SOUTH DAKOTA MINES
An engineering, science and technology university

Accelerator Neutrino Neutron Interaction Experiment (ANNIE)

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annie

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Outline

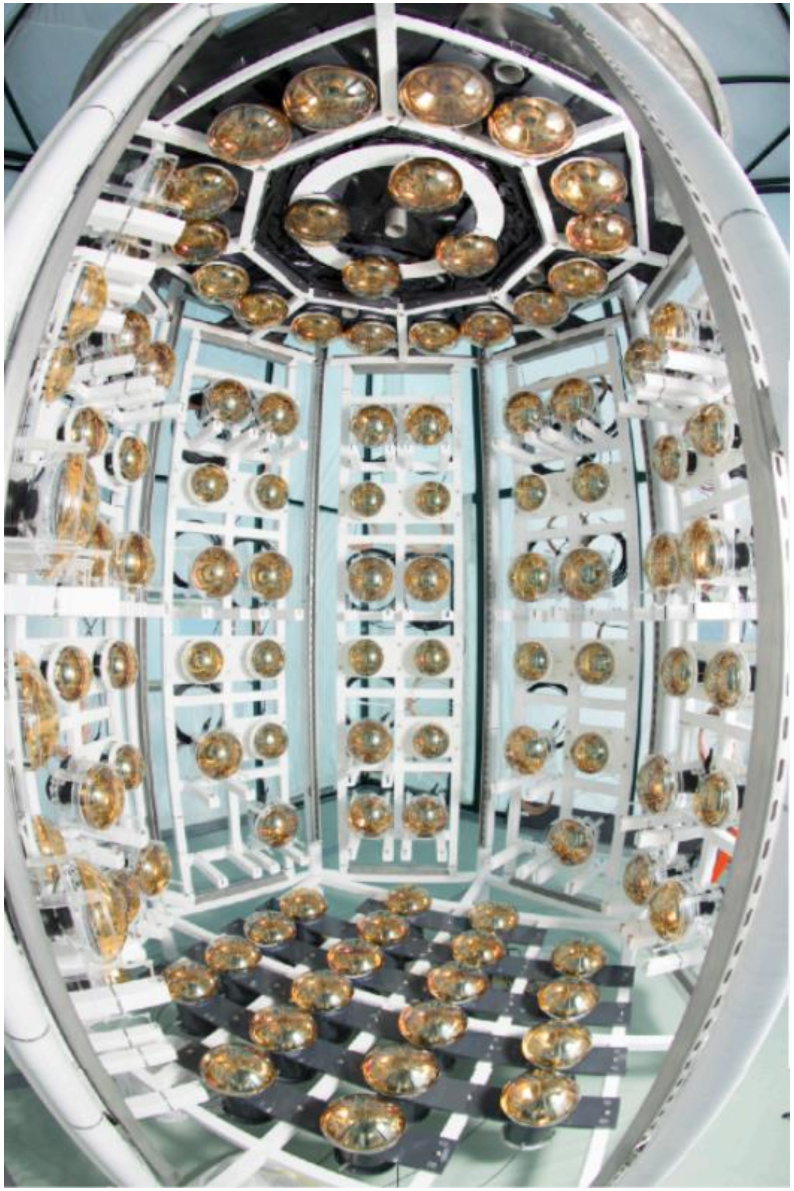
- Introduction to ANNIE
- Physics Motivation
- The ANNIE Detector
- Neutrino Interactions in ANNIE
- Data Analysis Status of ANNIE
- Summary

The ANNIE Collaboration

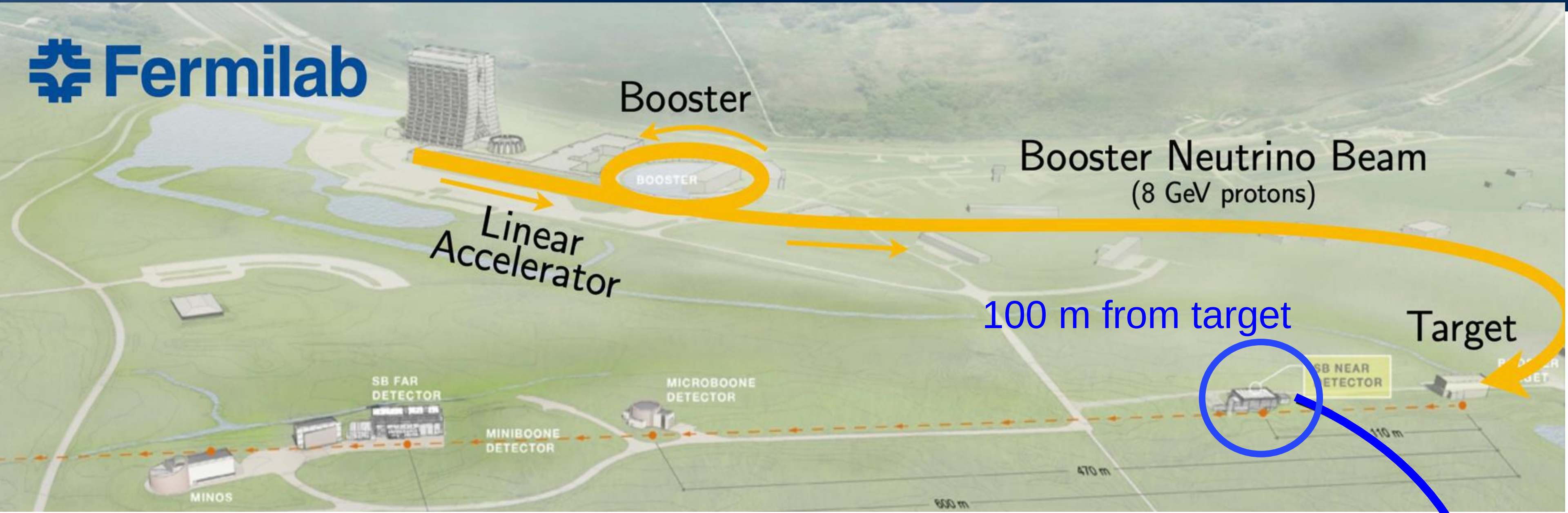
17 Institutions from 6 Countries, ~45 collaborators

What is ANNIE?

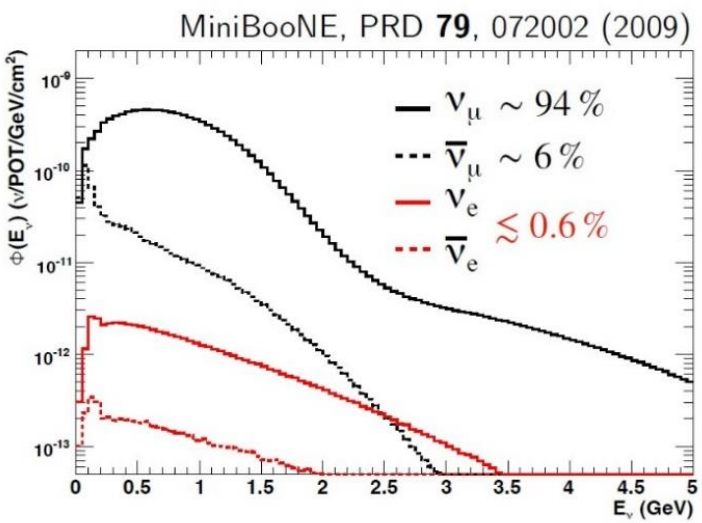
- The **A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment (**ANNIE**)
- 26-ton **Gd-loaded Water Cherenkov detector**, located 100 m downstream at the Booster Neutrino Beam line at Fermilab
- **Physics Goals:**
  - Neutrino-induced neutron multiplicity as a function of momentum transfer
  - Neutrino interaction cross sections
- **R&D Goals:**
  - **L**arge **A**rea **P**icosecond **P**hoto**D**etectors (**LAPPD**s)
  - **W**ater-**b**ased **L**iquid **S**cintillator (**WbLS**) as a new detection medium



ANNIE Location at Fermilab

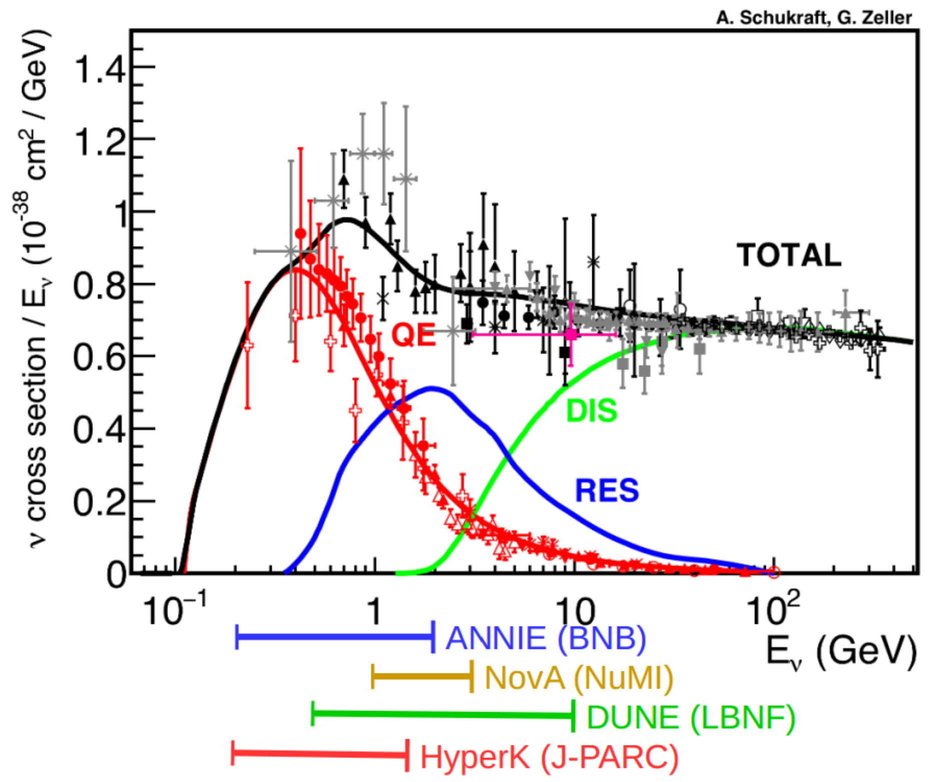


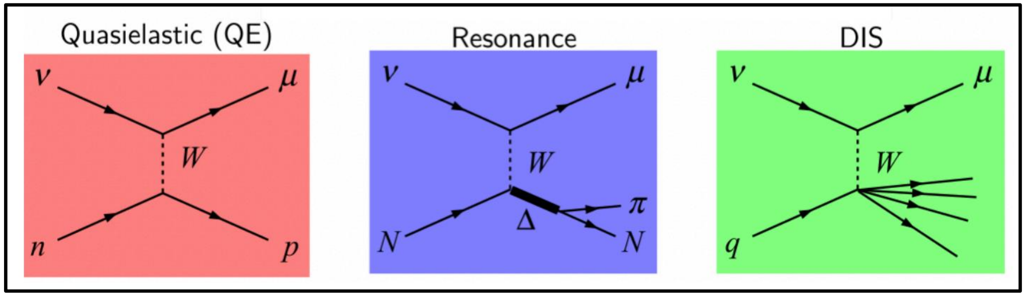
~10,000
Charged current
neutrino events
per ton of target
water per year
expected at
ANNIE hall!



Neutrino Oscillation Physics

- Precision neutrino oscillation programs must accurately measure the neutrino energies.
- As neutrino energies increase to the GeV-scale, hadronic final states could be produced
- Neutrino–nucleus interactions are difficult to model due to nuclear effects, which complicates the energy reconstruction.
- **Measuring the final-state neutrons is a strong handle to refine the models** – Primary physics goal of ANNIE!

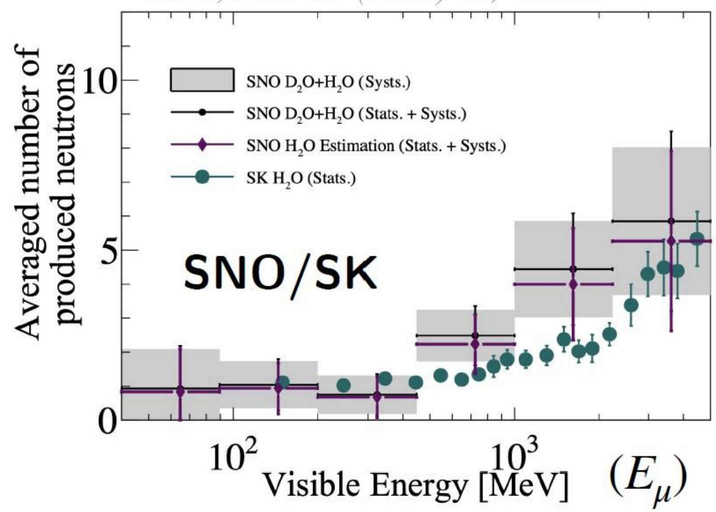


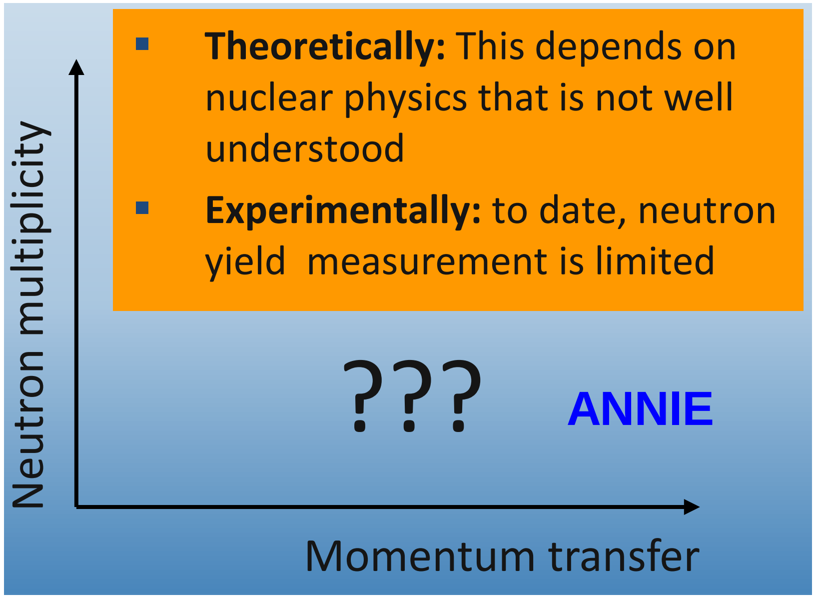


ANNIE Measurements

- **High-flux ν_μ interactions on water:**
  - Energy range where DUNE & HK overlap
  - Study of neutrino-nucleus interactions with a neutron beam
  - Currently taking data and analyzing more than 2-year data set
- **Measure final-state neutrons vs momentum transfer Q^2 in water**
  - Improve modeling of final-state interactions
  - Reduce energy reconstruction uncertainty
- **Measure Multi-target cross-sections**
  - Same beam as SBN Liquid argon TPCs
  - Correlated cross section, and hadron production between ANNIE and SBN, with H_2O and ^{40}Ar targets
  - Possible deployed argon target in the future

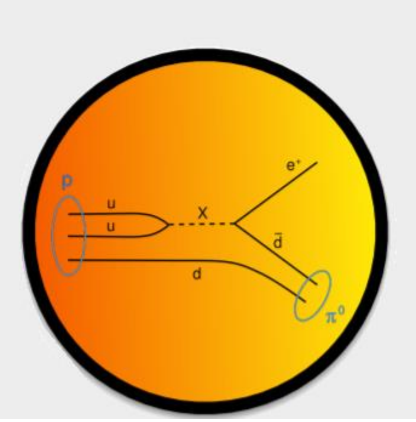
SNO, PRD 99 (2019) 11, 112007



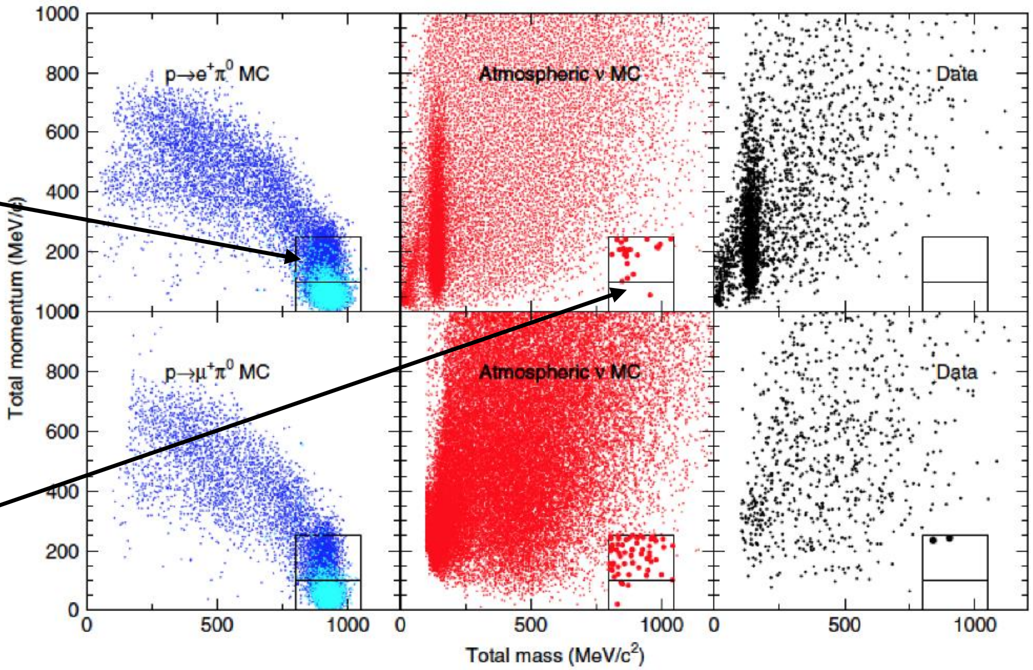


Proton Decay

- Predicted by Grand Unification Theories (GUT)
- Proton decay for a free hydrogen produces no neutrons
- Proton decay inside nucleus could emit neutrons through nuclear de-excitation or breakup (models predict <10%)
- Atmospheric neutrino background is likely to produce final state neutrons -> background rejection using neutron tagging (n-Gd capture)



K.Abe et al., Phys. Rev. D, 95:012004, 2017



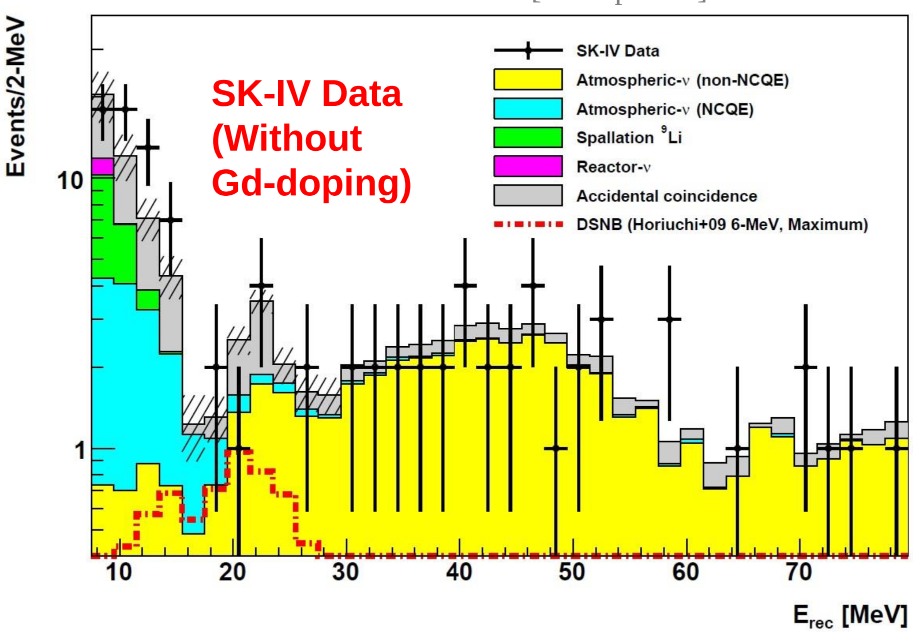
Proton decay events rarely produce
neutrons in the final state (<10% of the time)

Atmospheric neutrinos are the dominant background, likely with neutron production

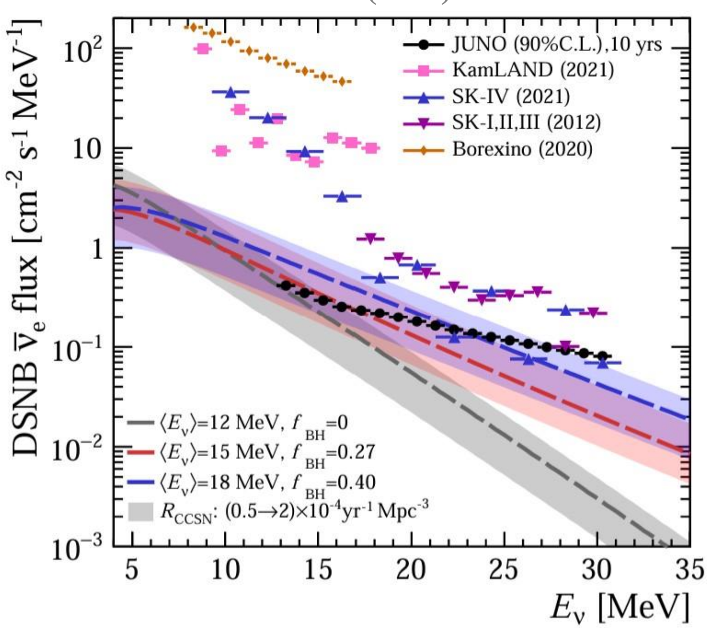
Diffuse Supernova Background

- DSNB events are detected via the Inverse Beta Decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$
- For E>20 MeV the dominant background is from decay of sub-Cherenkov muons produced by atmospheric neutrinos: need Gd-water for neutron tagging
- For E<20 MeV, a major background is from NCQE atmospheric neutrino interactions: need NC events identification
- ANNIE is studying this through measurement of NCQE cross section with Gd-Water.

arXiv:2109.11174v2 [astro-ph.HE]



JCAP 10 (2022) 033

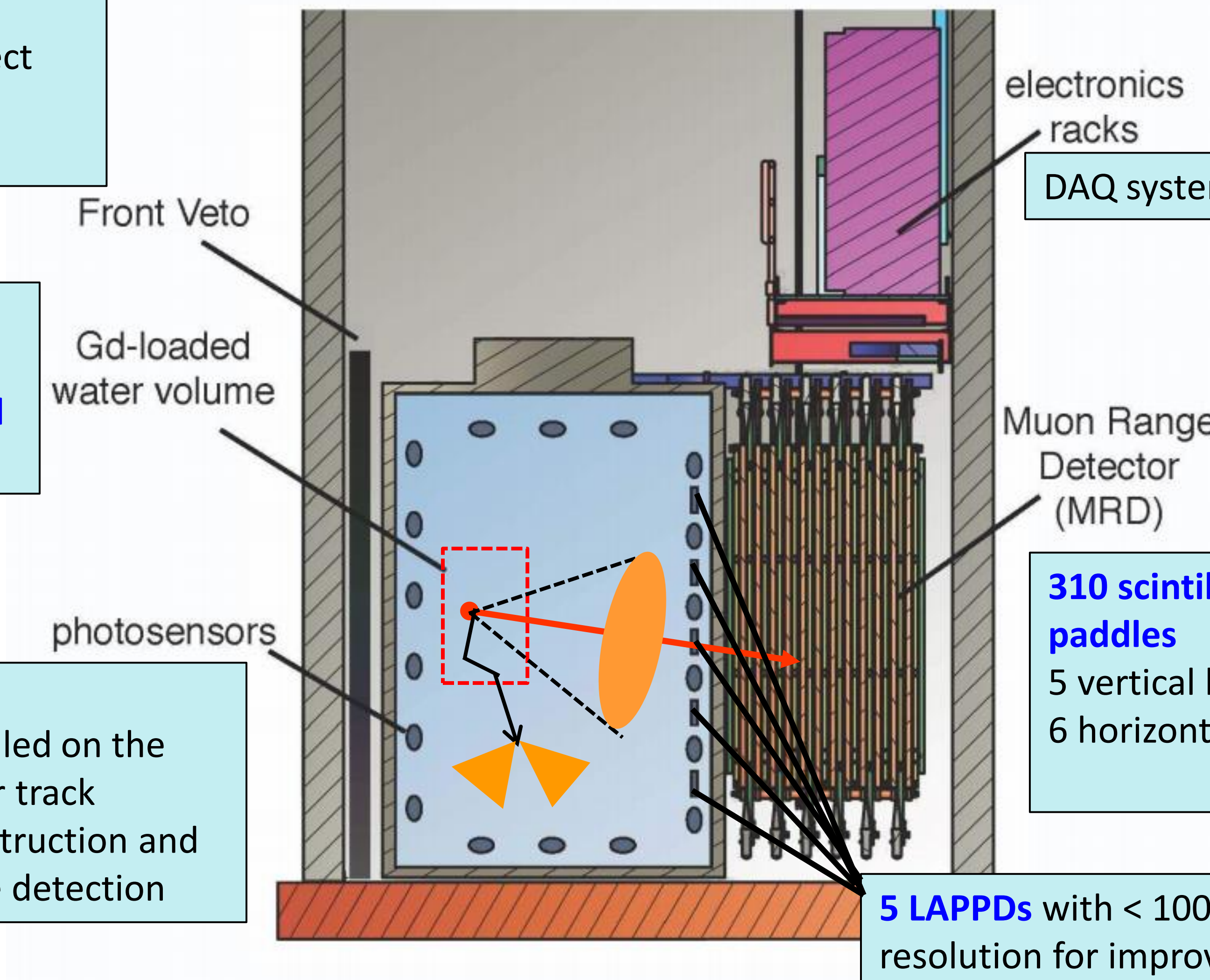


The ANNIE Detector

26 scintillator paddles to reject muons from upstream

3 m x 4 m tank filled with 26-ton **Gd-loaded water (0.1%)**

Inside the tank:
132 PMTs installed on the inner surface for track direction reconstruction and neutron capture detection



DAQ system

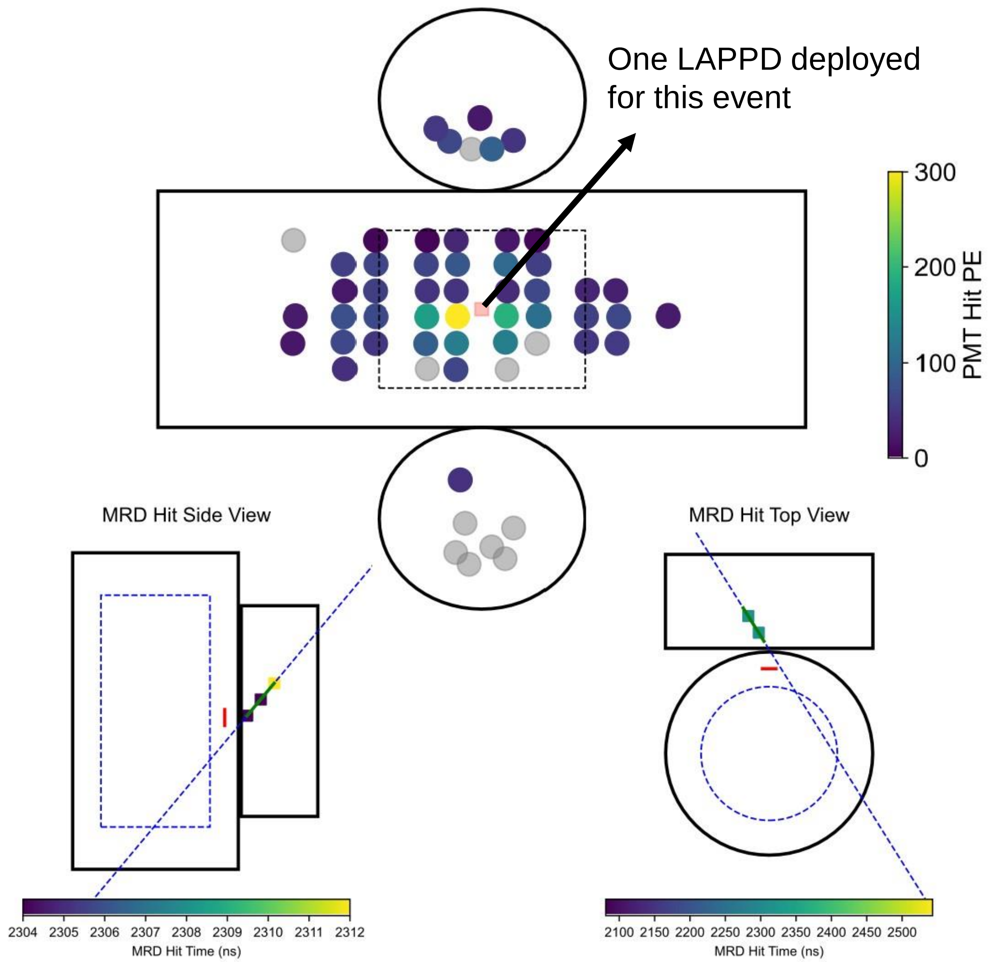
310 scintillator paddles
5 vertical layers
6 horizontal layers

5 LAPPDs with < 100 ps time resolution for improved vertex reconstruction

Neutrino Detection in ANNIE

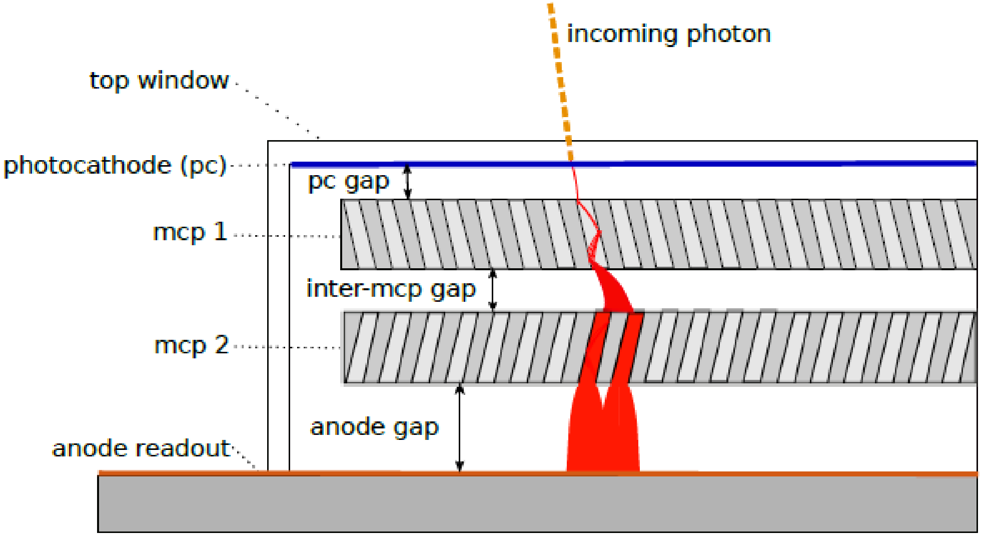
- **ANNIE has been taking neutrino data for over three years with Gd-water**
- Charge Current Quasi-Elastic (CCQE) interaction candidates are selected for the determination of neutron multiplicity.
- Candidates are identified by a Cherenkov disk in the tank, a coincident track in the MRD and no signal in the FMV.
- Right: typical neutrino event contains data from tank PMTs, LAPPD, and MRD.

Neutrino Event Display



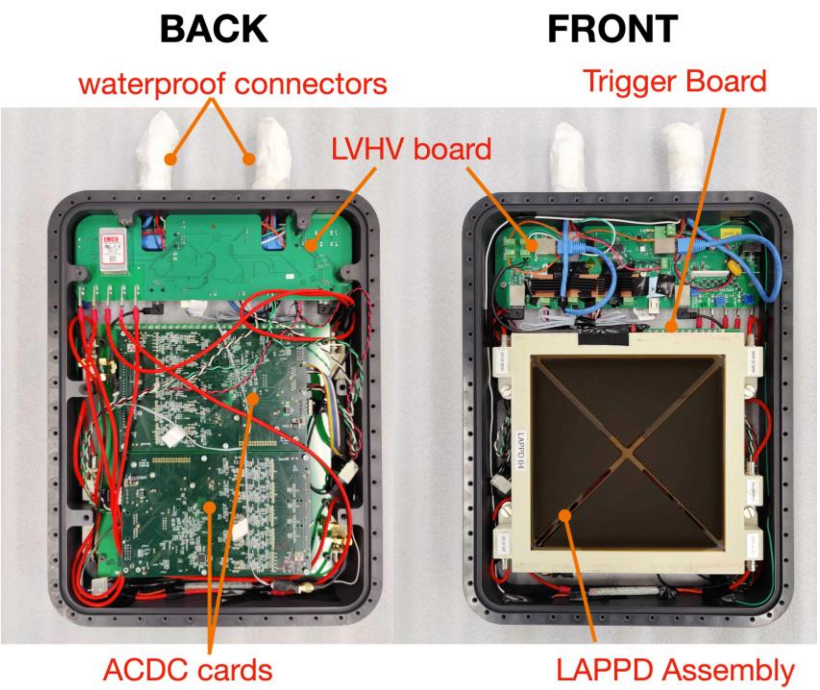
A CCQE example
Red box shows the LAPPD position

Enabling Technology: LAPPD



Large-Area Picosecond PhotoDetectors are Micro-channel Plate-based fast-timing photodetectors

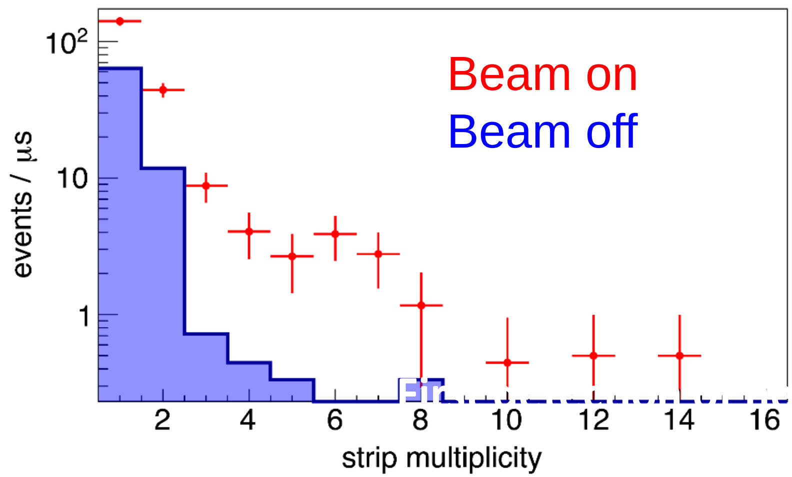
- Flat, Large-area: 20 cm × 20 cm
- Picosecond timing: **<100 ps** for SPE
- Quantum efficiency: >20%
- Position resolution: mm level

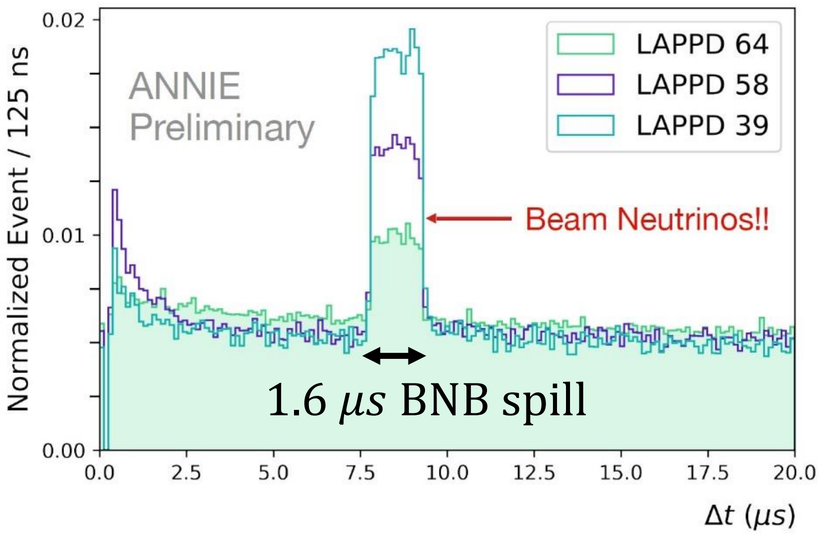


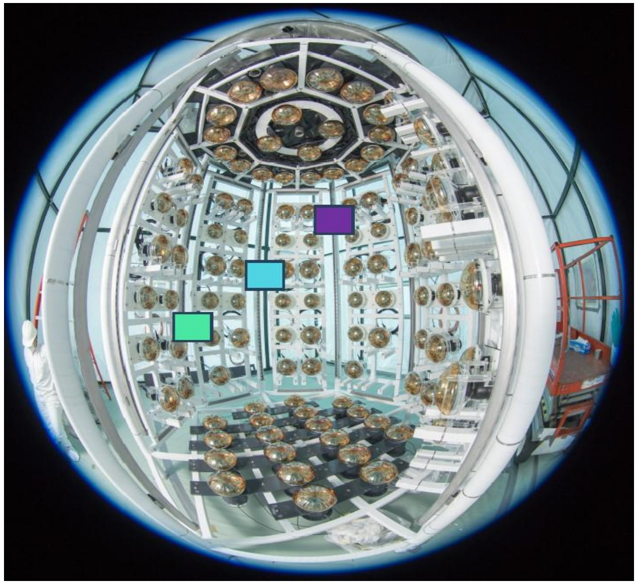
- ANNIE is the first physics experiment employing LAPPDs
- Adding 5 LAPPDs into ANNIE detector can improve the vertex resolution from ~40 cm (PMT-only) to ~15 cm (PMT+LAPPD) (see backup slide)
- Deployed multiple LAPPDs and detected beam neutrinos

First-ever neutrino detection with LAPPDs

World's first: neutrinos observed with multiple LAPPDs!





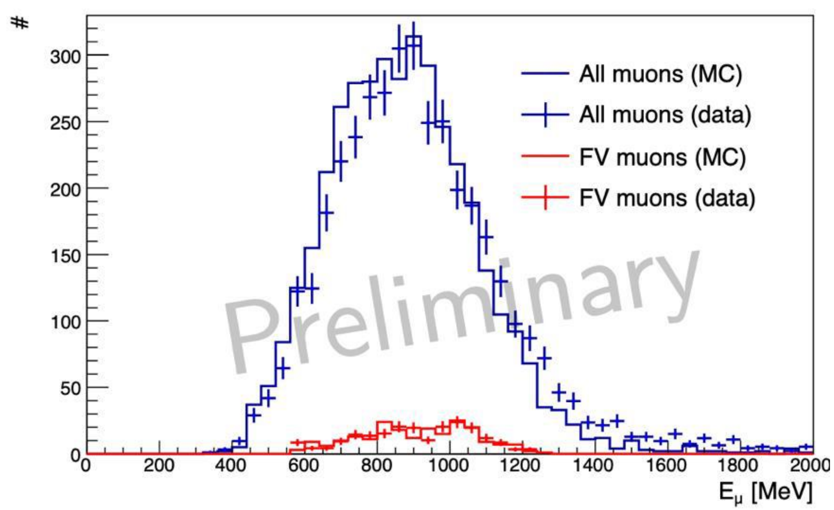


- Deployed multiple LAPPDs and performed timing calibration with laser
- BNB spill width was correctly detected.
- ~1200 neutrino candidates identified after cuts for data in ~one beam year. (~10^{20} POT)
- Will ultimately deploy all 5 LAPPDs to enhance the event reconstruction capability

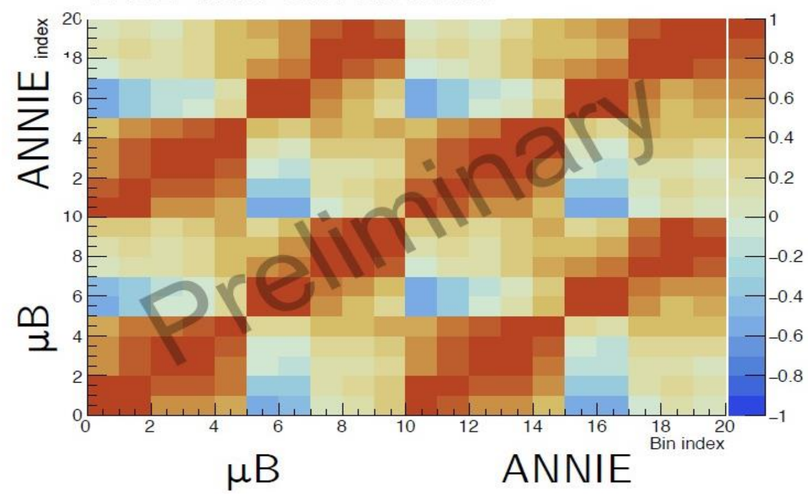
CC0π Measurement in ANNIE

- Select CC0π events using MRD-based muon track reconstruction and ML-based multi-ring rejection (without deployed LAPPDs so far)
- Developed a minimal version of reconstruction tools (known as Reco-1; paper in preparation).
- Reconstruction achieved good agreement between Data and MC in muon energy and angle
- Performing joint cross section analysis with MicroBooNE, using the same cross section extraction tools.

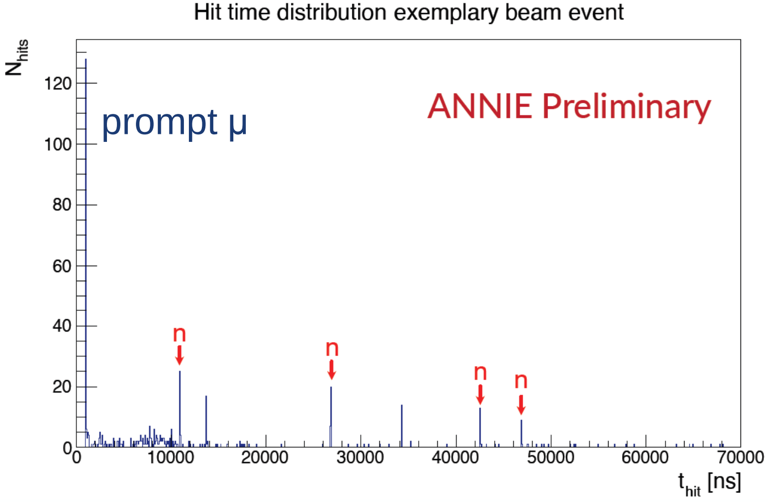
Muon energy reconstruction

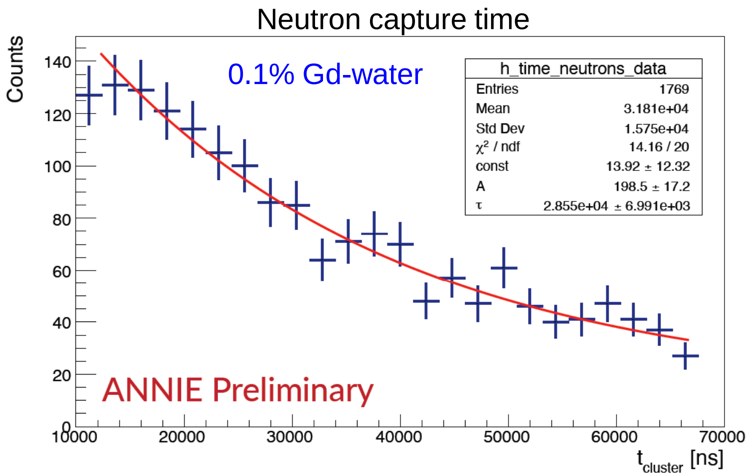


BNB flux correlations



Neutron Multiplicity in ANNIE

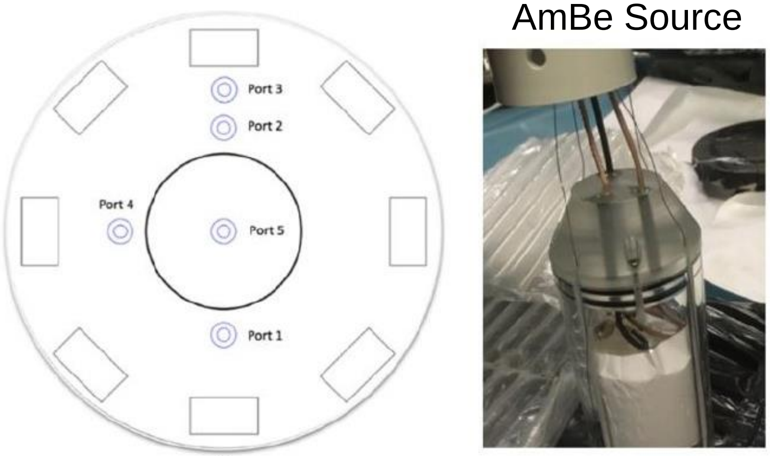




τ ~ (29 ± 7) μs in agreement with theoretical expectation (30 μs)

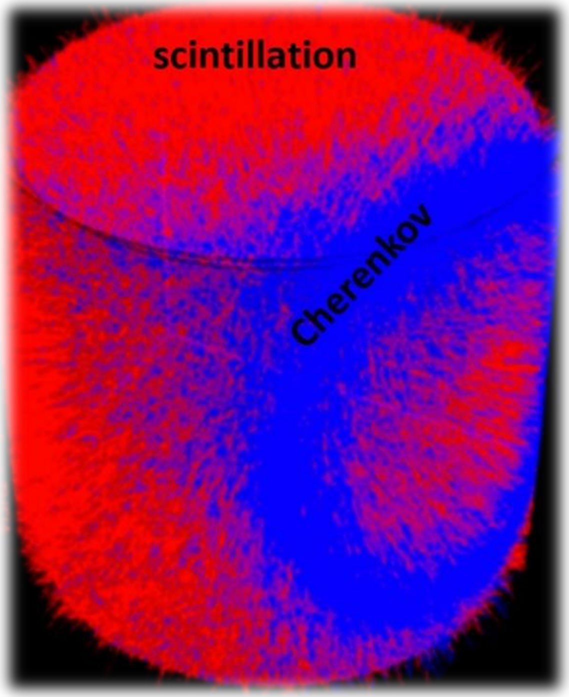
- CC0π events are selected.
- Neutron captures are detected by PMTs within a ~70 μs acquisition window.
- Neutron capture time from beam data agrees well with prediction for 0.1% Gd.
- Neutron capture efficiency is calibrated by a deployed AmBe source.
- ANNIE's first neutron multiplicity analysis will conclude within a year.

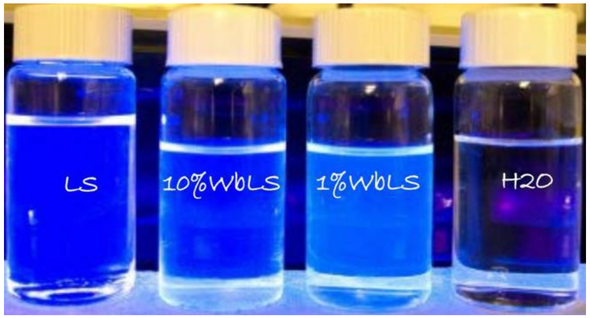
AmBe Source

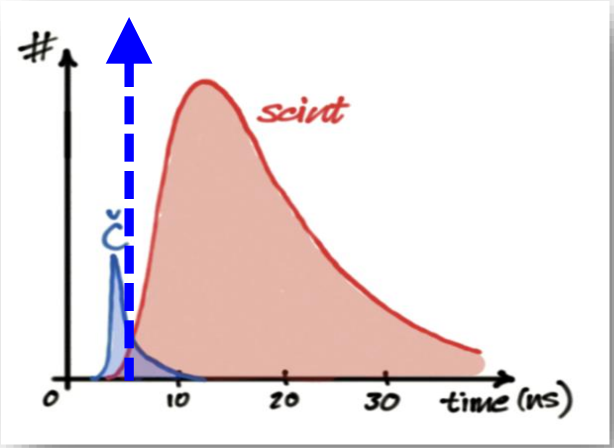


Hybrid Event Detection in ANNIE

- Water Cherenkov detectors provide directionality, and Scintillation detectors provide low threshold
- **How about a hybrid event detection?** Combine Cherenkov and scintillation signals
- **Water-based Liquid Scintillator (WbLS) in ANNIE:** novel detection medium combining advantages of both scintillation and Cherenkov light
- LAPPDs' fast timing can potentially be used to separate prompt Cherenkov light from the slower emission of scintillation light.



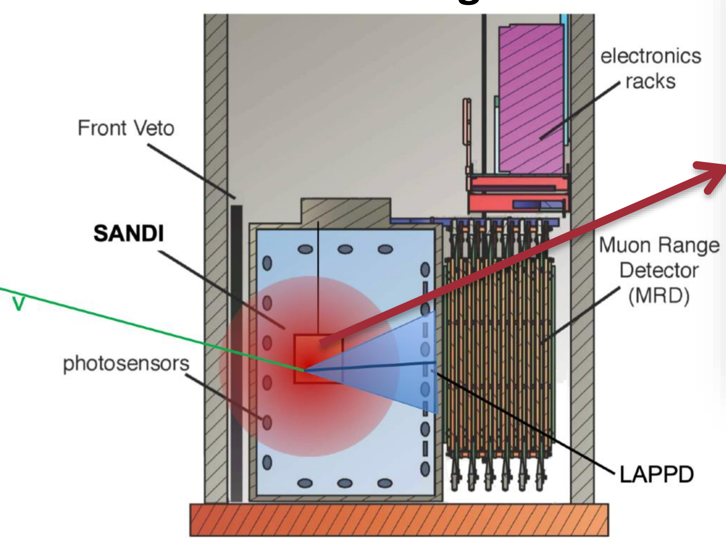


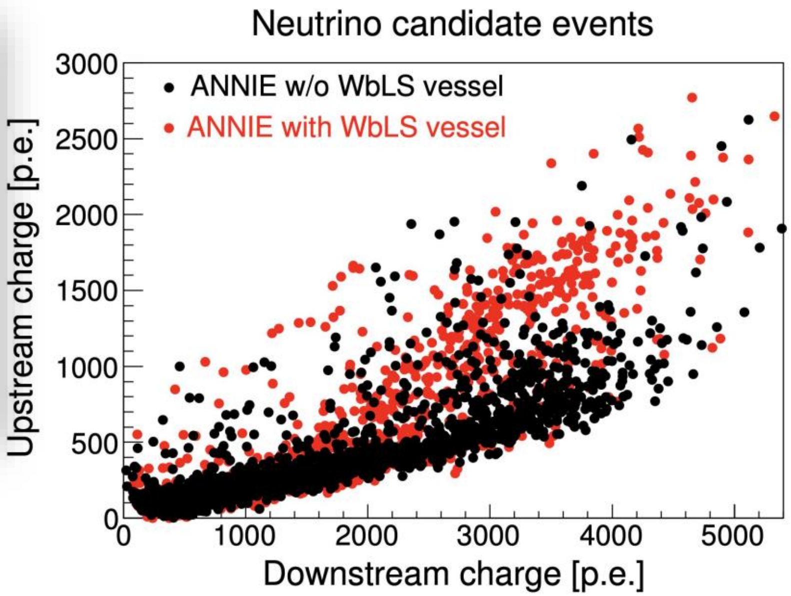


Water-based Liquid Scintillator

- Higher light yield, better particle identification, improved energy reconstruction, access to sub-Cherenkov particles, and more…
- **Scintillator for ANNIE Neutrino Detection Improvement (SANDI)**: ~3'×3' acrylic vessel containing 356 kg of water-based liquid scintillator (WbLS), deployed in 2023 for two months
- First beam *ν* observed in WbLS! Light yield increased by a factor of 1.4-1.7 (through-going muon and Michel electron analyses published in JINST)

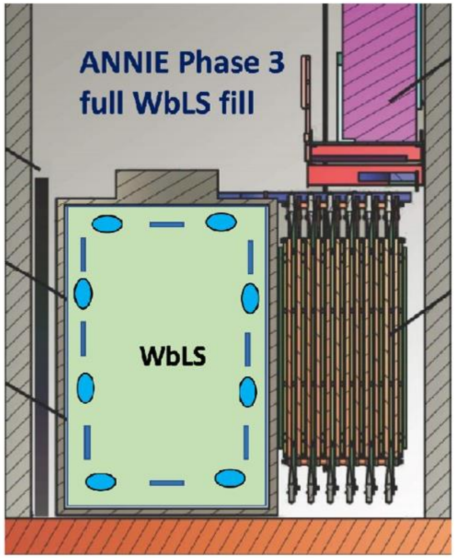
ANNIE 365 kg vessel

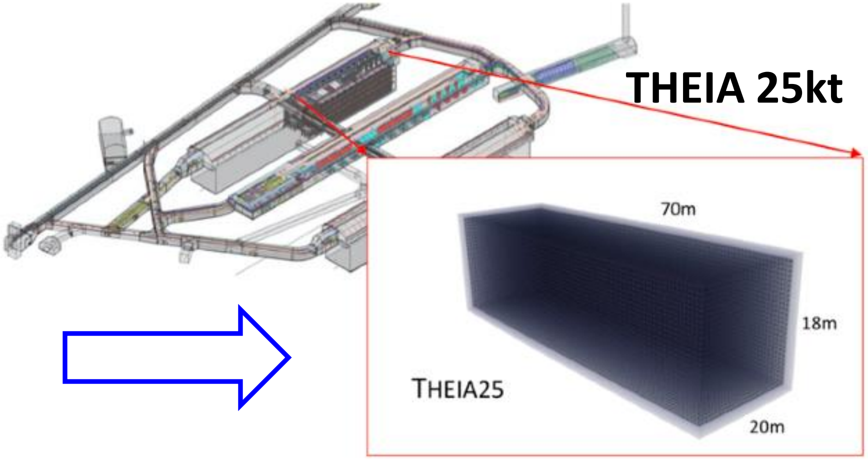




WbLS for DUNE Phase-II

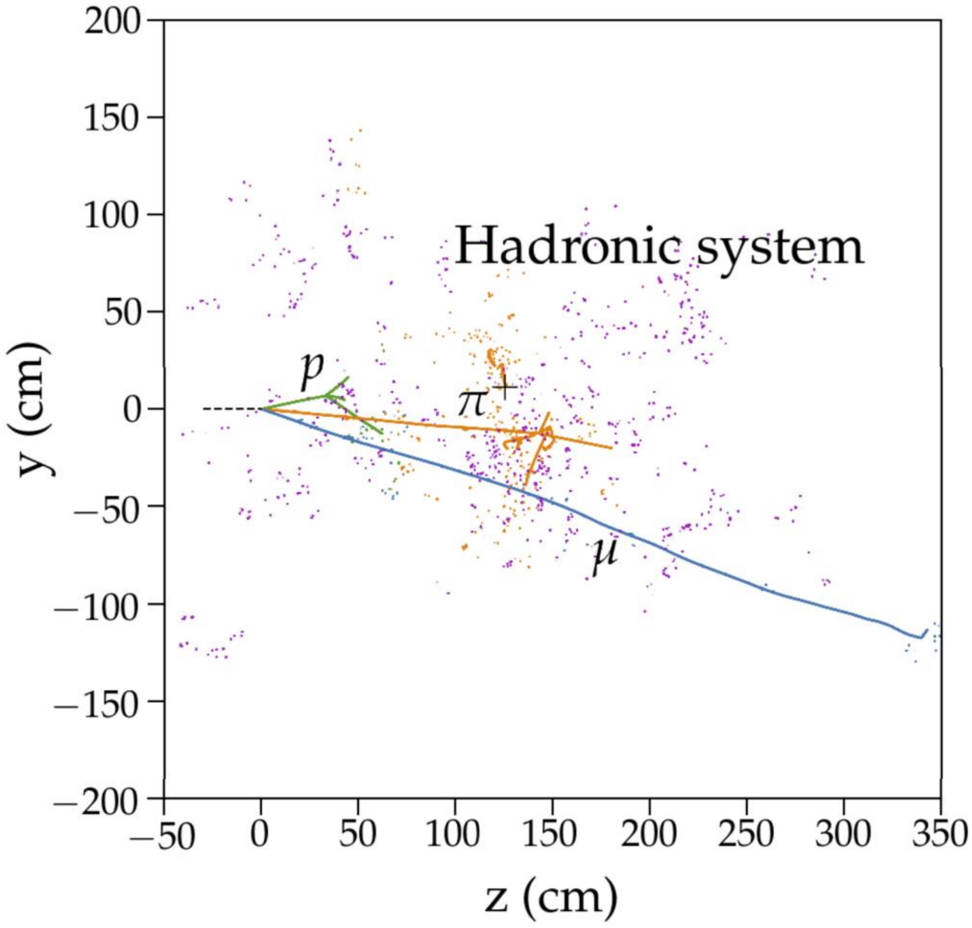
- WbLS is the candidate technology for building the fourth far detector in DUNE (Module of Opportunity): similar oscillation sensitivity, broader physics programs
- **US P5 report**: “A range of alternative targets, including low radioactivity argon, xenon-doped argon, and novel organic **or water-based liquid scintillators**, should be considered to maximize the science reach, particularly in the low-energy regime” (Also see the Theia whitepaper for the proposed DUNE detector)
- ANNIE just finished the 2nd deployment with SANDI+LAPPDs. A future full WbLS-filled phase is being planned for ANNIE Phase 3.





THEIA 100kt

Neutrino Energy in DUNE



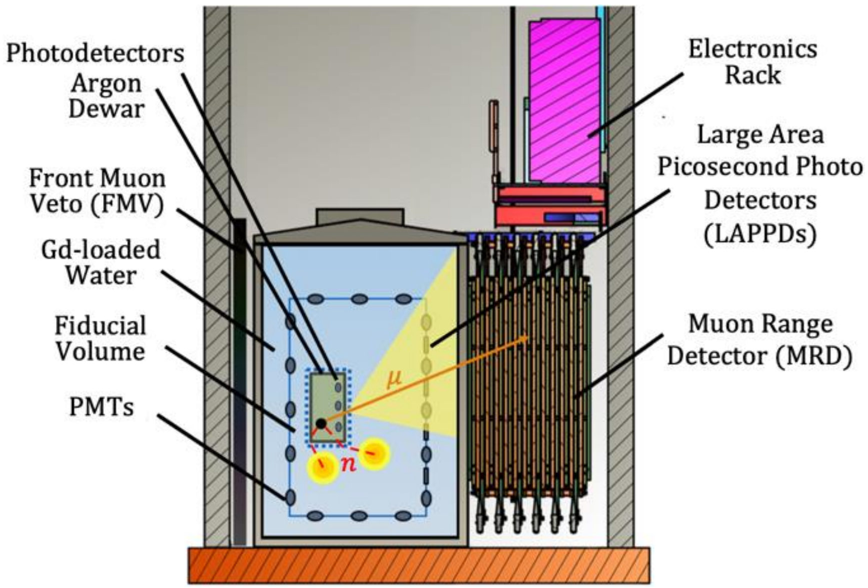
Hadronic composition of CC ν_μ+^{40}Ar scattering event (E_ν = 4 GeV). For 10,000 ν_μ+^{40}Ar CC scattering events with E_ν=4 GeV, there was 19% energy loss to neutrons Simulated with GENIE 2.12.8 default tune.

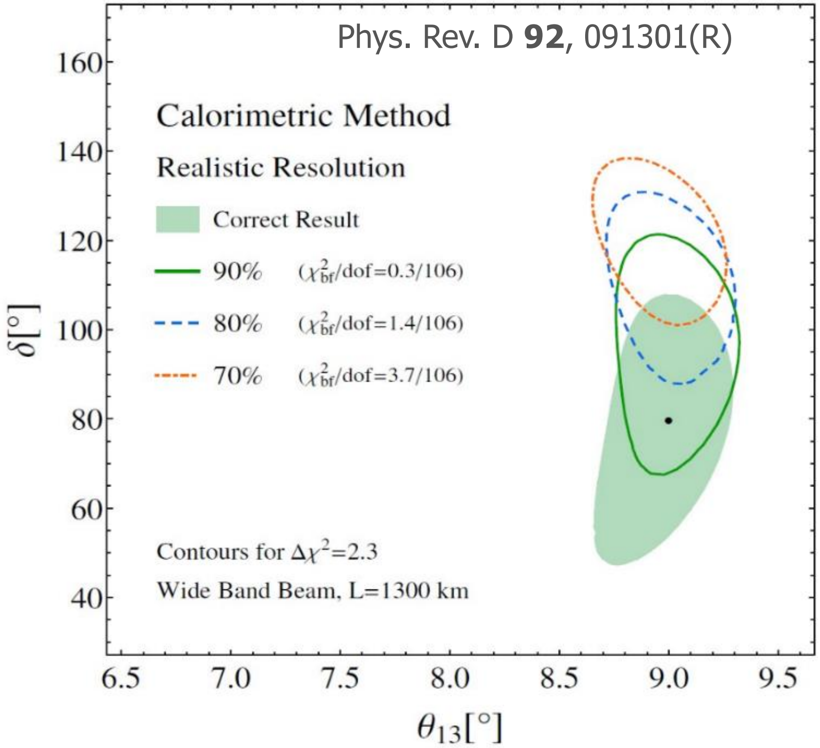
- It is necessary to be able to account for neutron "missing energy" in order to make precision oscillation measurements
- however, neutrino-induced neutrons was never measured with argon

Alexander Friedland, et. al., arXiv:1811.06159 [hep-ph]

Possible Argon Target in ANNIE

- The mis-modeling of the neutron missing energy may lead to a large bias in CP angle measurement. However, no data yet.
- Possibly perform a direct neutron multiplicity measurement with a deploye argon target in ANNIE (idea under development)
- One month data taking will yield ~4000 CCQE events with LAr, or ~1500 with GAr at 300 atm (5E12 POT/pulse@5Hz)





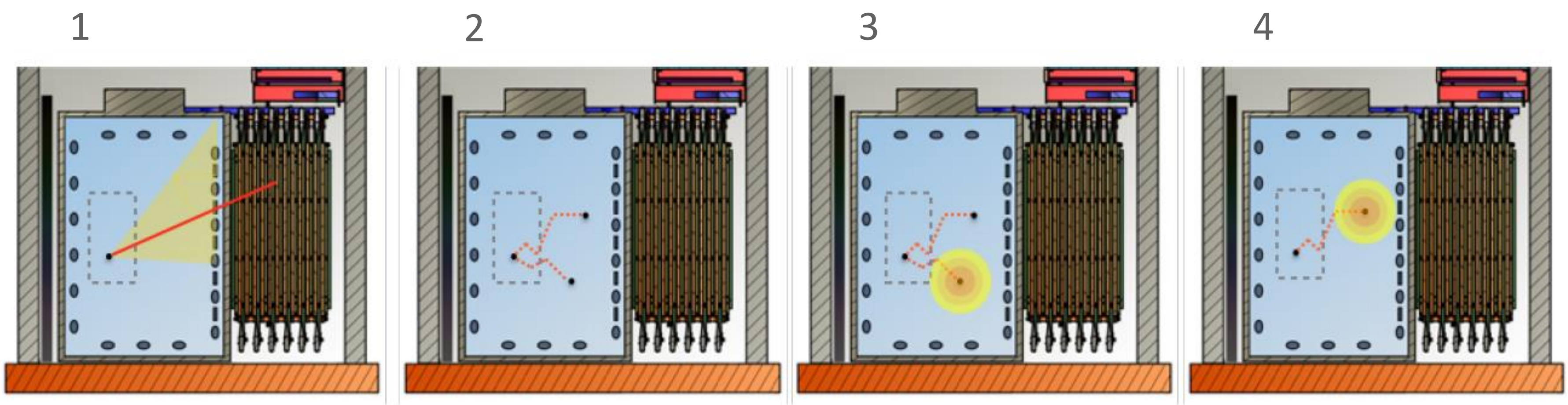
Summary

- **ANNIE** is a **Gd-loaded water Cherenkov detector (26 tons mass)** located in the Booster Neutrino Beam at Fermilab
- **ANNIE Physics:**
  - Neutron multiplicity measurement as a function of momentum transfer
  - Joint cross section measurements with SBN liquid argon detectors
- **ANNIE R&D:**
  - Demonstrate enabling technologies: Gd-loaded water, fast-timing LAPPDs
  - Test hybrid neutrino detection with WbLS: SANDI deployment
- **ANNIE Accomplishment:**
  - First beam neutrinos detected with Gd-water
  - First neutrinos detected with LAPPDs
  - First neutrinos detected with WbLS
- Exciting physics results underway! Several papers in preparation.

Backup

ANNIE Event Schematic

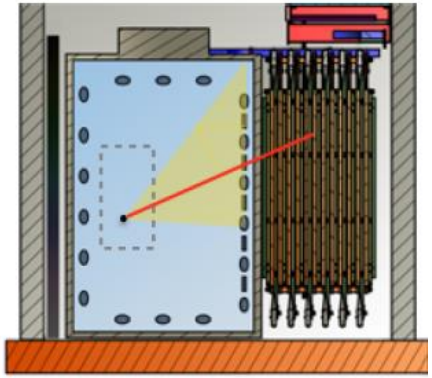
Example of Charge-Current neutrino event

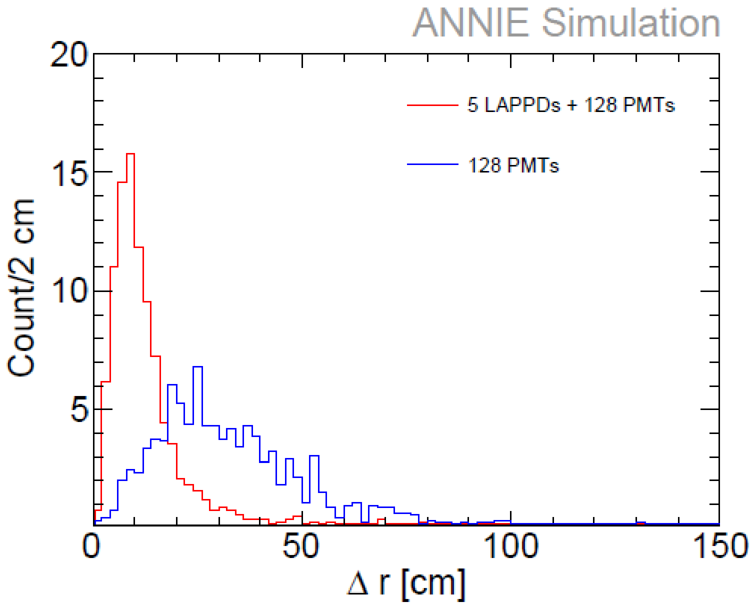


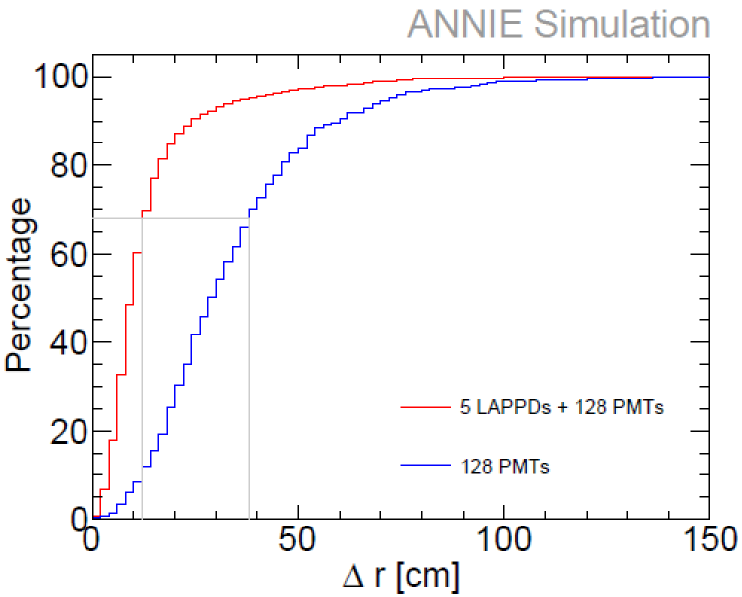
- 1 – **Charge Current neutrino interaction** in the fiducial volume
- 1 - Muon direction reconstructed using LAPPDs
- 1 - Muon momentum reconstructed by the MRD
- 2 - Final state neutrons are getting thermalized in the Gd-water volume
- 3 - Neutron capture on Gd emitting 8 MeV gammas
- 4 – Delayed gamma rays are detected by PMTs

LAPPDs are Essential for ANNIE

- LAPPDs provide high time and spatial resolutions to enhance neutrino vertex resolution and tracking angular resolution
  - Reduce uncertainties on fiducialization
  - Improve precision of energy reconstruction
- By adding 5 LAPPDs to the existing PMTs the accuracy of the vertex reconstruction is improved by a factor of >2

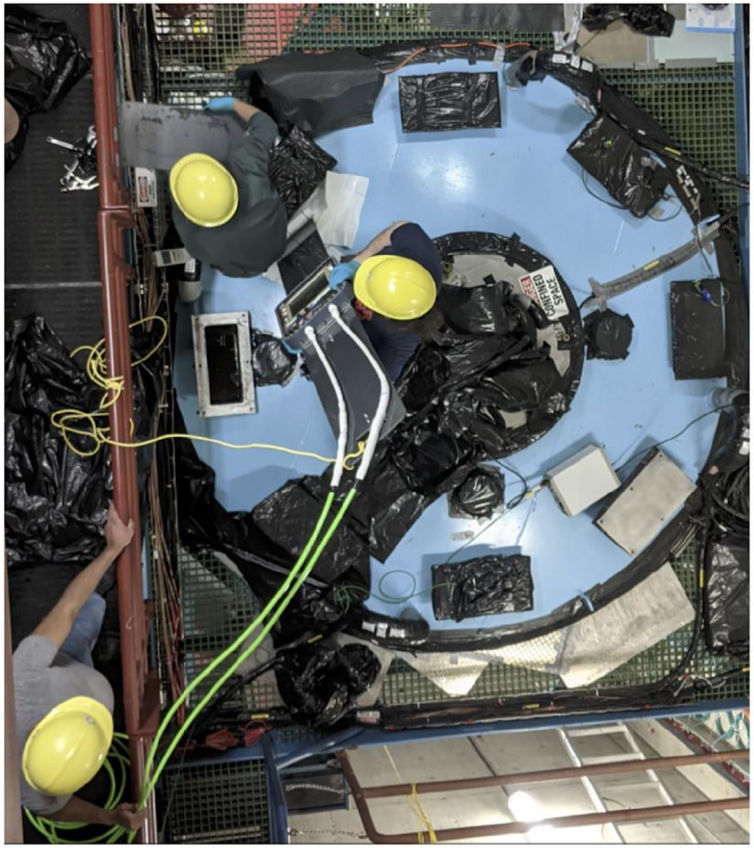


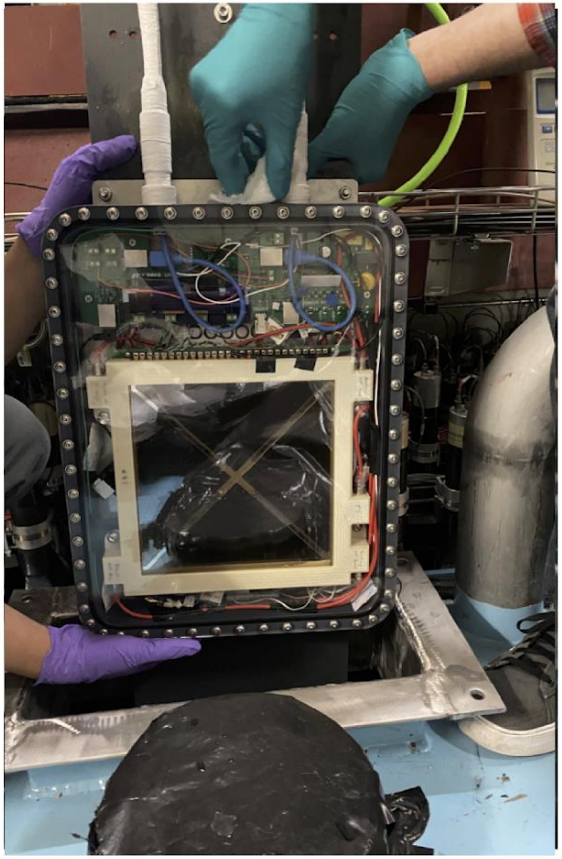




LAPPD Deployment in ANNIE

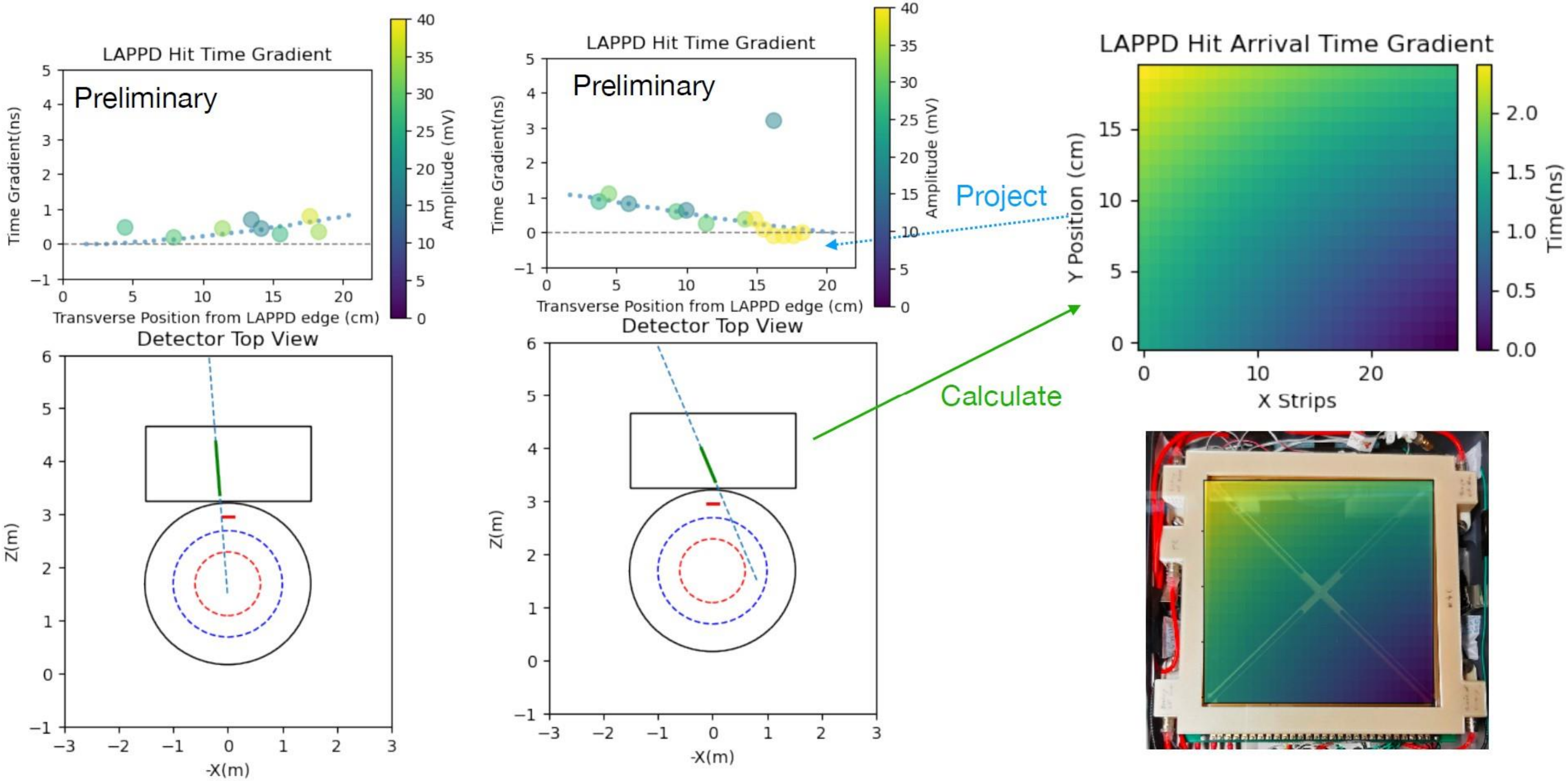
- Six LAPPDs deployed in ANNIE (max 3 at one time). Mix of alkali and non-alkali MCP substrates.





LAPPD Imaging for Muon Tracks

- By using this "hit time“ between strips, we can construct the LAPPD timing gradient of a muon track.
- A single LAPPD’s hit image shows sensitivity of the track direction (work ongoing)

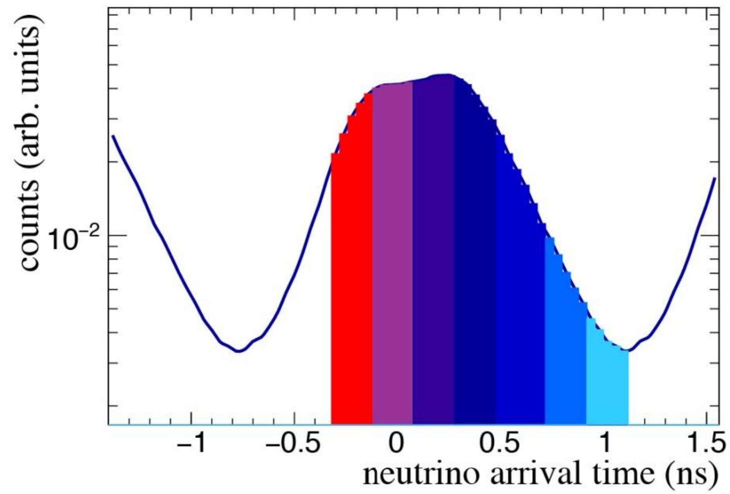


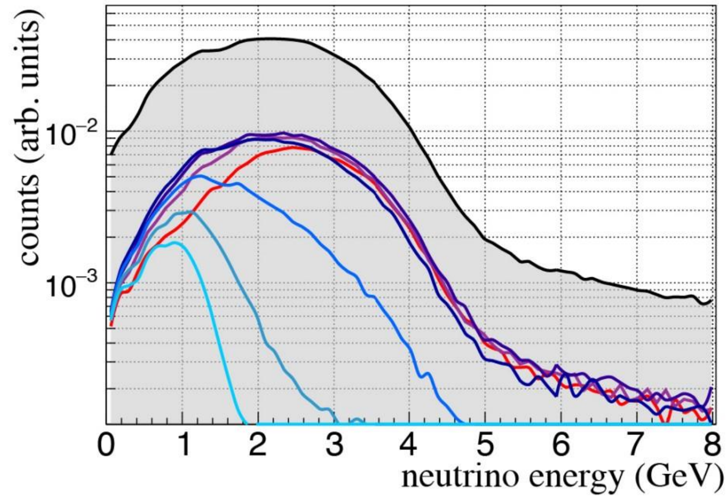
Stroboscopic Approach with LAPPDs

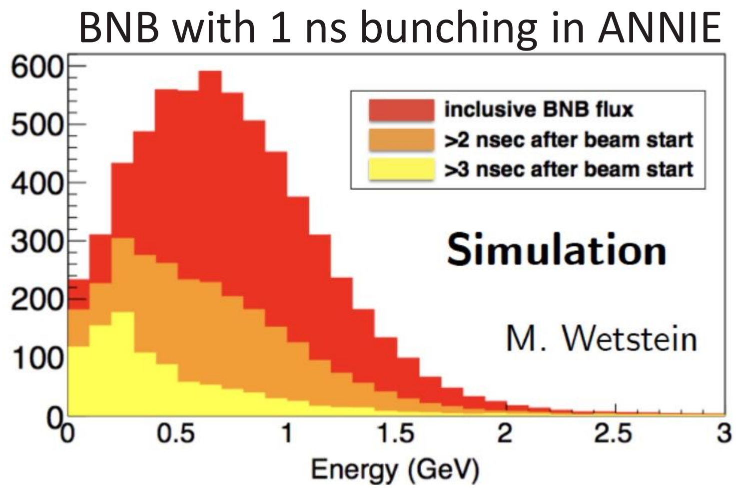
- Neutrino energy sorting with stroboscopic approaches enabled by LAPPDs.
- Fast timing (detector and beam) could enable a new handle on neutrino flux complementary to off-axis "prism" approaches.
- ANNIE can demonstrate this technique ns-scale binning and the BNB
- LAPPDs are candidate for building the ND-GAr near detector

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

(“LBNF” with rebunching)







Missing Energy

- **Neutron multiplicity measurements** will be very useful to verify models

COMPARISONS AND CHALLENGES OF MODERN NEUTRINO- … PHYS. REV. D **105,** 092004 (2022)

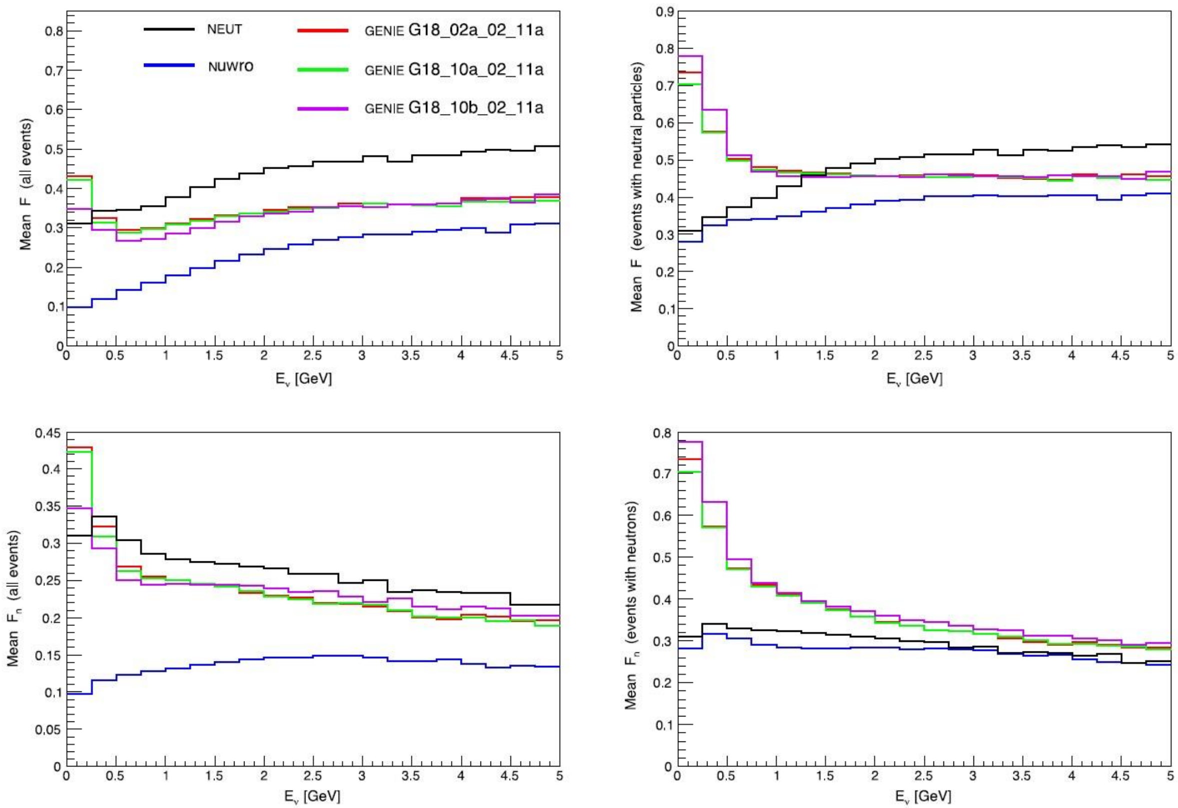


FIG. 37. Mean fraction of the leptonic energy transfer imparted to final-state neutral particle species. All panels show distributions calculated for charged-current ν_μ interactions on ^{40}Ar. Top left: Predictions including all neutral particles and all events in the sample. Top right: Predictions including all neutral particles for events containing at least one final-state neutral particle. Bottom left: Predictions including final-state neutrons only and all events in the sample. Bottom right: Predictions including final-state neutrons only for events containing at least one final-state neutron.

M. Avanzini, et., al., *Comparisons and challenges of modern neutrino-scattering experiments*

Neutron Multiplicity Simulations

Eur. Phys. J. Spec. Top. (2021) 230:4449–4467 4459

Genie Collaboration, *Recent highlights from GENIE v3*

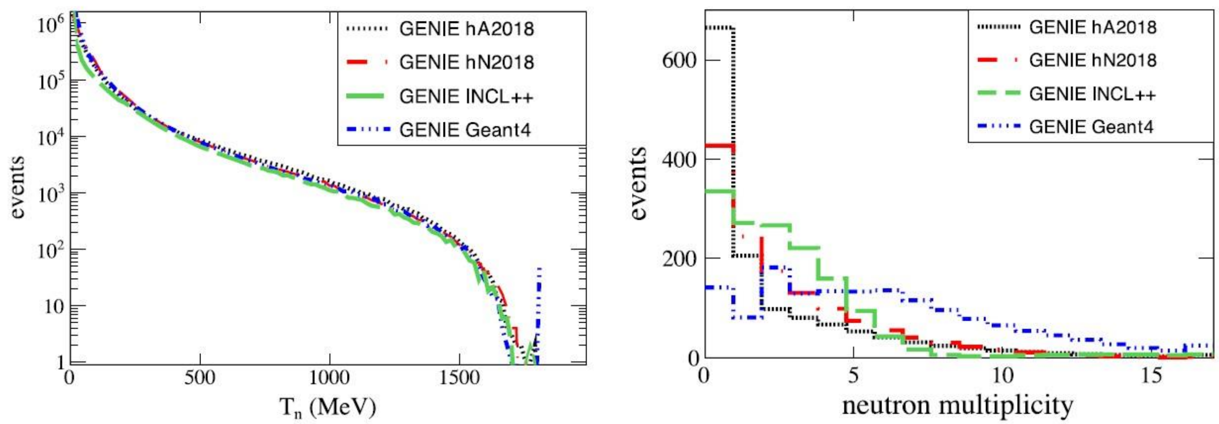


Fig. 8 Neutron distributions from a simulation of 2 GeV ν_μ ^{40}Ar, kinetic energy (left) and multiplicity (right). In each case, results from all 4 models described in the text are shown

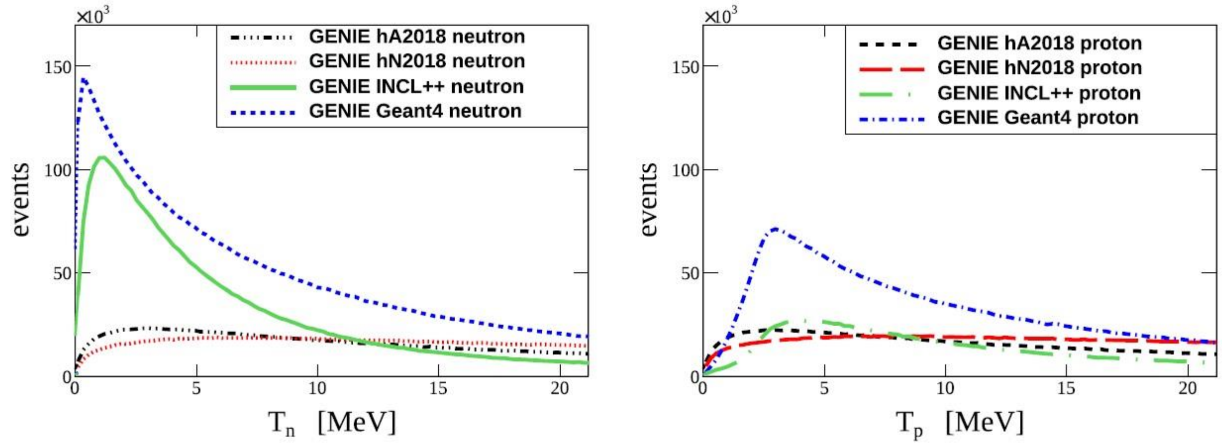
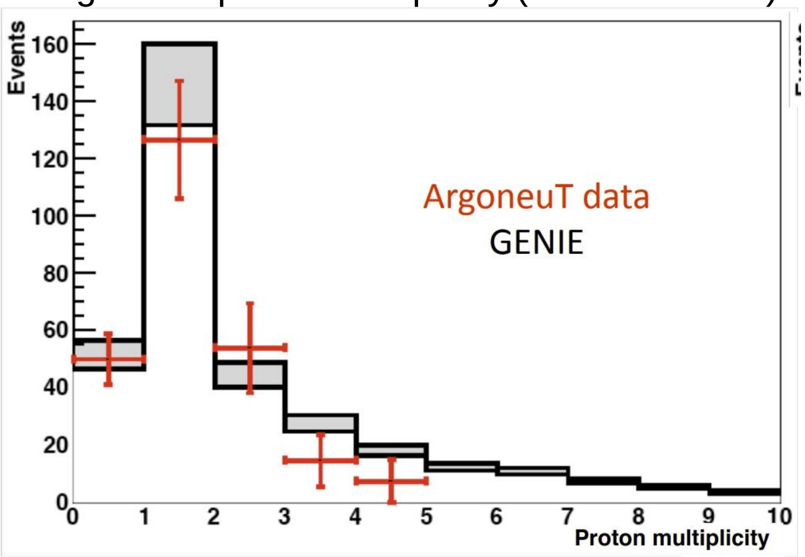


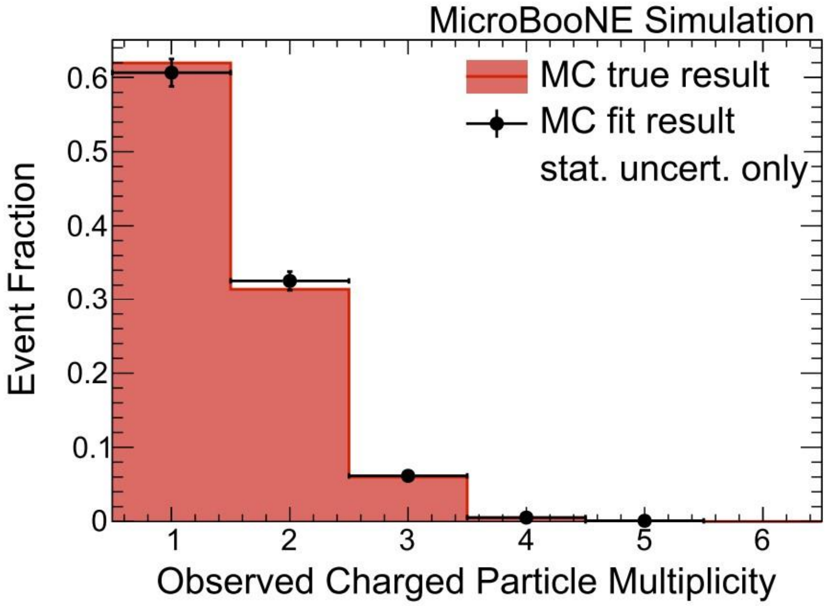
Fig. 9 Left: Neutron (left) and proton (right) kinetic energy distributions from a simulation of 2 GeV ν_μ ^{40}Ar focusing on low energy responses, in each case, results from all 4 models described in the text are shown. Results from INCL++ and Geant4 models described in the text are shown

No measurement done with argon

- Existing Measurements of neutrons
  - MINERvA measured neutron multiplicity on hydrocarbon target
  - SNO measured neutron multiplicity on heavy water and Cl-mixed water
  - Super-K measured neutron multiplicity on water
- Existing liquid argon experiments measured protons (or charged particles), but neutrons are hard to detect (most will escape DUNE far detector module)

ArgoNeuT proton multiplicity (neutrino beam)





SNO Measurement

arXiv:1904.01148v3 [hep-ex] 19 Jun 2019

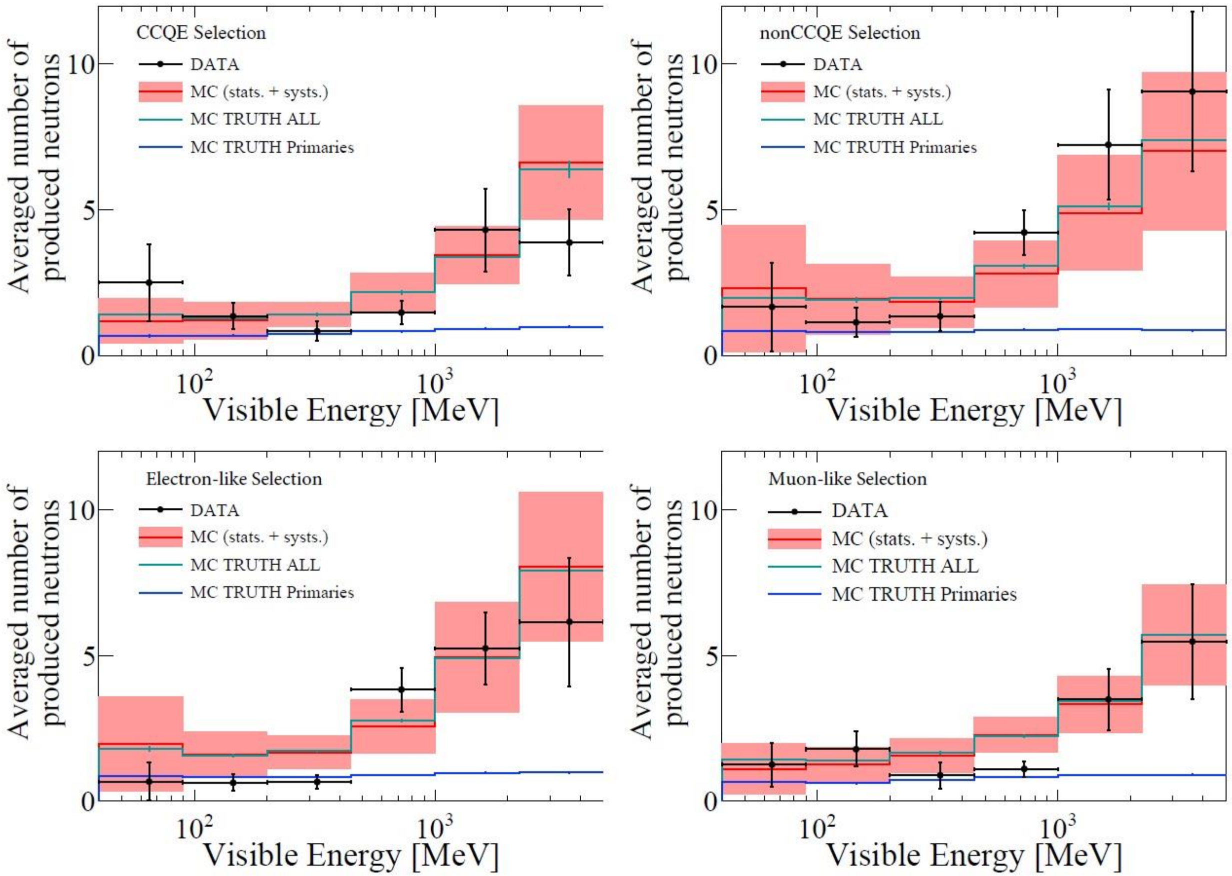


FIG. 15. Averaged number of produced neutrons vs visible energy for both phases together. We show the different selections: CCQE (top left), nonCCQE (top right), electronlike (bottom left) and muonlike (bottom right). The points represent data with statistical uncertainties. The reconstructed MC is shown with red boxes with the size corresponding to the systematic uncertainties. The green line represents the average total number of neutrons given by the MC truth, and the blue line corresponds to the average number of primary neutrons given by the MC truth.

Super-K Measurement

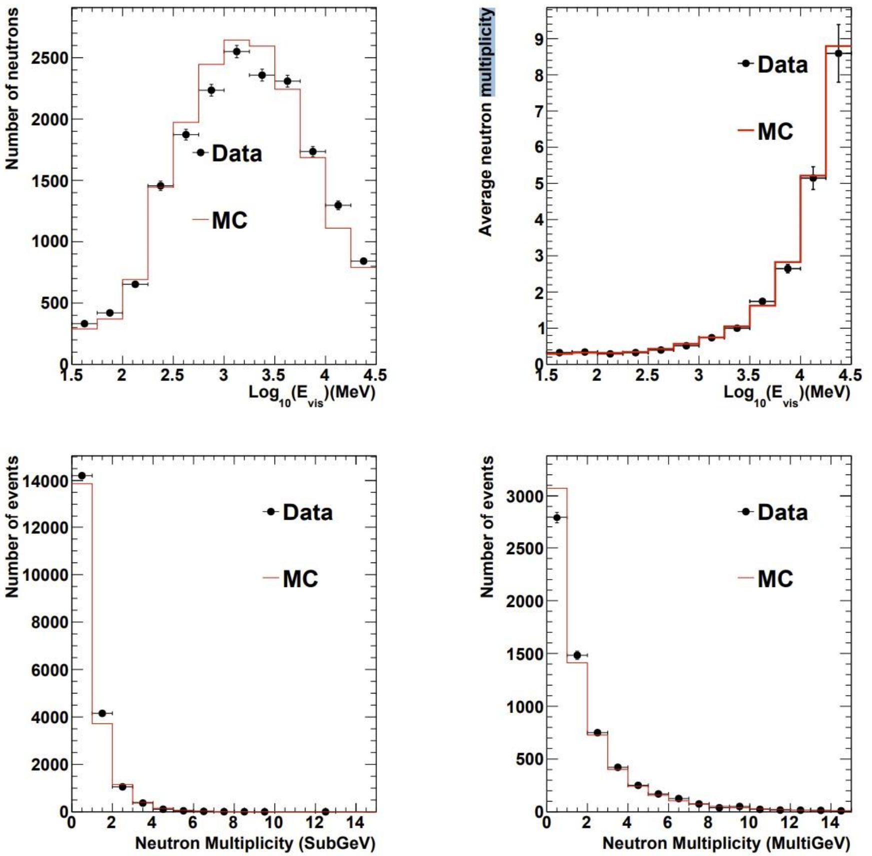


Figure 13. Comparison of data and MC for tagged neutrons in the SK-IV atmospheric neutrino data. The top left (right) plot shows the total number of neutrons (average neutron multiplicity) as a function of visible energy (E_{vis}). The bottom left plot shows the neutron multiplicity for sub-GeV events ($E_{\mathrm{vis}} < 1.33\,\mathrm{GeV}$) and the bottom right plot shows that for multi-GeV events ($E_{\mathrm{vis}} \geq 1.33\,\mathrm{GeV}$). These plots are normalized to the number of neutrino events observed in the data. Only statistical errors are shown.

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Minerva Measurement

arXiv:1901.04892v2 [hep-ex] 20 Sep 2019

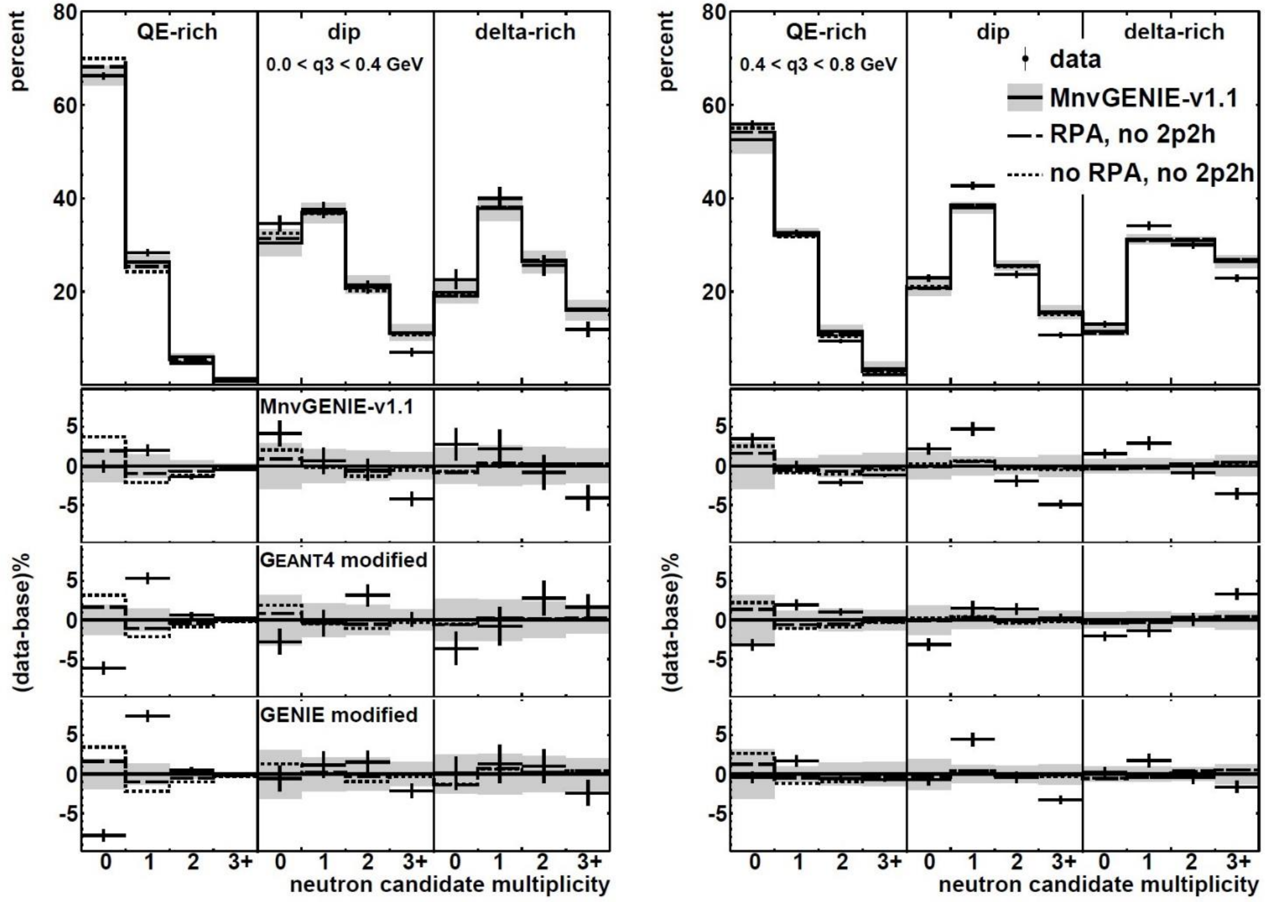


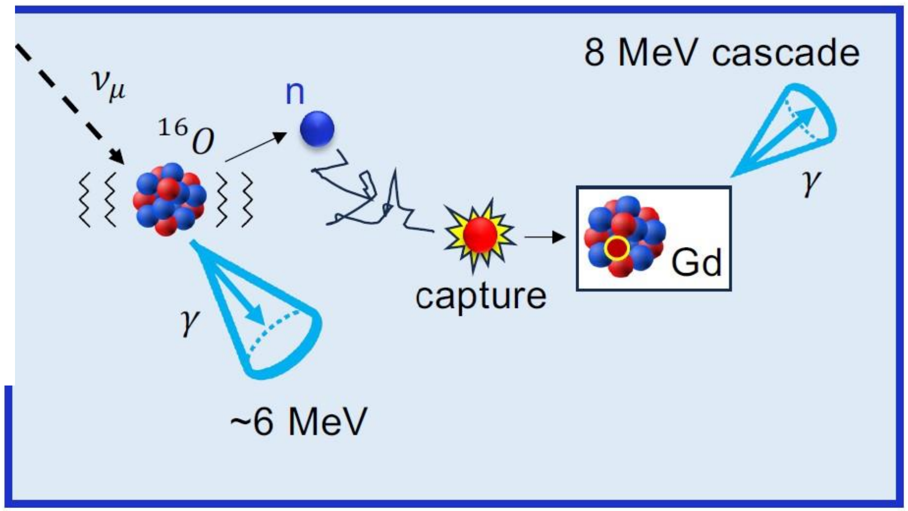
FIG. 10: Candidate multiplicity distribution for all six subsamples, $0 < q_3 < 0.4$ (left) and $0.4 < q_3 < 0.8$ GeV/c (right), with subpanels for the QE-rich, dip, and Δ-rich regions. The top plot shows the reference MnvGENIE-v1.1 simulation with a solid line and error band, and two variations that turn off completely the *2p2h* component and then also turn off the RPA component. The next row shows the difference from the reference simulation. The middle (lower) row of difference plots uses the modified GEANT4 benchmark (modified GENIE benchmark) for all distributions.

NCQE Signals in ANNIE

- νNCQE (truth)
  - ~6 MeV prompt (+ secondary) gammas
- Signal-like (reconstructed)
  - Pre-activity, only cluster
  - Beam-spill (1.6μs)
  - No FMV/MRD activity
  - Charge-based cuts
  - 3 MeV < E_{rec} < 12 MeV
  - Within FV
  - Bunch timing cuts

$$\langle \sigma_{\nu NCQE}^{measured} \rangle = \frac{N^{obs} - N_{bkg}^{exp}}{N_{\nu NCQE}^{exp}} \times \langle \sigma_{\nu NCQE}^{theory} \rangle$$

$\nu + {}^{16}O \rightarrow \nu + n + {}^{15*}O \rightarrow \nu + n + \gamma$



NCQE signal in a water cherenkov detector

Steven Doran, Iowa State University
APS Joint March and 9 April Meeting, 2025