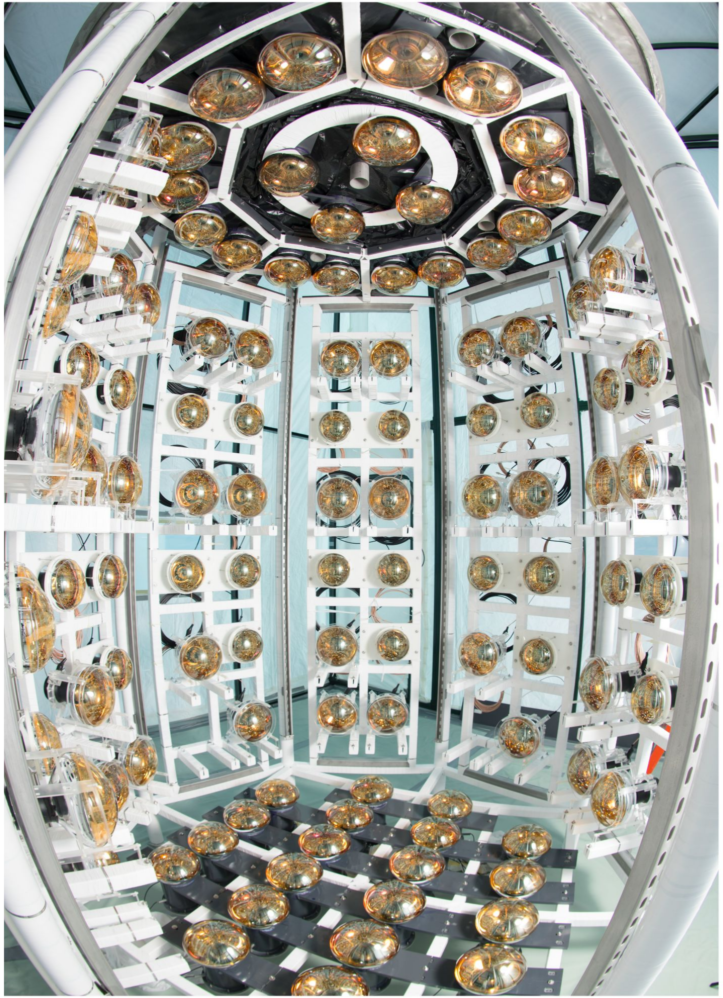


Status Report of ANNIE

Fermilab PAC Meeting
01/09/24

Mayly Sanchez (FSU)
Michi Wurm (Mainz)

annie



ANNIE in a nutshell

ANNIE : Accelerator Neutrino Nucleus Interaction Experiment

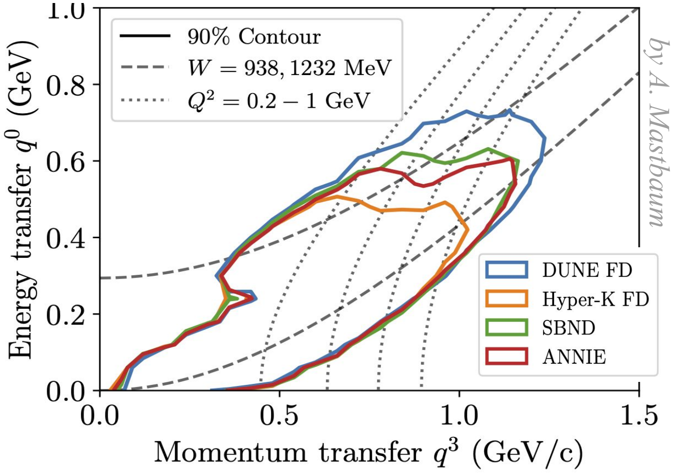
- Physics goal: Study neutrino interactions in water (on oxygen), especially the neutron yield
- Setup: 26-ton Water Cherenkov detector with ~100 PMTs in the Booster Neutrino Beam (BNB)
- Detector R&D goals:
  Demonstrate novel neutrino detector technologies
  - Gadolinium loaded water target
    → enhanced neutron tagging
  - Water-based liquid scintillator
    → detection of sub-Cherenkov particles
  - LAPPDs → sub-nanosecond timing, sub-cm spatial resolution photo sensors to improve event reco

ANNIE's physics

Direct relevance for long-baseline neutrino program since kinematic parameters of BNB neutrino interactions largely overlap with DUNE and HK FDs

- ANNIE shares the BNB with several liquid-argon experiments
  → direct comparison of oxygen & argon cross-sections (MicroBooNE, SBND)

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

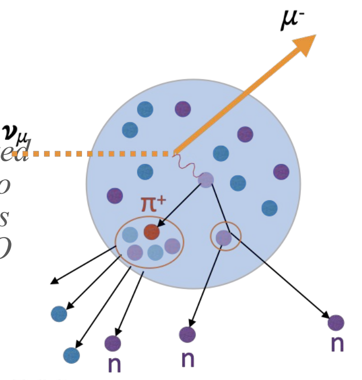


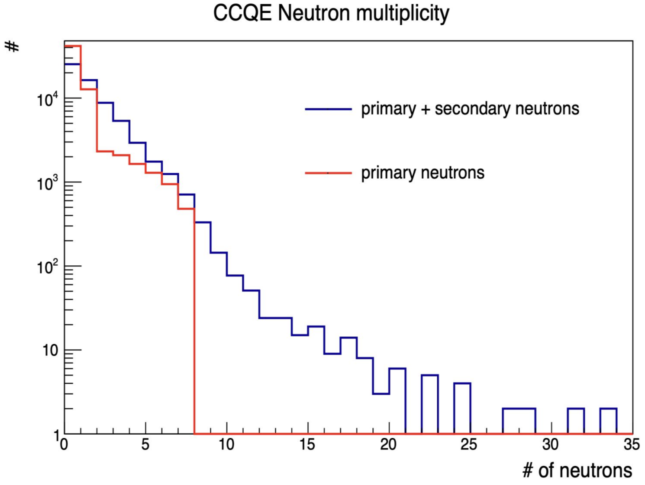
ANNIE's physics

Direct relevance for long-baseline neutrino program since kinematic parameters of BNB neutrino interactions largely overlap with DUNE and HK FDs

- ANNIE shares the BNB with several liquid-argon experiments
  → direct comparison of oxygen & argon cross-sections (MicroBooNE, SBND)
- Neutron multiplicity from CC interactions and differential cross-sections on oxygen
  → important input for neutrino event generators

In CCQE interactions, primary neutrons are created by nuclear effects. Added to this are secondary neutrons caused by e.g. $^{16}O(n,2n)^{15}O$ reactions on neighboring nuclei.





ANNIE's physics

Direct relevance for long-baseline neutrino program since kinematic parameters of BNB neutrino interactions largely overlap with DUNE and HK FDs

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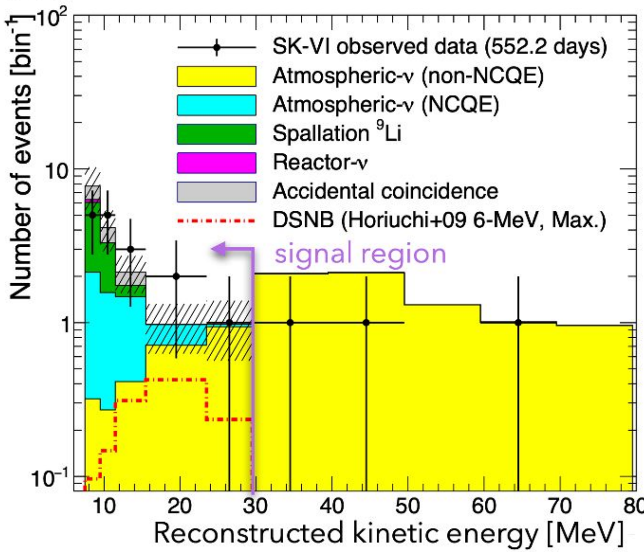
  → direct comparison of oxygen & argon cross-sections (MicroBooNE, SBND)
- Neutron multiplicity from CC interactions and differential cross-sections on oxygen
  → important input for neutrino event generators
- NC interactions: background for
  - Long-baseline oscillation experiments
  - Diffuse Supernova Neutrino searches
  - Proton decay searches

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



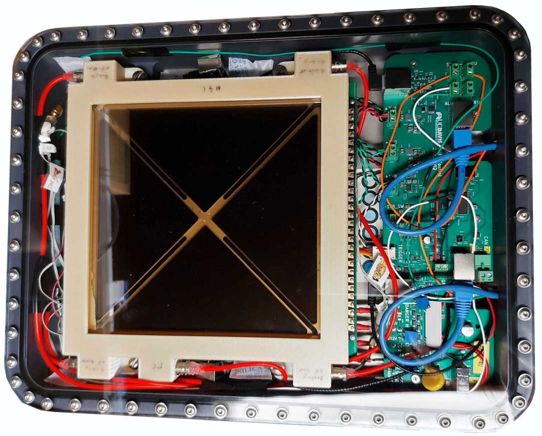
by SK collaboration, TAUP 2023

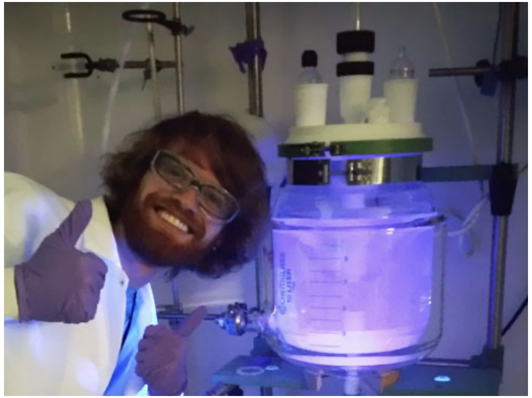
ANNIE’s accomplishments

- First-ever physics experiment to operate multiple LAPPDs long-term and under experimental constraints (submerged on-board electronics, long transmission cables etc.)
- First-ever detection of neutrinos with LAPPDs
- Highest concentration Gd-water target in operation
- First neutrino experiment to deploy a close-to ton-scale vessel of WbLS (365kg) and detect neutrinos within

→ several technical papers in preparation, preprint with first WbLS results online [arXiv:2312.09335]

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





Large vat of Water-based Liquid Scintillator (WbLS) in the Davis lab

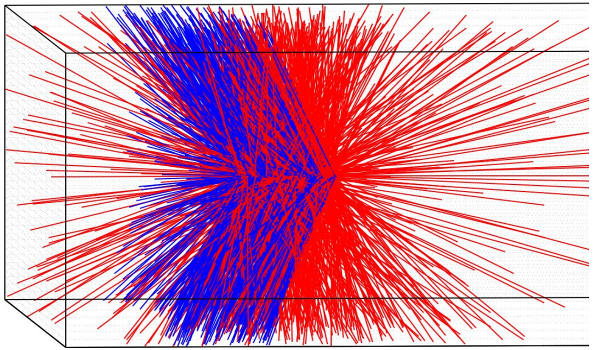
ANNIE's plans for further R&D on hybrid detectors

ANNIE is in a unique position to evaluate performance of novel techniques for GeV neutrino detection

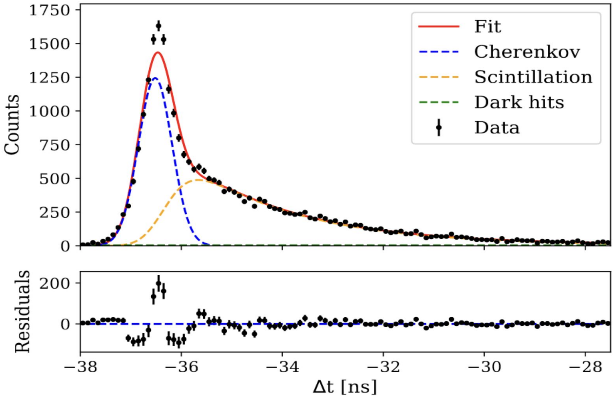
- Water-based Liquid Scintillator (WbLS) is a suitable target medium for a 4th (non-LAr) DUNE module
- WbLS features fast fluorescence times and LAPPDs are ideal photo sensors for time-based separation of Cherenkov and scintillation signals
- Gen-II LAPPDs perform better in environment with large photon-hit occupancies

→ A high-statistics measurement in an expanded WbLS volume with additional Gen-II LAPPDs is a key step in demonstrating these technologies for long-baseline neutrino experiments.

Artistic view of a DUNE-WbLS module

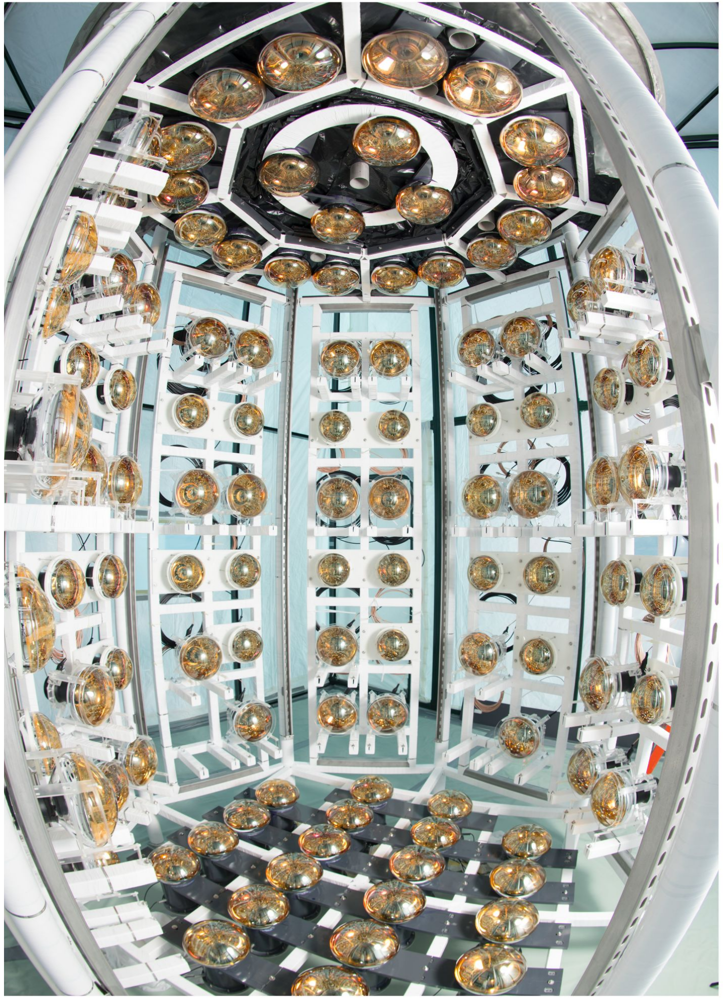


Separating Cherenkov and scintillation signals with an LAPPD (CHESS@UC Berkeley)



ANNIE in the context of the US Physics Program

- ANNIE's physics goals are directly relevant to the US neutrino program as measurements of neutron yield in neutrino interactions are essential input to the reduction of systematic uncertainties for long-baseline neutrino experiments.
    - Goals match the 2023 P5 driver: *Elucidate the Mysteries of Neutrinos*
- ANNIE's R&D goals in demonstrating and testing detector technologies such as LAPPDs and WbLS are relevant to a potential non-LAr DUNE FD4.
    - From the P5 report, section 3.1.4: *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 [of DUNE FD4], particularly in the low-energy regime.*
- ANNIE's is an exceptional training ground for early career scientists.
    - 10+ Postdocs/PhD students are now university faculty or national laboratory staff.



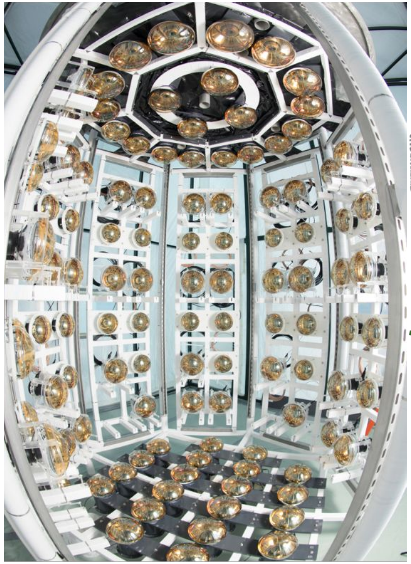
ANNIE Status Overview

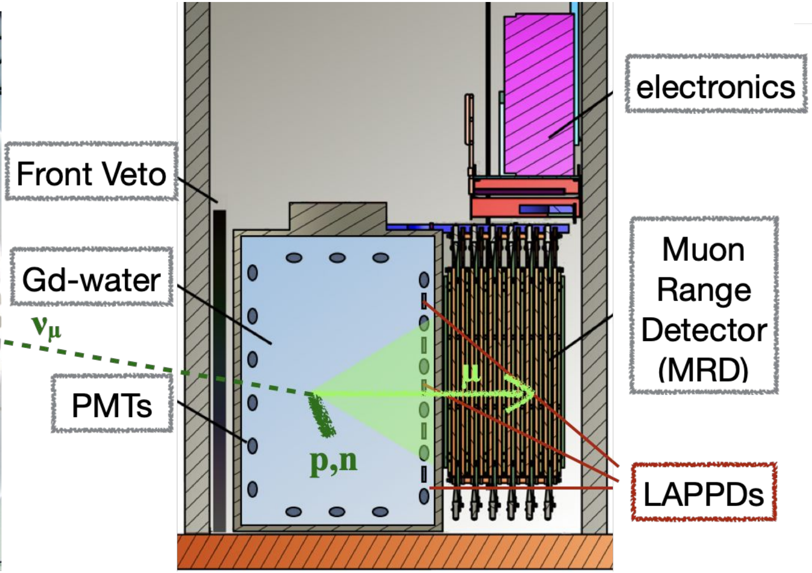
- Installed and commissioned in the BNB
- Progress on analyses with first Gd data set
  → Neutron multiplicity measurement
  → Water/LAr cross sections with MicroBooNE+SBND
- First deployment of multiple LAPPDs
  → commissioned and ready for neutrino data taking
- First ton-scale WbLS deployment
  → neutrino events and light yield estimates
- Plans for continuing R&D program using expanded WbLS volume and Gen-II LAPPDs
  → demonstrate hybrid event reconstruction
  for GeV neutrinos in future LBL experiments

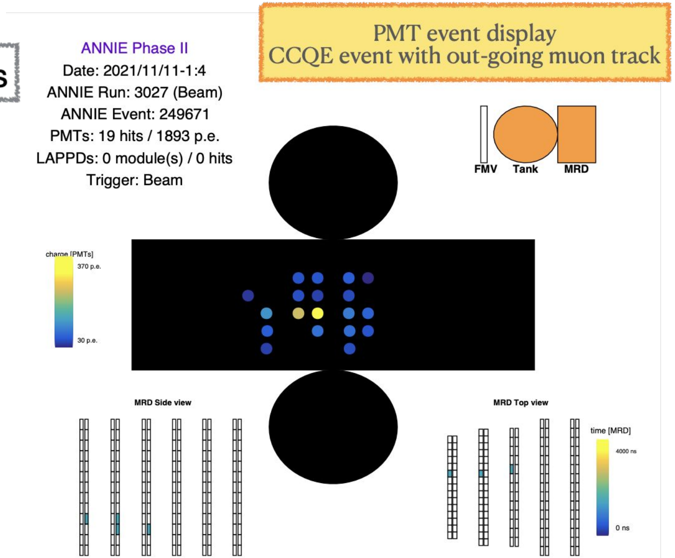
Experimental Setup of ANNIE

- Steel tank: 26t of Gd-water
- 132x 8"-11" bi-alkali PMTs
- 5x LAPPDs with 100ps timing
- MRD: iron-plastic scintillator sandwich to track outgoing μ's
- Front Veto to catch dirt muons

Inside View

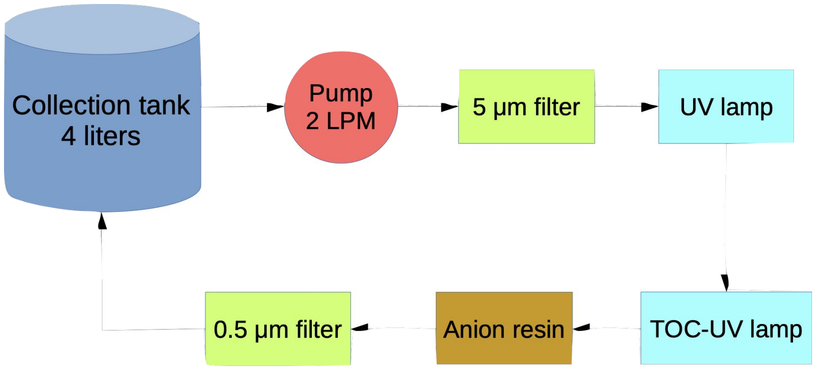


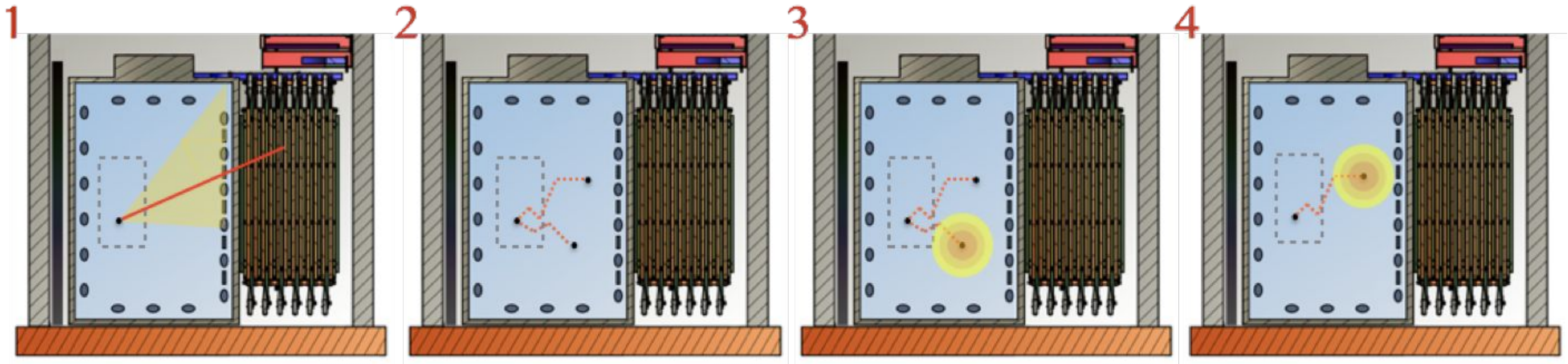




Gadolinium loading for enhanced neutron detection

- General idea: recoil neutrons thermalize and capture on gadolinium with a 30μs delay
- Allows counting (multiplicity, including secondary neutrons) and potentially energy measurement by distance of capture point to vertex
- Technical challenge: keep Gd-water chemically stable over extended periods (circulation)



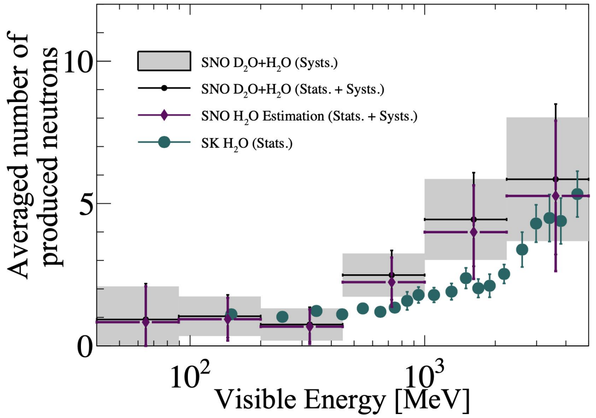


ANNIE's physics: Neutron multiplicity

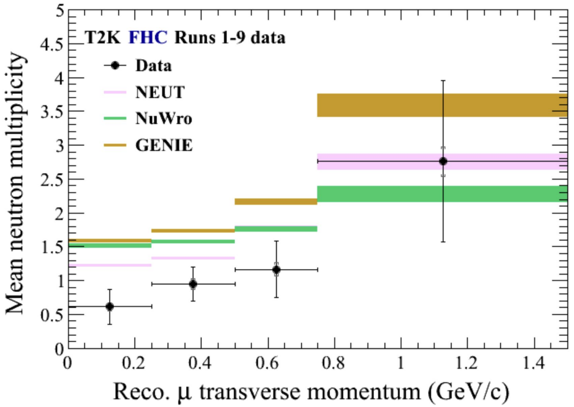
- Improve understanding of CC interactions on oxygen
- 3-dimensional differential cross-section measurement:
  a. Final-state lepton energy
  b. scattering angle
  c. neutron multiplicity
- High-statistics measurement, several 10^4 neutrino events per beam year
- Comparison to LAr cross-sections measurements (neutrons versus recoil protons!)

SNO, PRD 99 (2019) 11, 112007

SNO/SK: neutron production from atmospheric neutrinos vs. ***lepton energy***



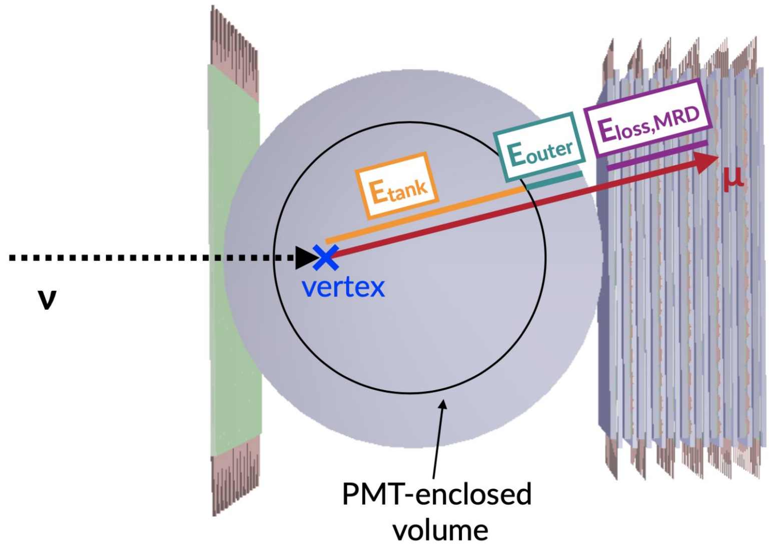
T2K: neutron production vs. ***transverse momentum****, limited statistics*

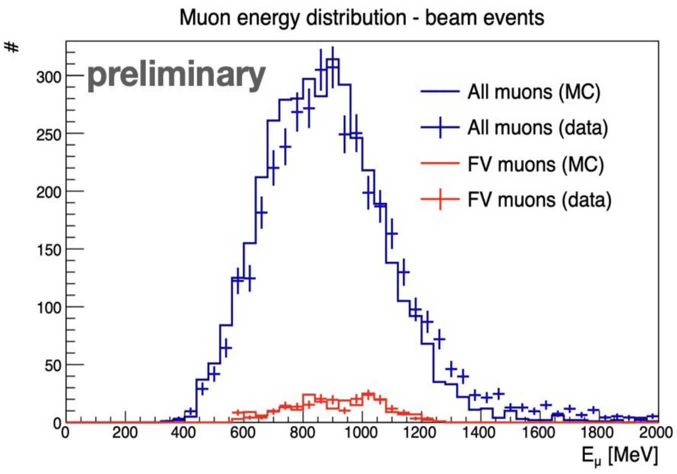


T2K, TAUP 2019

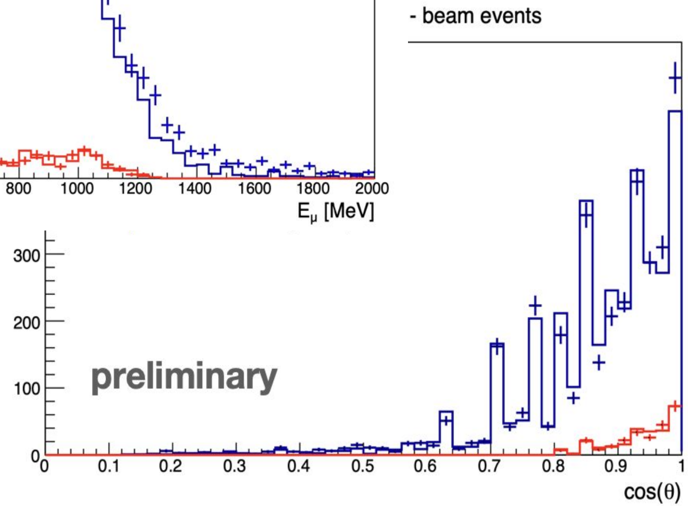
On-time and delayed event reconstruction (PMT only)

- **On-time:** CC ν_μ interaction, muon energy and scattering angle
- **Delayed:** 8 MeV gamma signals from neutron capture on gadolinium





Reconstruction of ***final-state muon energy and scattering angle*** *based on light output in water tank and MRD muon track information*



On-time and delayed event reconstruction (PMT only)

- **On-time:** CC ν_μ interaction, muon energy and scattering angle
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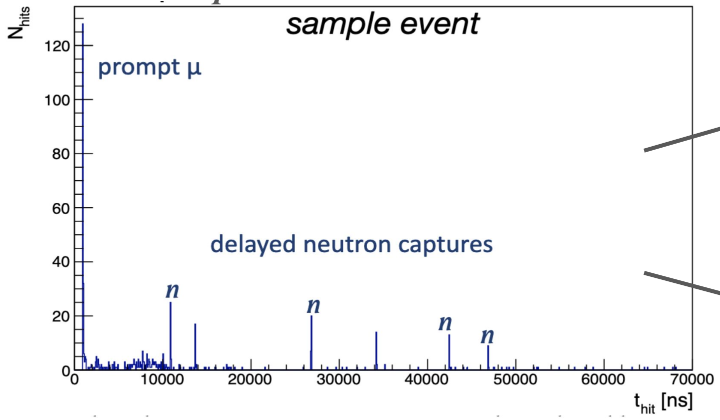
Neutron captures in extended readout window

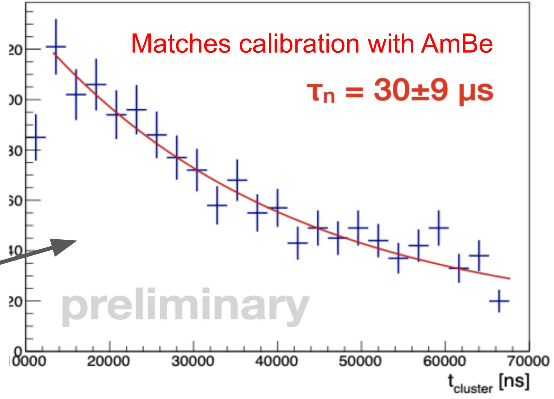


→ Preliminary measurement of neutron multiplicity without LAPPDs in progress

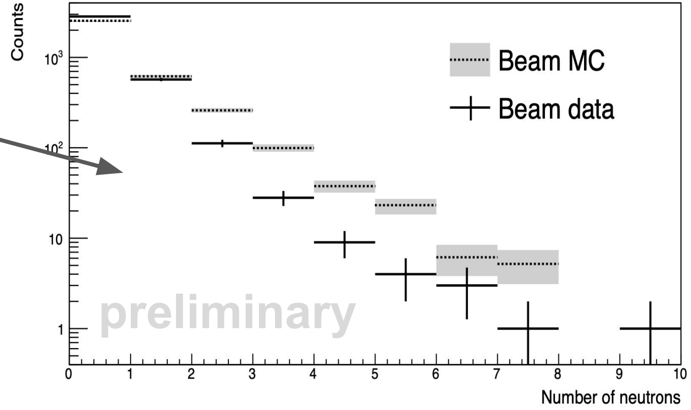
Neutron capture time *(beam events)*

From PhD thesis of M. Nieslony (2022):*

Time distribution of neutron captures recorded for beam data set (1.5 months)



*Basic **neutron multiplicity** in beam events*

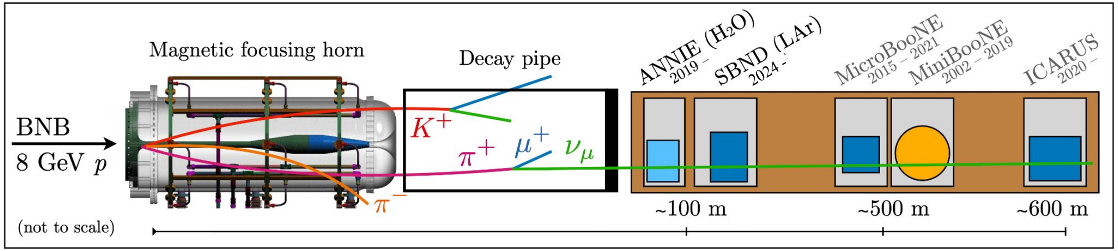


M. Nieslony's PhD thesis:

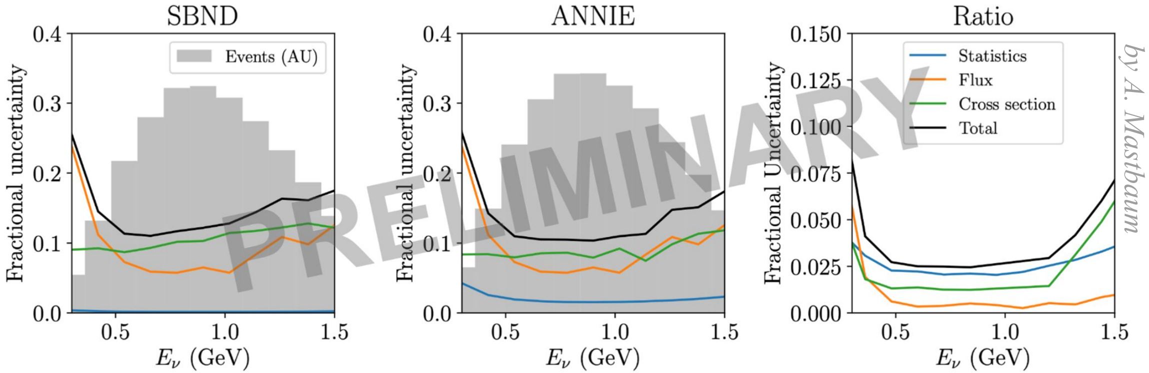
Multiplicity of neutron captures per beam event (1.5 months of data, no fiducial volume cut)

Comparison of oxygen and argon cross sections

- ANNIE + SBND or MicroBooNE
  → unique opportunity for joint cross section measurements on water and argon targets
- Same beam (BNB) means
  → significant cancellation of flux systematics
  → precision σ comparison
- Goals:
  → measure cross-section ratios
  → correlated measurements of hadron yield (neutrons vs. protons)



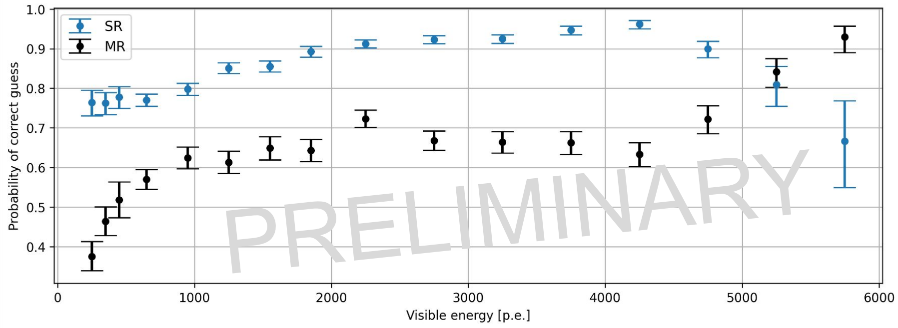
Shaded areas: Neutrino energy spectra expected for SBND and ANNIE
Lines: Systematic rate uncertainties based GENIE v3 MC
Right-most plot: systematics of a direct comparison of SBND/ANNIE data

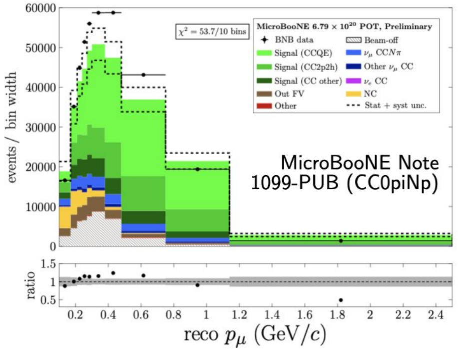


Status of joint ANNIE/MicroBooNE analysis

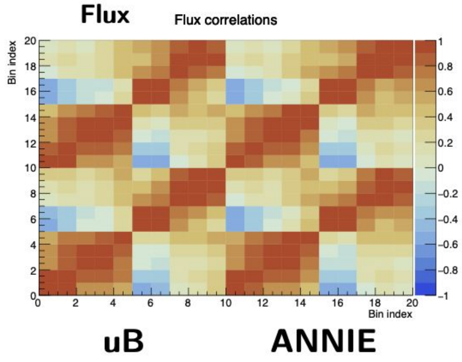
- O/Ar analyses need comparable data sets, e.g. CC events without pions (CC0pi)
- **ANNIE:**
  - Basic selection as for neutron multiplicity
  - Event ID for single-/multi-ring events
- **MicroBooNE:**
  - Corresponding analysis already existing
  - Adaptation of standard tooling to extract an ANNIE-like CC0pi sample
- Common handling of BNB flux and GENIE cross section systematics between SBN and ANNIE already implemented for joint analysis
- MicroBooNE-ANNIE MoU is under development for limited data sharing

Current status of Single-Ring (SR) vs. Multi-Ring (MR) discrimination based on PMT patterns (ML) (by Daniel Schmid)





MicroBooNE 0pi analysis (courtesy by Steven Gardiner)



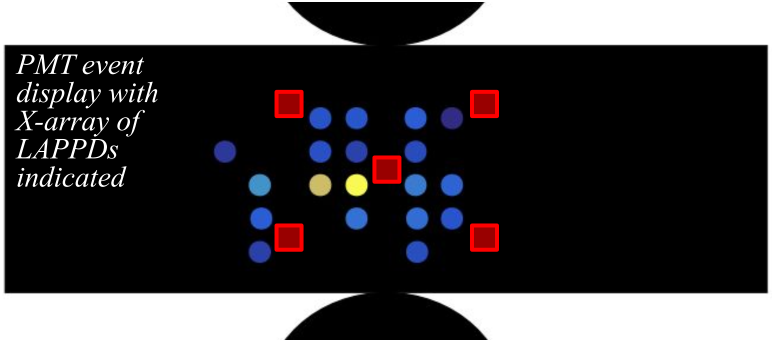
Flux correlations ANNIE/MicroBooNE (by James Mynock)

Expected impact of LAPPDs

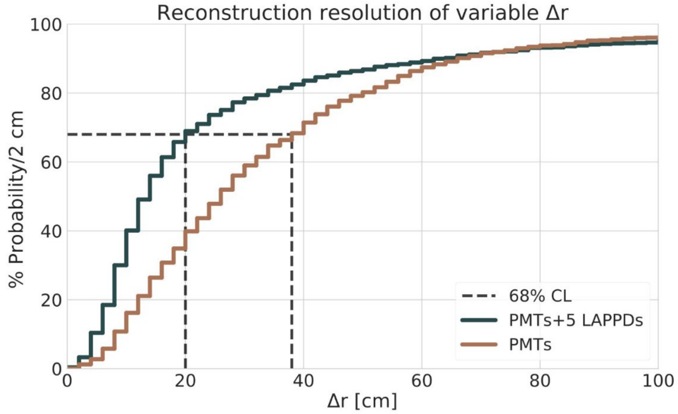
- Simulation studies show that X-shaped arrangement of 5 LAPPDs provides optimal performance for vertex reconstruction
- Relevant for physics program:
  → improved energy and angular resolution of final-state muons
- Integration of LAPPDs in vertex reconstruction on-going (see below)

→ collect data for differential cross-section analysis for 2 years

→ explore potential for beam timing (by resolving substructure of spills)

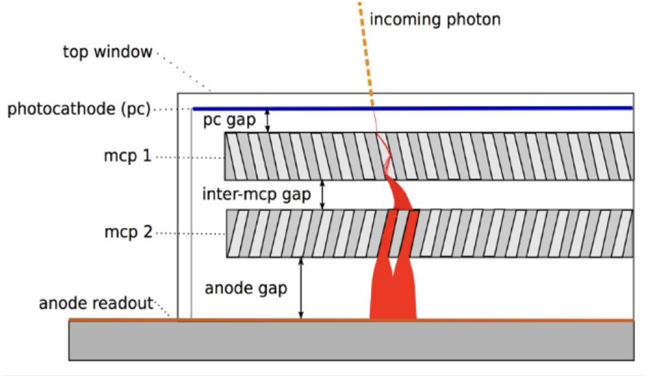


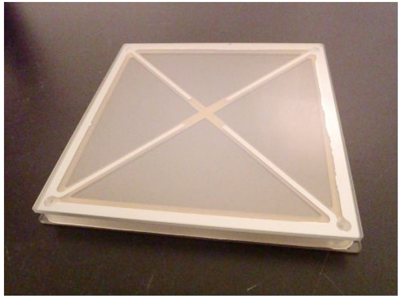
Simulation of vertex resolution with 5 LAPPDs (X-array) vs. PMTs-only



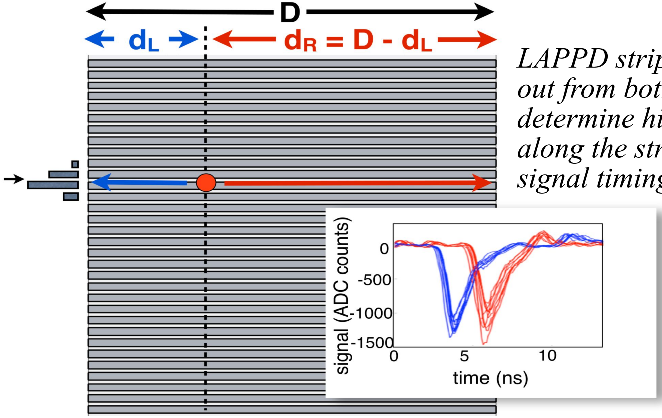
Sub-nanosecond timing with LAPPDs

- Electron amplification in flat geometry
  → excellent timing
- Incom's Gen-I LAPPDs feature
  - Large detection area (8" x 8")
  - Timing: - in-situ ~ 50ps
    - absolute ~ 100ps
  - Anode structured in strips,
    28 strips with double-sided readout
    → spatial resolution better ~1cm
- To maintain sub-ns resolution, signals have to be digitized directly at LAPPD
  → underwater electronics (10 GS/s)
  → waterproof housing





LAPPDs use two layers of multi-channel plates to enable electron amplification in a very uniform geometry for a large photocathode



LAPPD strips are read out from both ends to determine hit positions along the strip by relative signal timing.

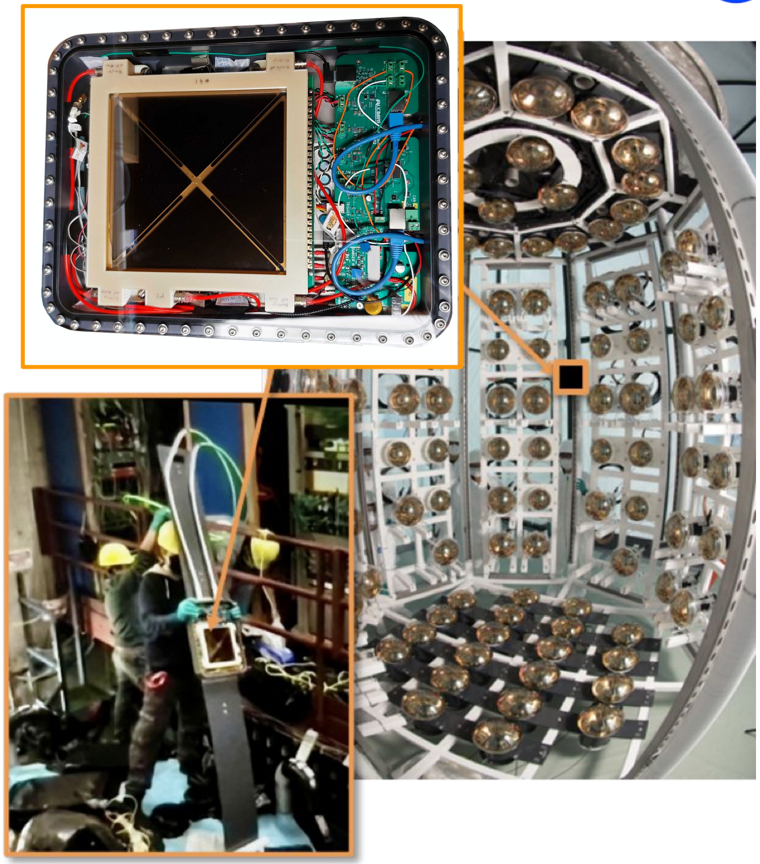
Deployment of first LAPPD in water

Spring 2022:

- Completed commissioning of LAPPD 40 and PSEC electronics in waterproof housing
- Full characterization of LAPPD 40 in local test stand (Lab 6)
- LAPPD deployed in the ANNIE water tank (center front position)
- Several months of integration work into ANNIE's DAQ framework

→ successful integration of an LAPPD in a module suitable for neutrino detectors

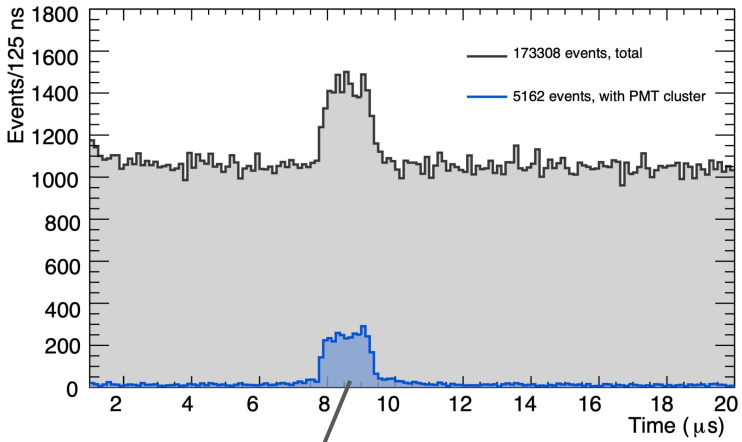
→ first deployment of an LAPPD in a particle physics detector (done!)

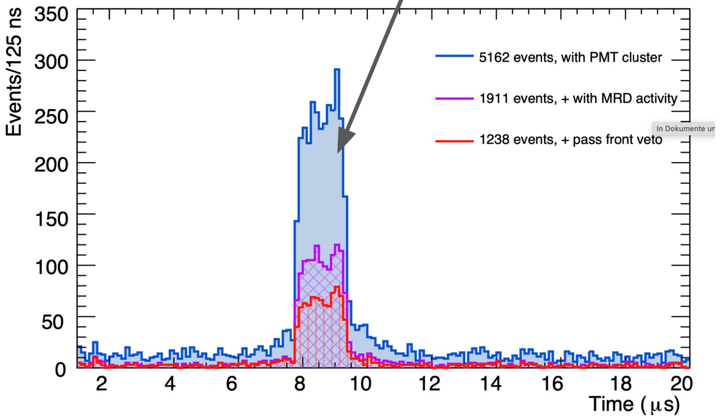


First-ever detection of neutrinos on LAPPDs

- **LAPPD triggers** are issued within a 20µs window around the beam spill
- Dark noise accidentals can be substantially reduced by requiring a **time coincidence with tank PMTs**
- Further background reduction by requiring **MRD coincidences**
- **CC neutrino interactions** inside the water tank selected with front veto cut

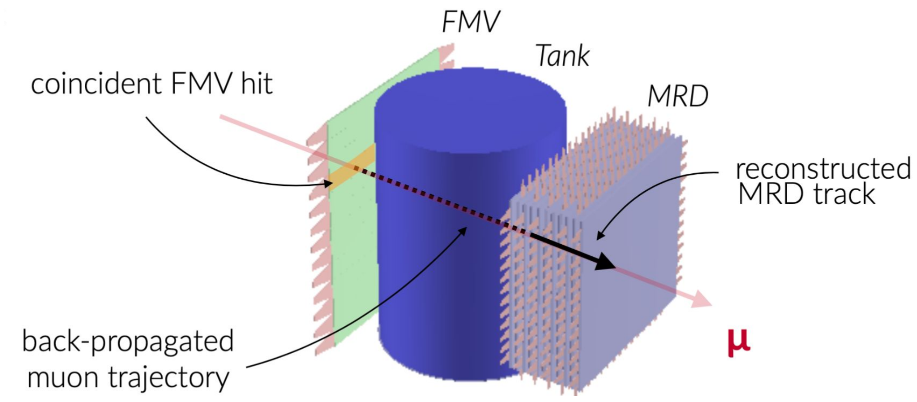
→ LAPPDs are now fully integrated with all other detector systems

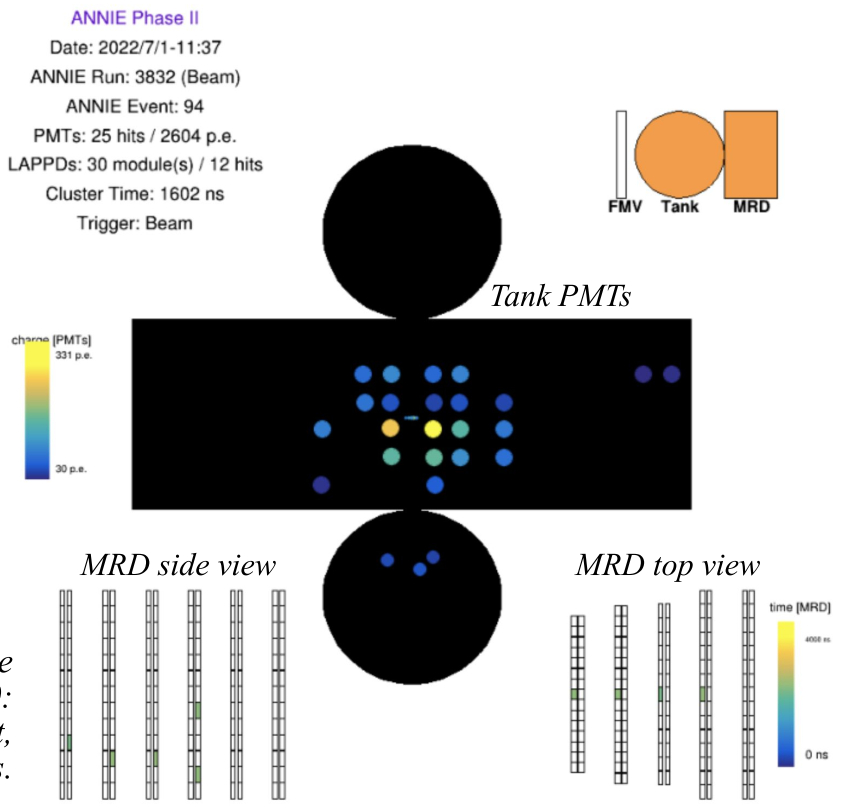




An ANNIE neutrino candidate on LAPPD – A first!

Detector components of ANNIE



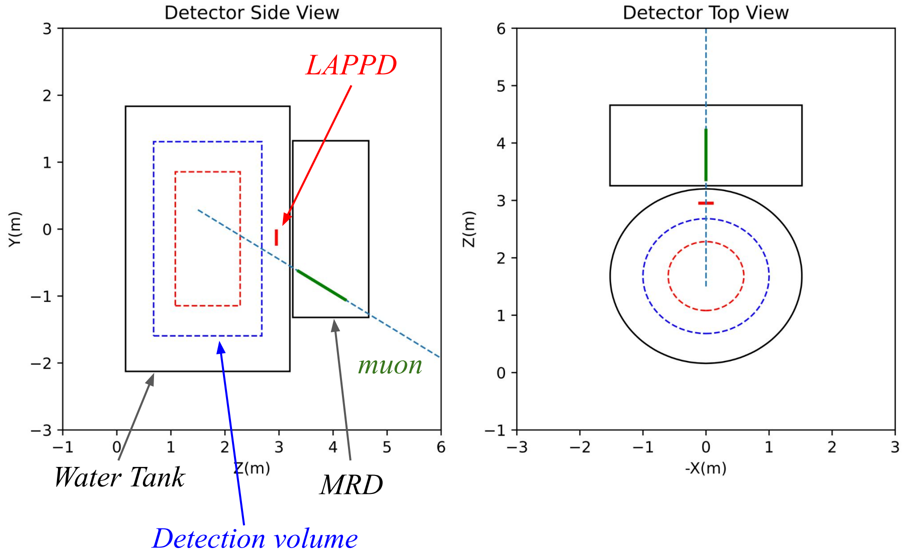


ANNIE event display of an example neutrino event recorded with LAPPD 40: MRD registers out-going muon, FMV quiet, forward Cherenkov ring/disc on PMTs.

An ANNIE neutrino candidate on LAPPD

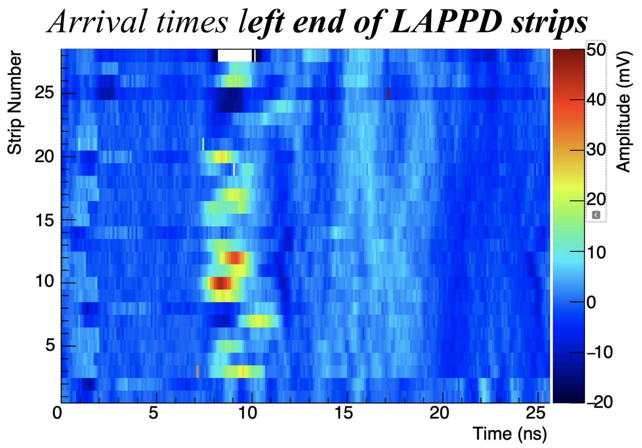
- For muon track exiting the tank close to an LAPPD, expect multiple strips hit (in more than one position)

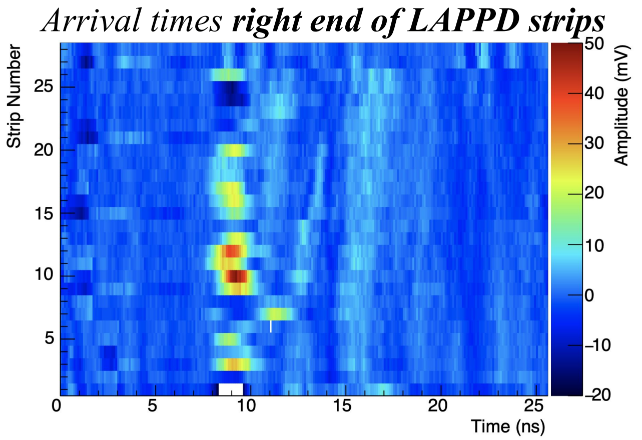
Example neutrino event, muon track as reconstructed by Muon Range Detector (MRD).



An ANNIE neutrino candidate on LAPPD

- For muon track exiting the tank close to an LAPPD, expect multiple strips hit (in more than one position)
- Information of hit time (and position along the strip) determined based on absolute (relative) time recorded on strip ends

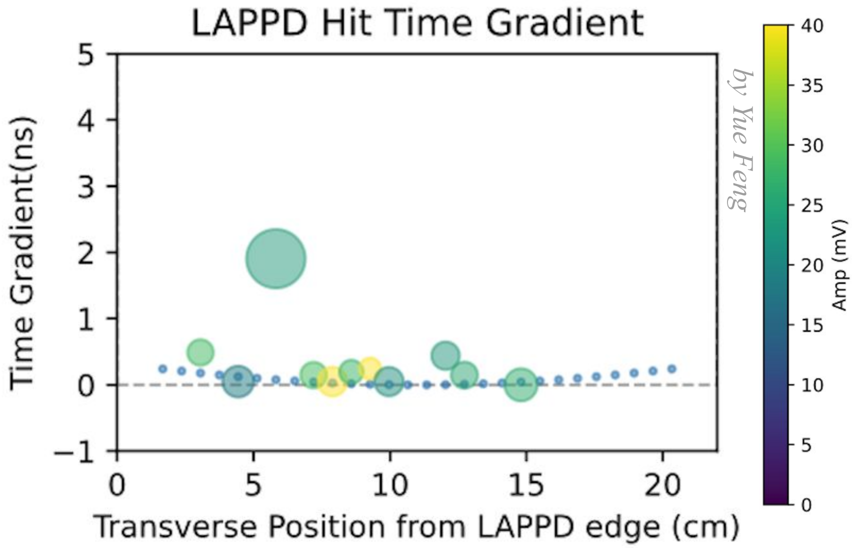




An ANNIE neutrino candidate on LAPPD

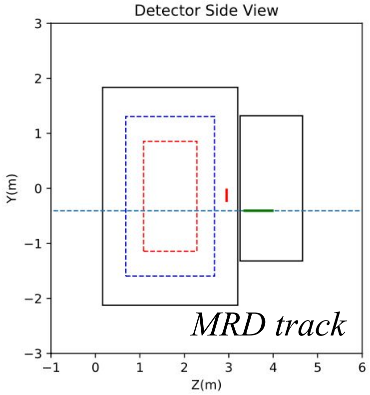
- For muon track exiting the tank close to an LAPPD, expect multiple strips hit (in more than one position)
- Information of hit time (and position along the strip) determined based on absolute (relative) time recorded on strip ends
- Reconstructed hit positions on strips compared to MRD prediction for Cherenkov ring → good agreement!
- Ongoing development of reco code forward-folding track hypothesis to predict (and fit) LAPPD hit pattern

Reconstructed photon hits on the LAPPD:
Green dots mark reconstructed arrival times and positions,
Blue dotted line is prediction based on the MRD track.

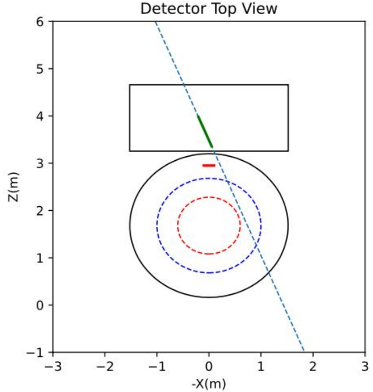


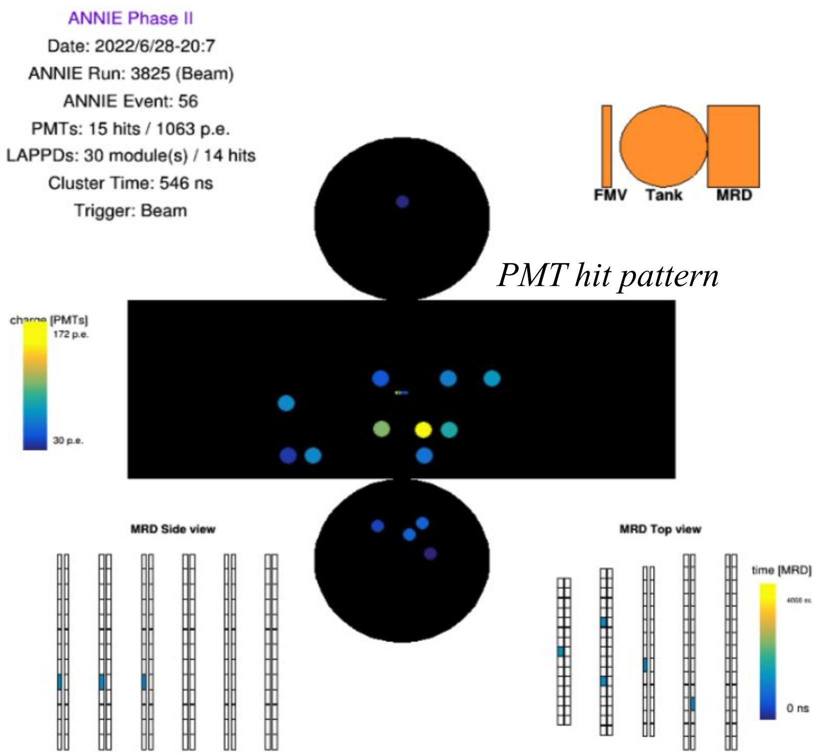
For comparison: Dirt muon with diagonal track

Horizontal muon track entering the water tank upstream and reconstructed diagonally by MRD.

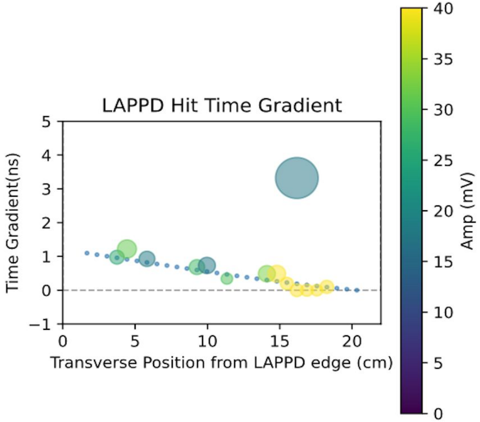


MRD track

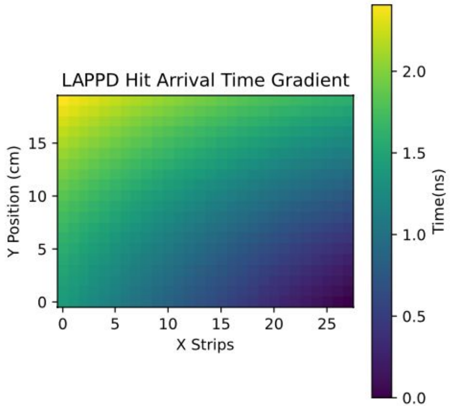




PMT hit pattern



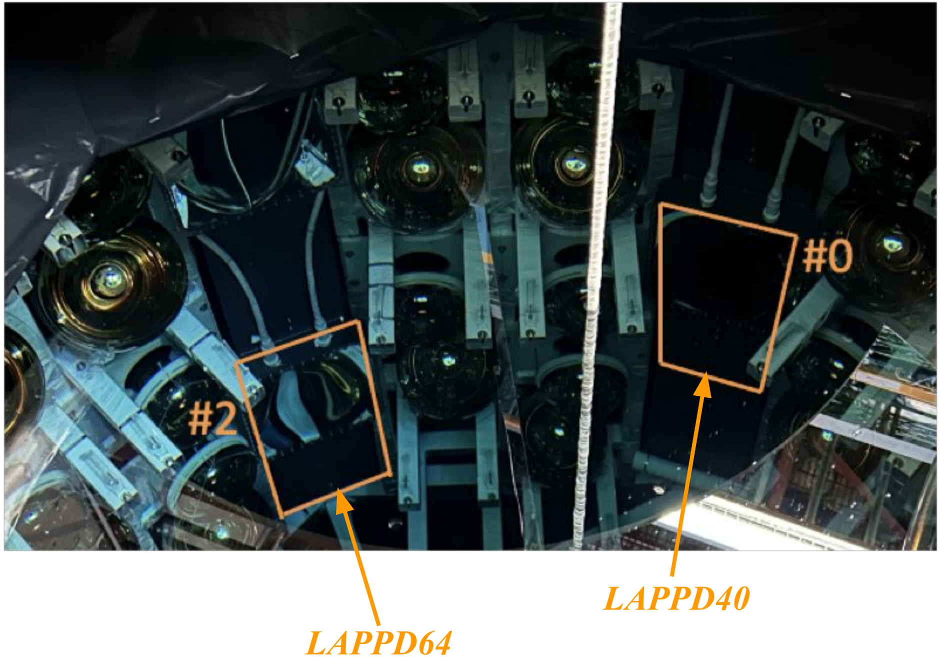
LAPPD hit pattern



First-ever multi-LAPPD system deployed

- Early 2023: LAPPDs 63+64 success-fully deployed and commissioned
- DAQ has been expanded to receive data from multiple LAPPDs
- Commissioned time synchronization amongst individual LAPPDs and global trigger
- Lesson learnt:
  current LAPPDs are all different
  → electronics have to be configured to match e.g. the resistances of MCPs
- First data set with multiple LAPPDs acquired towards end of beam year
  → analysis in progress

View of the LAPPDs in the Water Tank through the top hatch

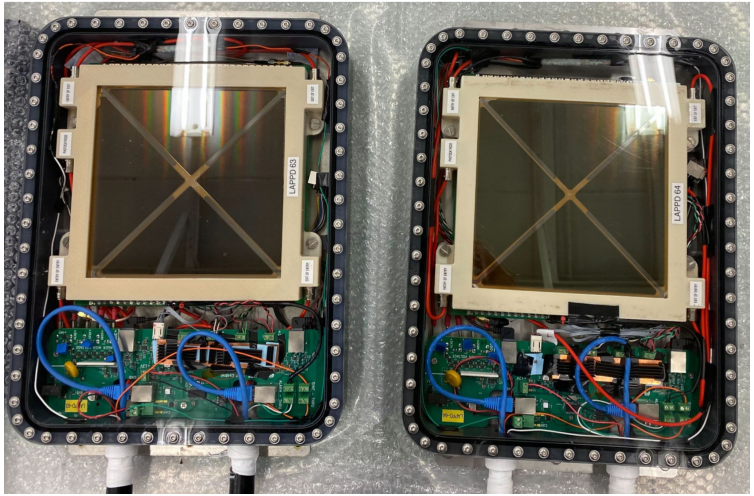


Longest LAPPD operational experience

- Due to hints of humidity inside waterproof housings, we removed all three LAPPDs from the water tank during fall
  → no serious issues were found, will replace water-tight seals
- Characterized post-deployed LAPPDs:
  - found problem with resistance of 2nd MCP of LAPPD 40 (significantly below specs)
  - sent to Incom for further investigation

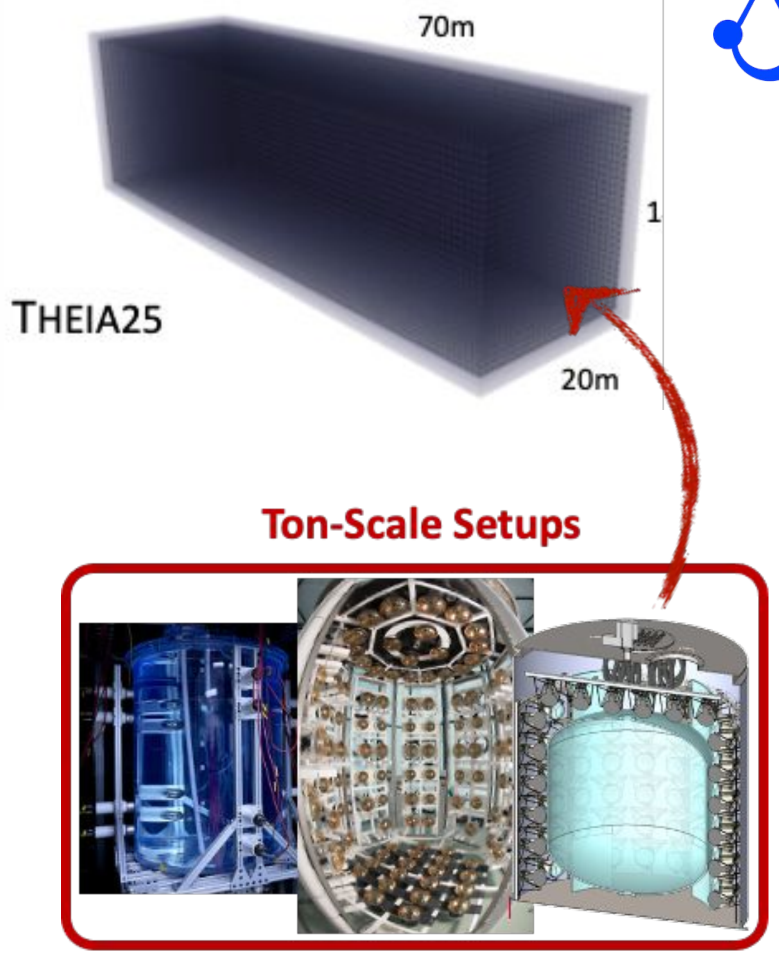
  → ANNIE is providing essential feedback on long term operation of LAPPDs in realistic deployment scenarios
- During January, we will re-deploy LAPPDs 63+64 and add LAPPD 39 in center position (all already characterized)
- Two additional LAPPDs to be characterized and deployed during the upcoming beam year

LAPPDs 63 and 64 during first inspection
After removal from the ANNIE Water Talk



A potential DUNE WbLS module

- Water-based Liquid Scintillator (WbLS) is being investigated as a target medium for DUNE FD4 “Module of Opportunity”
- P5 report highlights this module should keep long-baseline capability and expand physics capabilities (astrophysical neutrino detection, double-beta decay)
- Multi-pronged R&D program to demonstrate the versatility of WbLS
    - BNL1T/30T prototypes for online purification and chemical stability
    - EOS (Berkeley): MeV reconstruction
    - BUTTON (Boulby): WbLS radiopurity
    - ANNIE: GeV event reconstruction



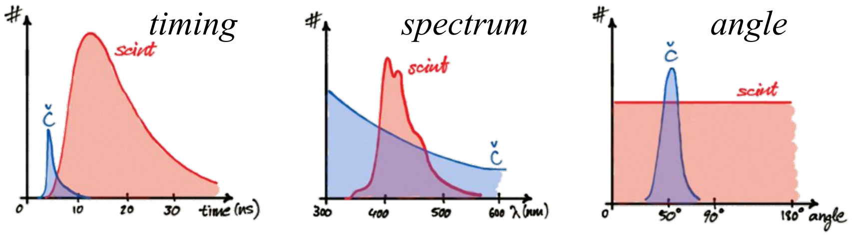
Hybrid Cherenkov/scintillation detection in WbLS

Water Cherenkov detectors are great in identifying (multiple) high-energy leptons/pions but no signal from low-energy hadrons

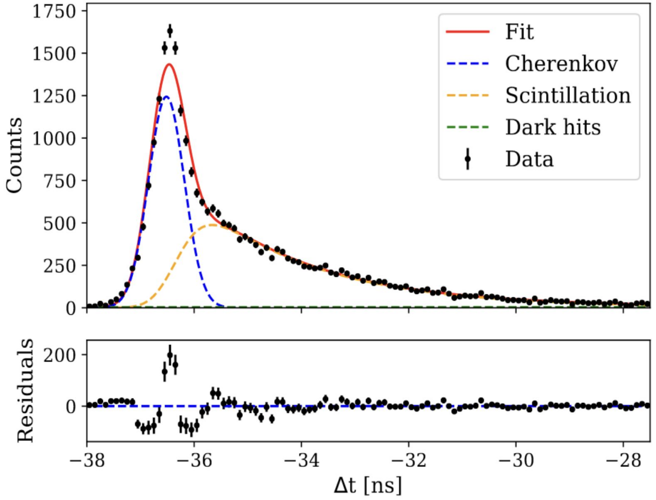
WbLS has the potential to

- Detect hadronic recoils by scintillation → calorimetric energy reconstruction
- Enhance Particle ID using the Cherenkov/scintillation ratio
- Improve position reconstruction due to isotropic light emission at vertex
- Add gadolinium to enhance neutron sensitivity

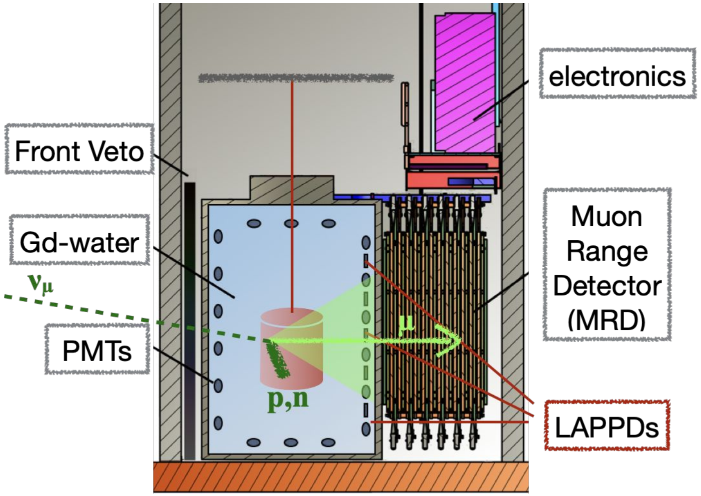
→ in ANNIE, Cherenkov/scintillation separation can be achieved by fast LAPPD timing

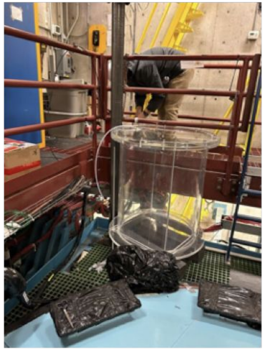


Separating Cherenkov and scintillation signals with an LAPPD (CHESS@UC Berkeley)

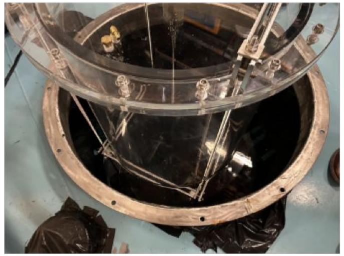


First deployment of WbLS in March 2023



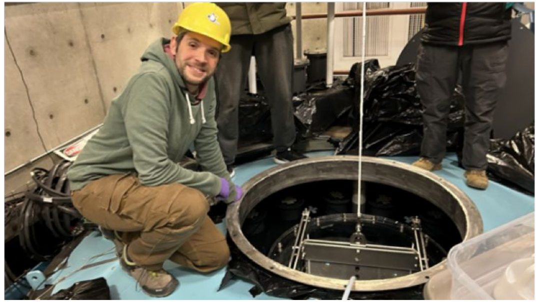


removed in May after taking 2 months worth of beam data



SANDI vessel & support frame inserted in Jan

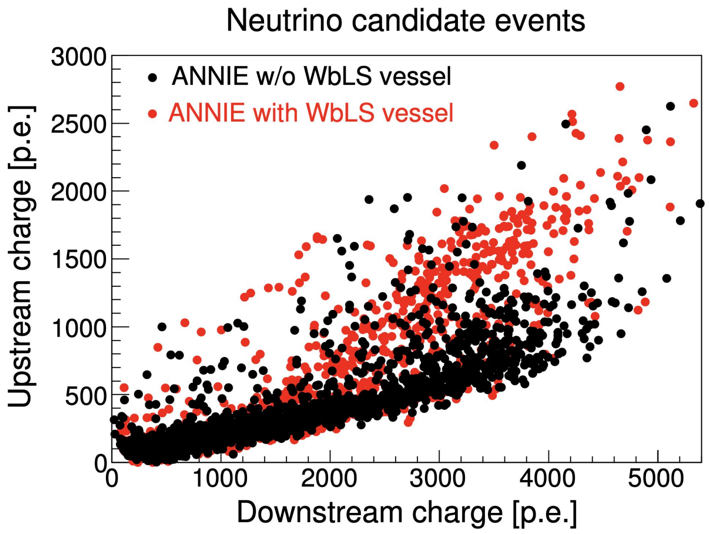
Insertion of vessel inside ANNIE tank in March



- “SANDI” acrylic vessel with 365kg of WbLS
- Organic fraction of 0.5% (Gd-ready)
  → scintillation cf. Cherenkov light yield
  → high transparency
- 2 months: few 10^3 events

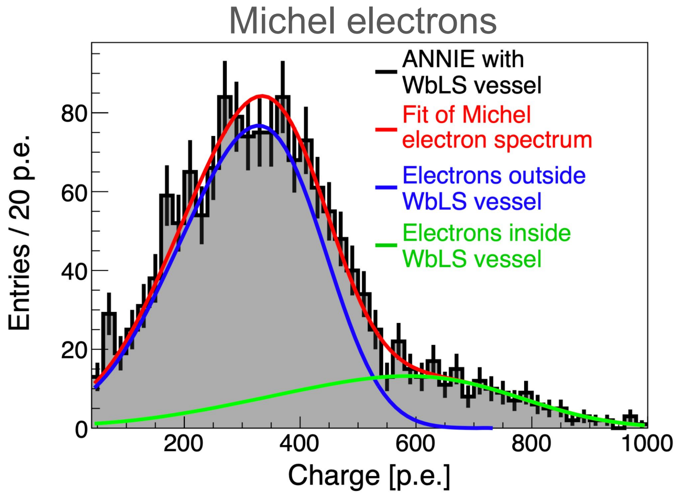
First SANDI WbLS data

arXiv:2312.09335
submitted to JINST



- Selecting neutrino candidates with (no) Front Muon Veto and track in Muon Range Detector
- Compare data with and without WbLS vessel

→ **WbLS:** new population of events with significantly more photons detected by upstream PMTs



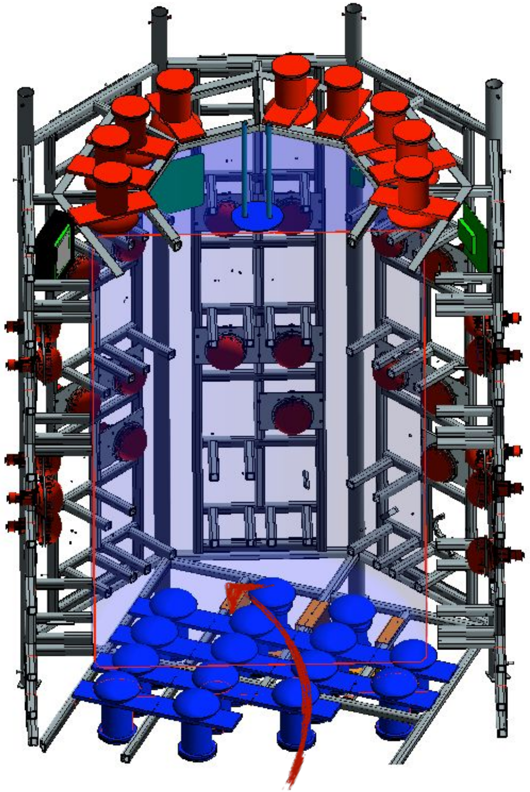
- Selection of Michel electrons from stopped muons
- New population of electrons in WbLS produces significantly more photons than electrons in water

→ effective increase in light output: (77±8)%

Next steps in R&D: more WbLS hybrid detection

- Existing data
  - Demonstrate C/S separation based on LAPPD data
  - Look for scintillation-only hadronic neutral current events
- Second SANDI vessel deployment (~1 month of data)
  - Gadolinium-loaded WbLS → enhanced neutron detection
  - Larger data sample with multi-LAPPD read-out
- Expanded WbLS fill (~1 year of data)
  - Inflatable nylon vessel to separate inside WbLS volume (~8 tons) from outside pure-water volume (material compatibility)
  - Vertex and all recoil particles (but muons) contained in WbLS

→ full vertex fit comparable to future DUNE WbLS-module

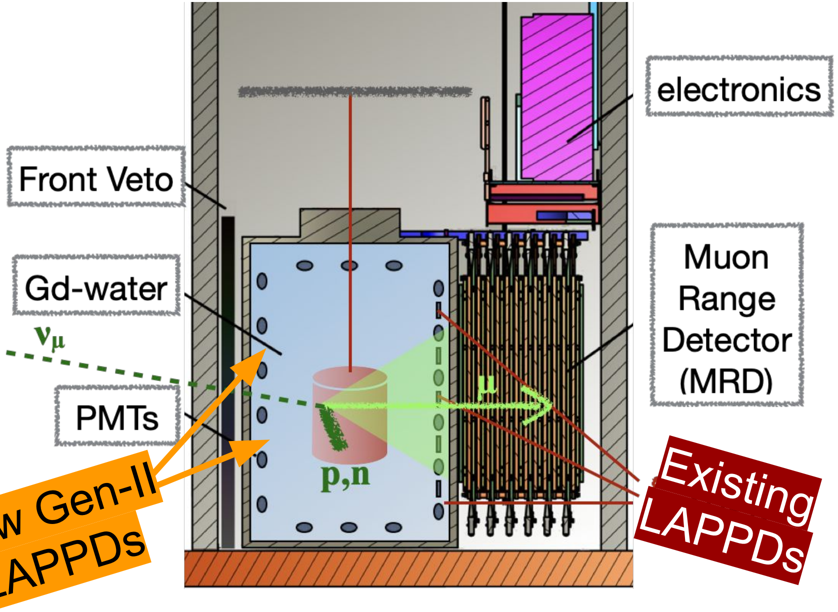


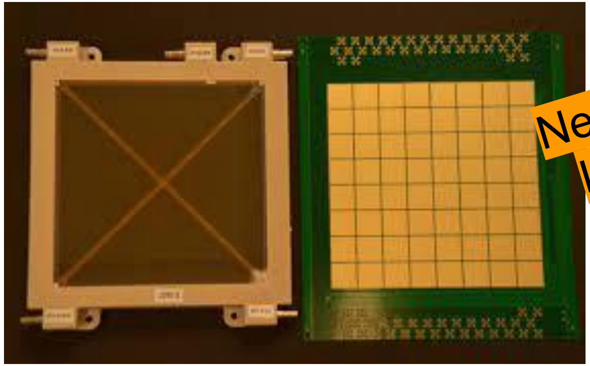
nylon bag holding 8t of WbLS

Next steps in R&D: Addition of upstream Gen-II LAPPDs

- Isotropic scintillation signal will hit upstream PMTs first → add LAPPDs to enhance timing to enhance vertex position reco & hadronic signal

- Deploy Gen-II LAPPDs with pad readout
  → counteracts photon pile-up
  → as for Gen-I, offers possibility to test under realistic experimental conditions
  → substantial community interest



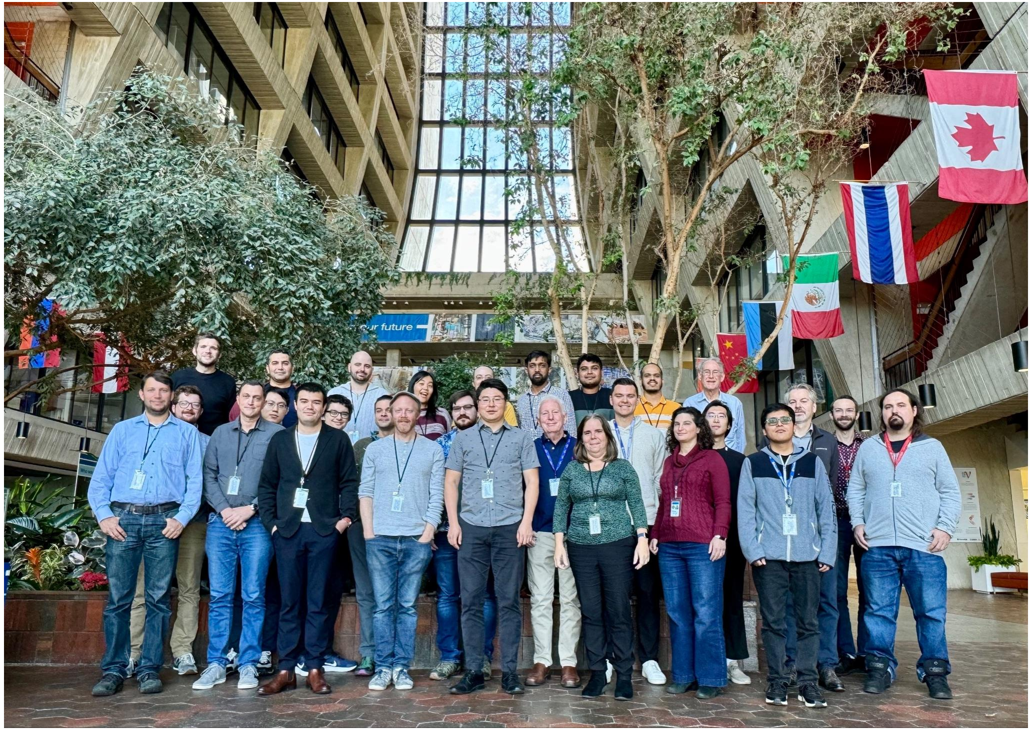


Recent Gen-II LAPPDs feature a pad-readout for the anode that reduces photon pile-up

ANNIE Collaboration (Fall 2023)

United States

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



Abroad

- Demokritos
- Erciyes
- Hamburg
- Kanpur
- Mainz
- Tübingen
- Warwick
- *Associate:*
  Sheffield

14 full member institutions (7 US/7 non-US) - 40+ collaborators

Expansion of the ANNIE collaboration

ANNIE unique R&D program continues attract new collaborators

- The WbLS component of the ANNIE program has already attracted several groups
  - LBNL/UC Berkeley (Gabriel Orebi Gann) → WbLS characterization & reconstruction
  - BNL (Minfang Yeh) → WbLS production
  - U Hamburg (Caren Hagner) → Advanced event reconstruction
  - U Mainz (Michael Wurm) → WbLS characterization, filling
  - U Tübingen (Tobias Lachenmaier) → C/S separation with LAPPDs
- Several new groups expressed interest to participate in continuing R&D
  - Further groups from BNL Instrumentation Division (David Asner) → Gen-II electronics
  - U Pennsylvania (Josh Klein) → Gen-II electronics, di-chroicons
  - Boston University (Christopher Grant) → WbLS, nylon bag
  - TU Munich (Hans Steiger) → WbLS, filling

Resources for running ANNIE

ANNIE activities are funded by university groups with important support by the lab(s)

	Item	Group
Support of the experiment	Overall Coordination Operations Calibration LAPPD integration Liquid Handling SANDI+WbLS PMT/MRD electronics DAQ & Software Computing Analysis	FSU, Mainz ISU, Erciyes UC Davis, Livermore, ISU ISU, FSU, FNAL (technical) UC Davis BNL, Davis, Mainz ISU, Rutgers Warwick Warwick, FNAL (technical) Rutgers, SDMST
New detector hardware	Gen-II LAPPDs New readout electronics Nylon bag & Filling system Water-based scintillator (8t)	ISU, FSU, Tübingen BNL, UPenn Mainz, UC Davis, Boston U BNL, LBNL/Berkeley, TUM

Resources for running ANNIE

Size of the collaboration

- Grown during past few years: healthy number of Postdocs and PhDs
- On-site crew plus steady stream of external visitors staying for few months, both national and international (10+ during last year)

Key resources of the lab

- Support concerning LAPPDs/electronics
  → working on expanding own expertise with university support (ISU/Rutgers)
- Minimal maintenance cost to the lab
  - Nitrogen dewars have been replaced by direct line from SBND
  - using 4-5 hours a week for liaison and tech time over 2023

Summary

- ANNIE is in a unique position to measure neutrino-nucleus-cross sections in water, 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: the very first experiment to use Gd-loaded water, water-based scintillator and LAPPDs for the detection of neutrinos.
- With 3+ LAPPD modules installed and commissioned, ANNIE is set for two years of high-quality data taking to profit from the excellent event reconstruction enabled by multiple LAPPDs.
- ANNIE is an ideal testing ground for WbLS for hybrid Cherenkov/scintillation reconstruction of GeV neutrino events in future long-baseline experiments.
- Plans for R&D program with an enlarged WbLS volume and new upstream LAPPDs →Critical R&D milestones to be demonstrated before long accelerator shutdown.