Accelerator Neutrino Neutron Interaction Experiment (ANNIE)

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On behalf of the ANNIE collaboration

SOUTH DAKOTA MINES
An engineering, science and technology university

annie

Phase II FD/ND Meeting
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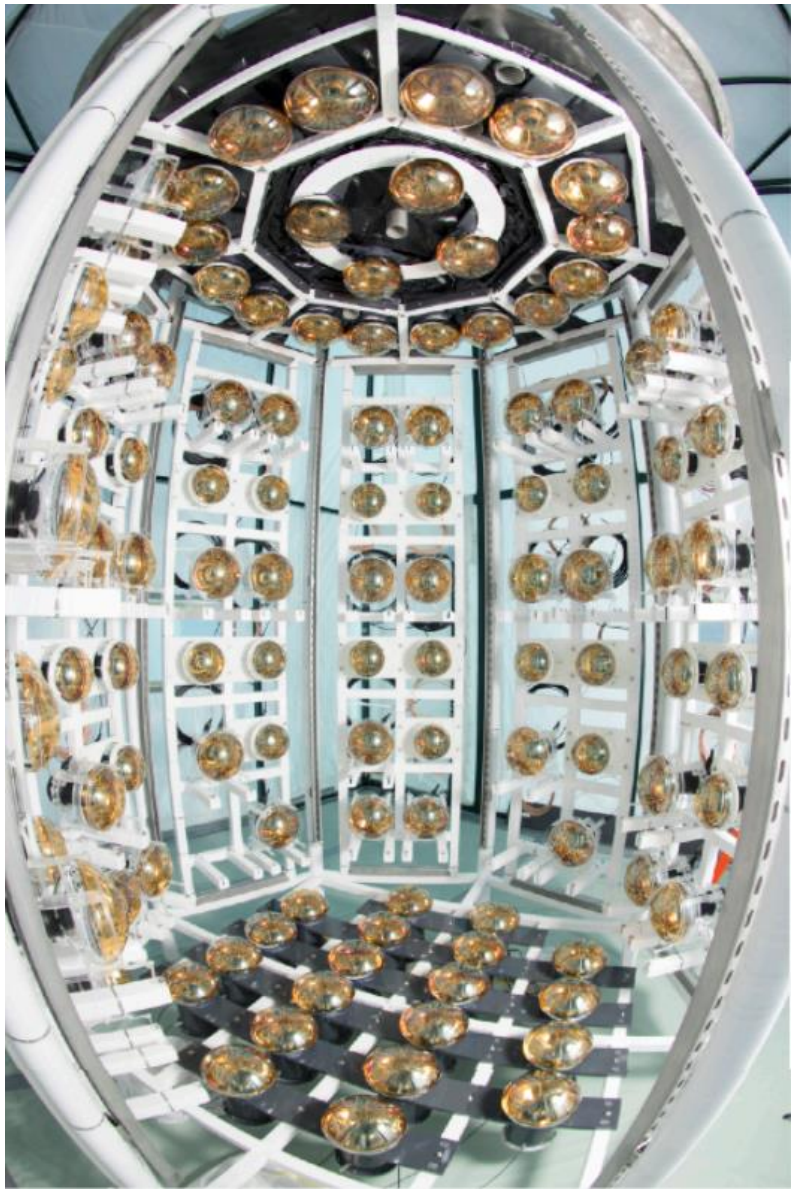
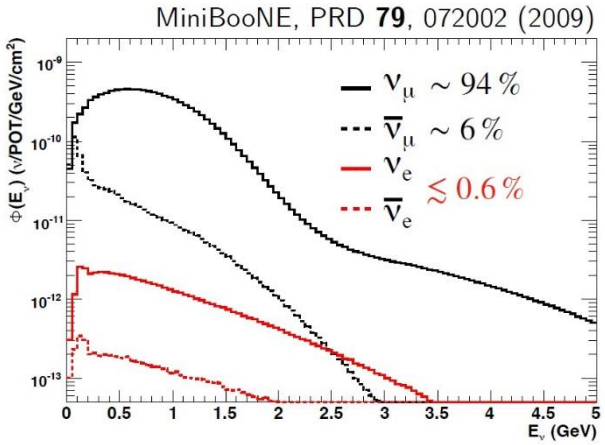
ANNIE

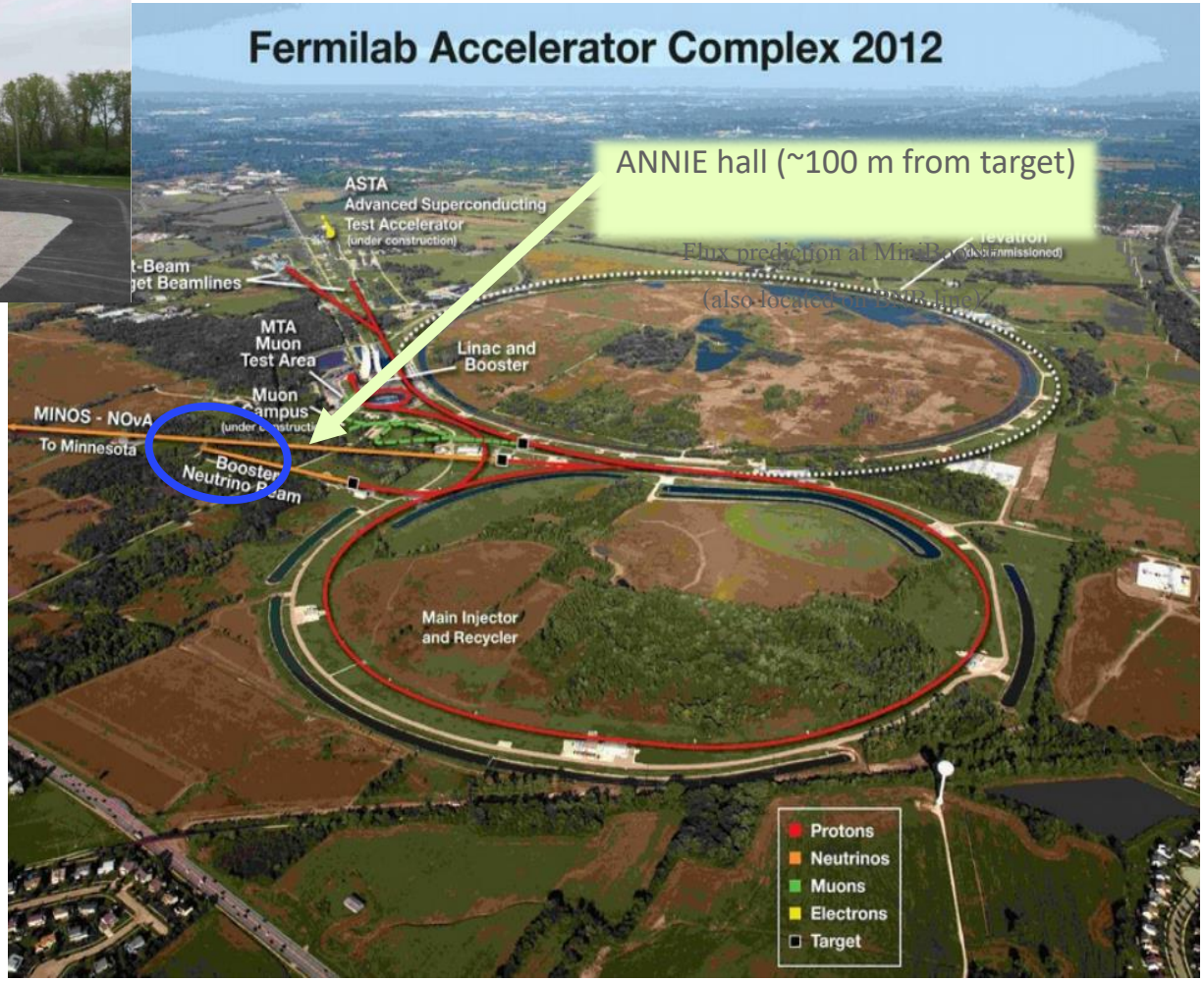
- The **A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment (**ANNIE**)
- 26-ton **Gd-loaded Water Cherenkov** detector, located 100 m downstream at the Booster Neutrino Beam line at Fermilab
- **Physics:** study neutrino-nucleus interactions
- **Technology:** R&D platform for new neutrino detection technologies
  - Gadolinium-doped water for neutron detection
  - Large Area Picosecond PhotoDetectors (LAPPDs)
  - Water-based Liquid Scintillator (WbLS) as a new detection medium



ANNIE Location at Fermilab

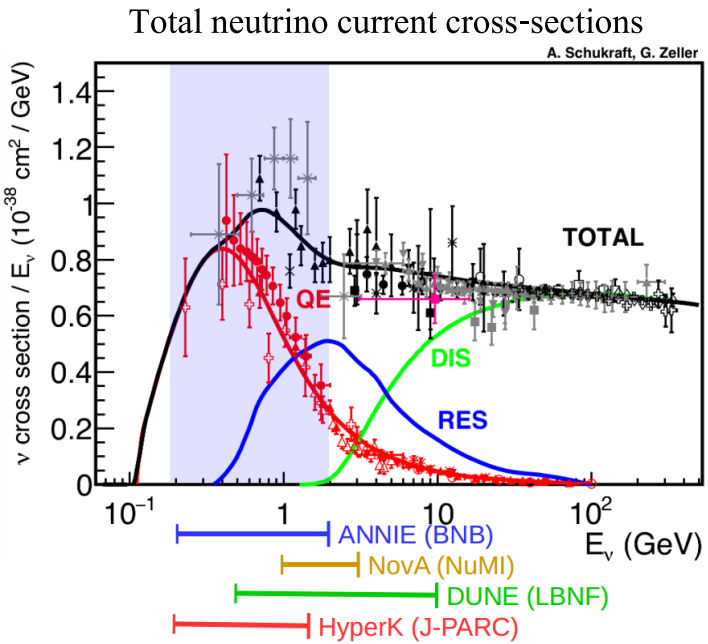


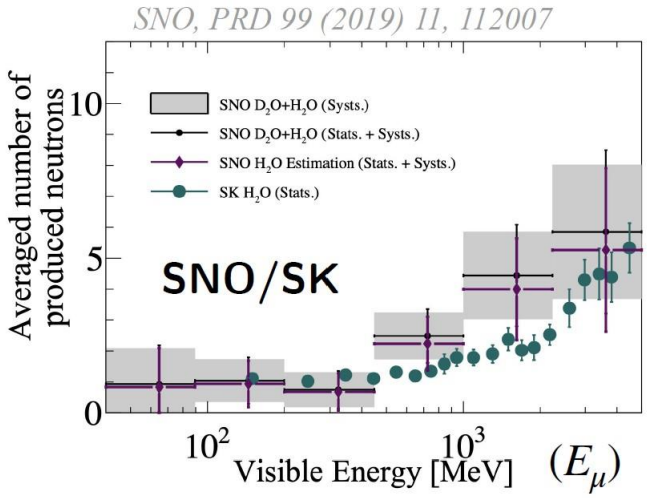
~10,000 Charged current neutrino events per ton of target water per year expected at ANNIE hall!



ANNIE Physics Program

- **High-flux GeV ν_μ on fixed target:** Study of neutrino-nucleus interactions
- **Measure final-state neutrons vs momentum transfer Q^2**
  - Improve modeling of final-state interactions
  - Reduce energy reconstruction uncertainty
  - Constrain atmospheric neutrino backgrounds in proton decay and DSNB searches
- **Measure Multi-target cross-sections**
  - Same neutrino beam as SBN: joint analysis
  - Correlated cross section, and hadron production with $^{40}\mathrm{Ar}/\mathrm{H_2O}$ targets



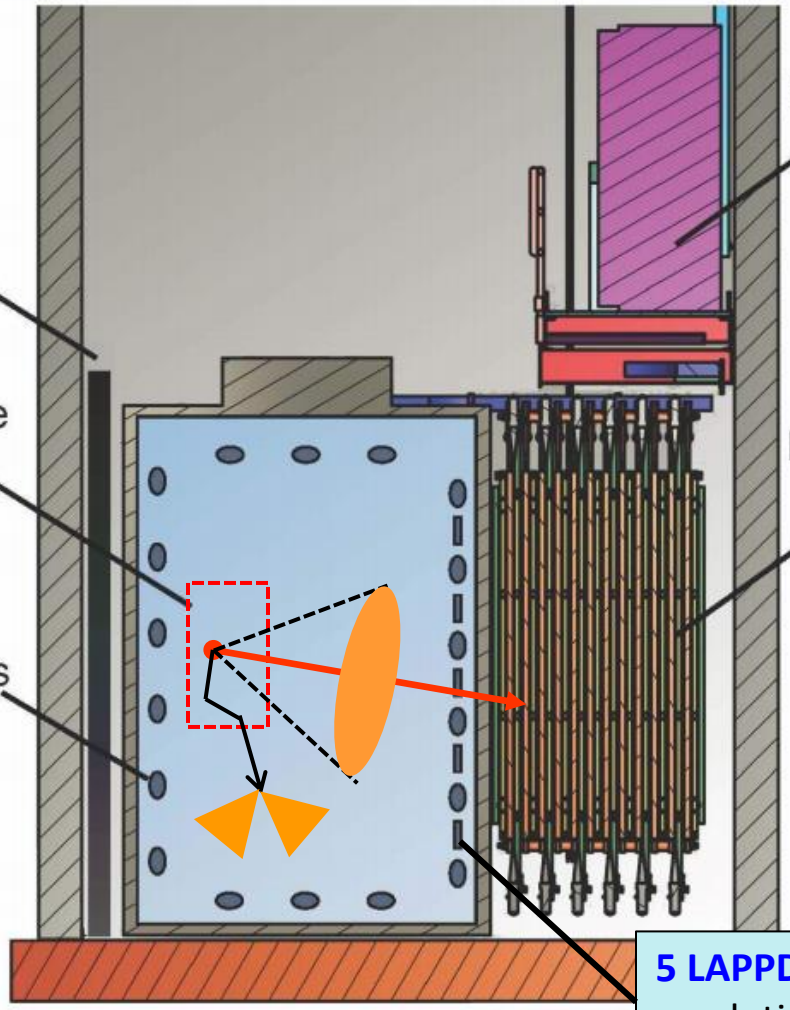


ANNIE Detector

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 neutron capture detection

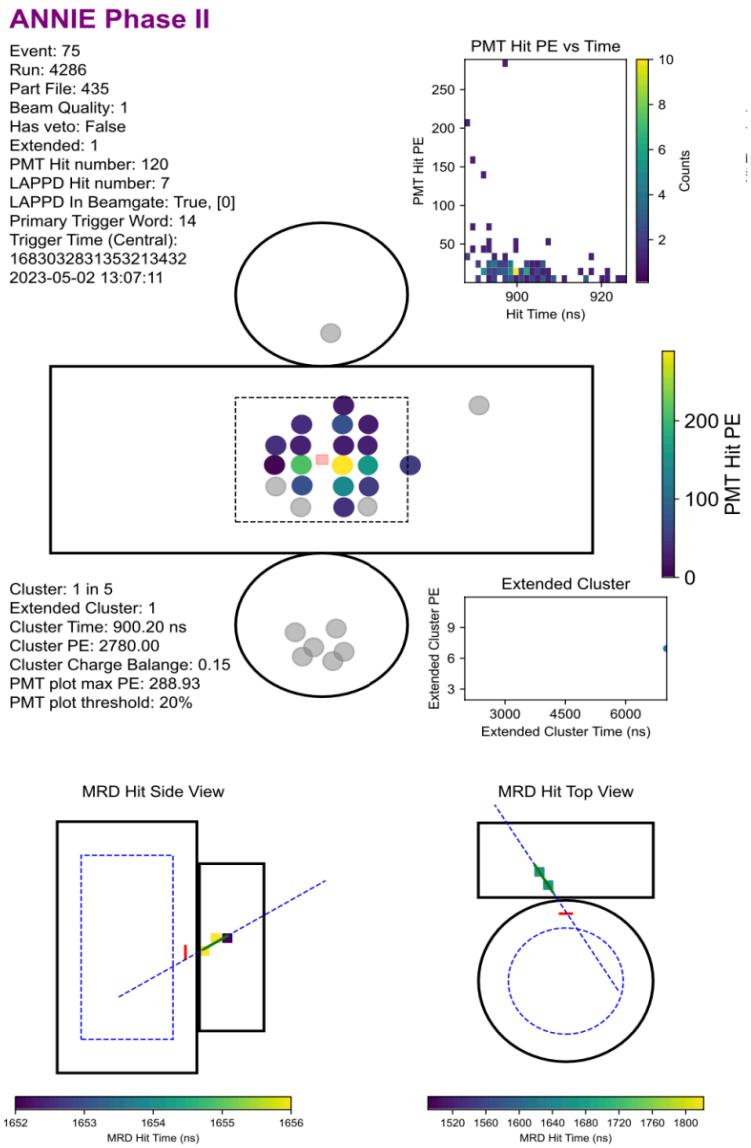


310 scintillator paddles
5 vertical layers
6 horizontal layers

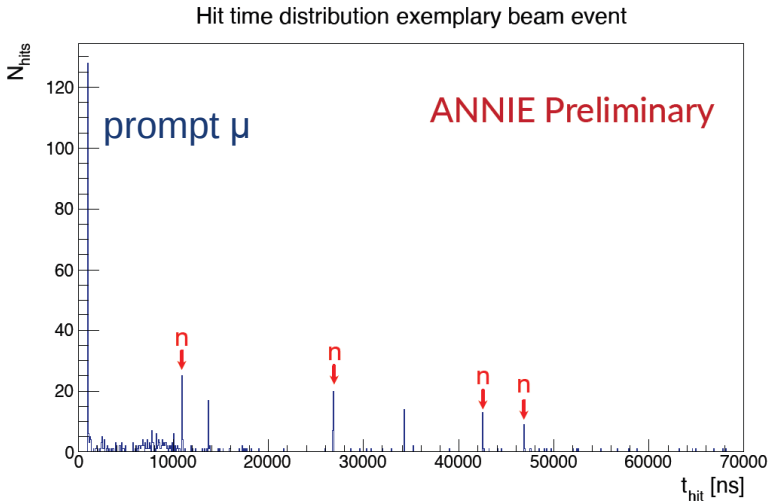
5 LAPPDs with < 100 ps time resolution for improved muon track reconstruction

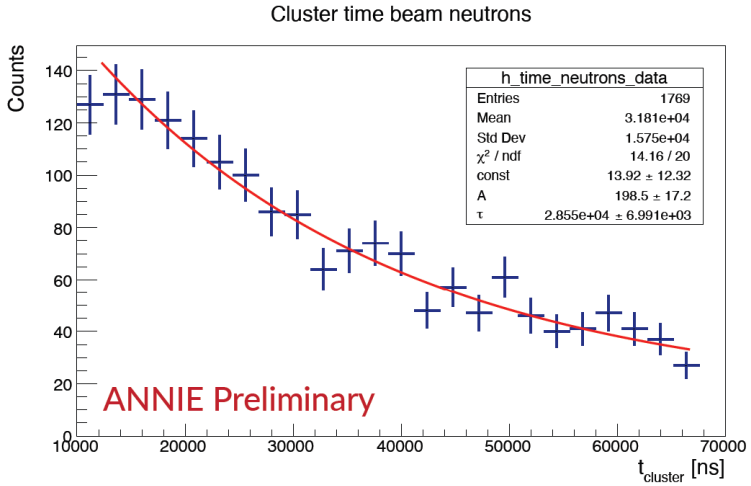
ANNIE Neutrino Candidate

- ANNIE has been taking neutrino data for over three years with Gd-loaded 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.



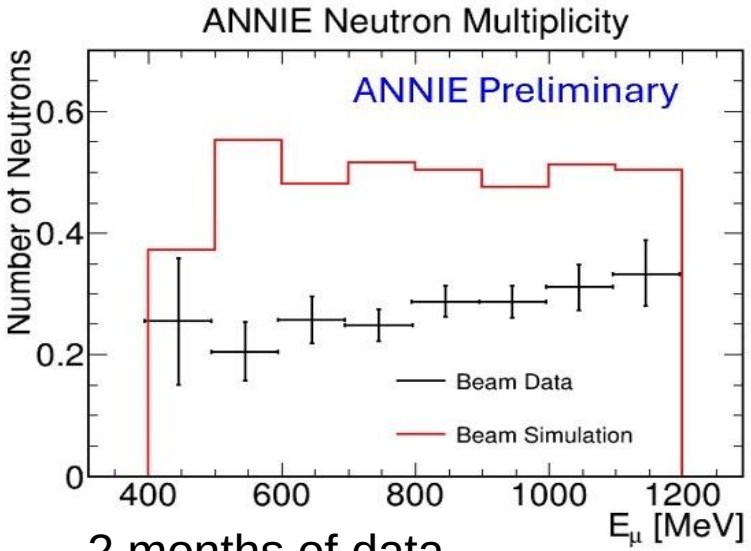
Neutron Multiplicity Analysis





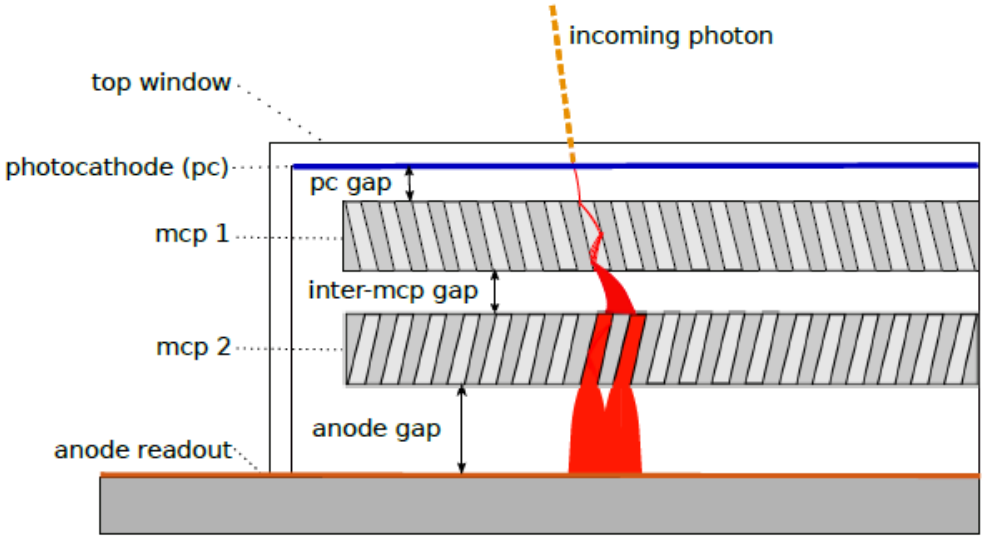
τ ~ (29 ± 7) μs in agreement with theoretical expectation (30 μs)

- Neutron captures are detected by PMTs within a ~70 μs acquisition window.
- Neutron capture time profile from beam data agrees well with prediction for 0.1% Gd.
- First neutron multiplicity analysis with PMTs will conclude within a year.



2 months of data

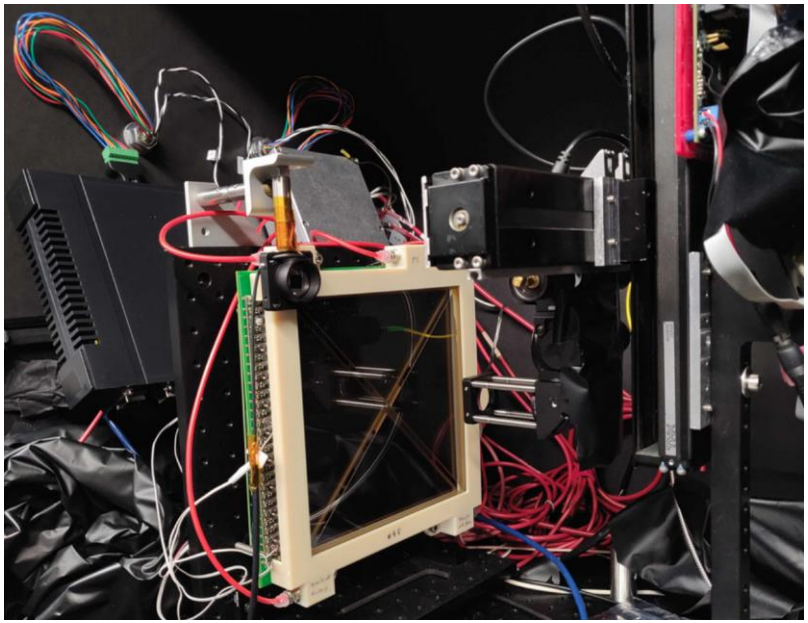
Enabling Technology: LAPPD



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

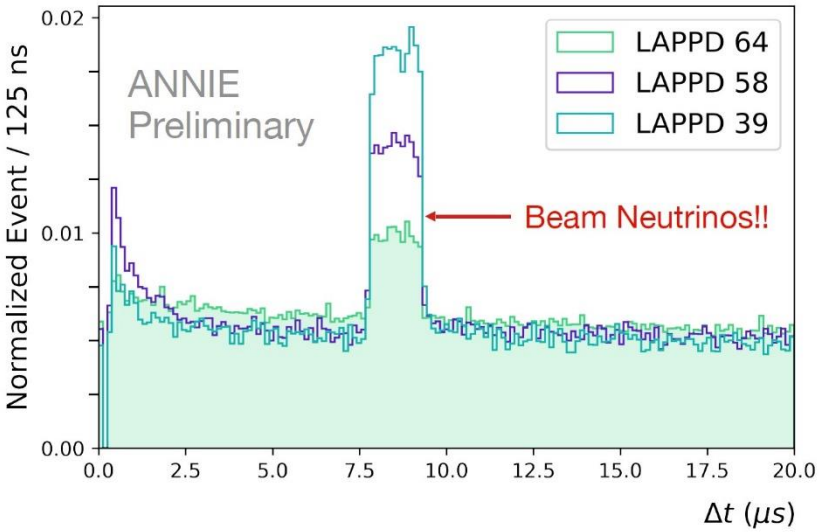
- Flat, Large-area: 20 cm × 20 cm
- Picosecond timing: <100 ps for SPE
- Quantum efficiency: >20%
- Position resolution: sub-mm

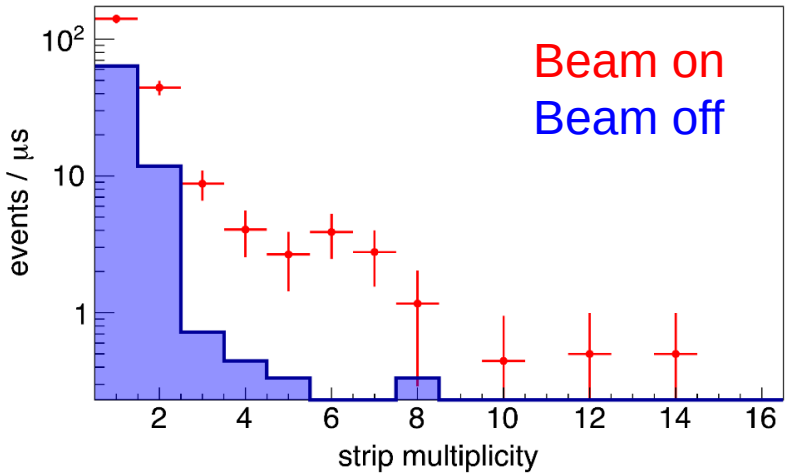
- ANNIE is the first physics experiment employing LAPPDs
- Deployed multiple LAPPDs and saw beam neutrinos
- 5 LAPPDs in ANNIE can improve the vertex resolution by a factor of >2

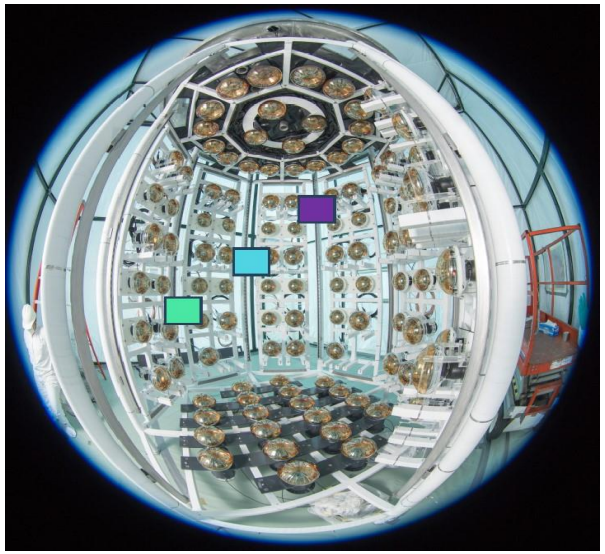


First Neutrinos Seen by LAPPDs

LAPPDs see the BNB neutrinos!





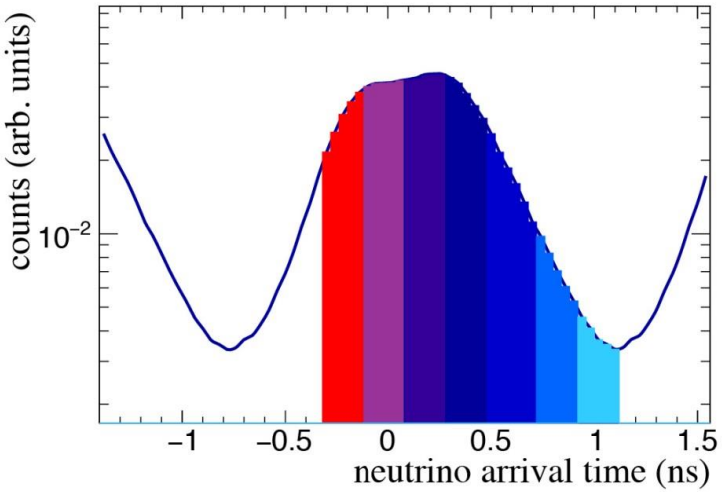


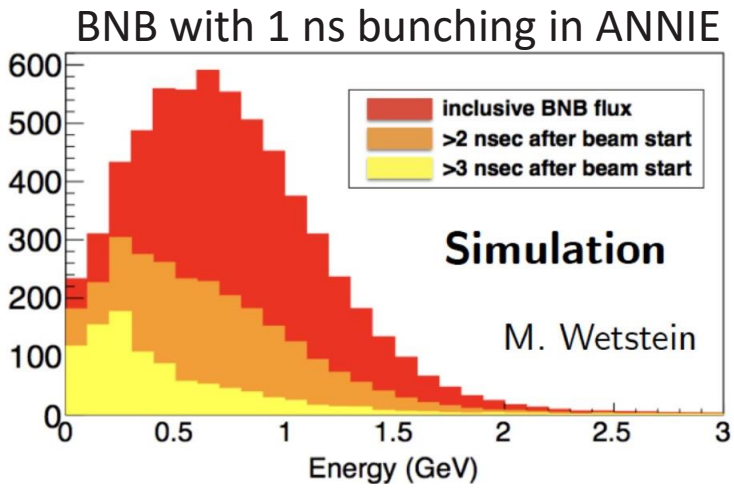
- Deployed 1-3 LAPPDs
- First detection of neutrinos using LAPPDs
- The excess above background are LAPPD-triggered events in-time with the BNB.
- Will ultimately deploy 5 LAPPDs and then update the neutron analysis

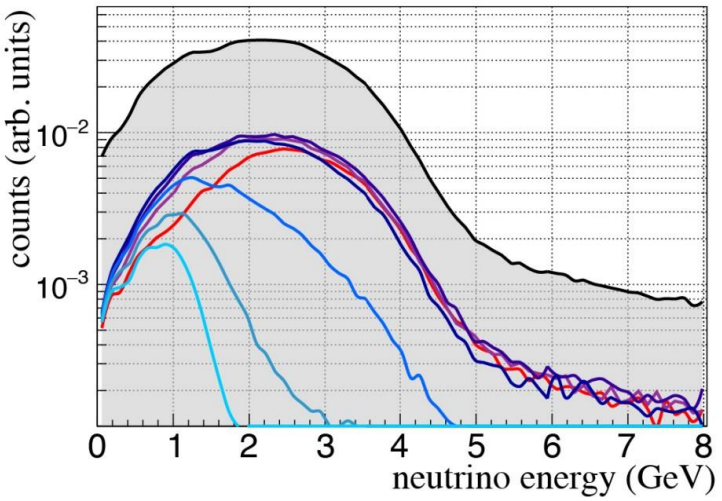
Stroboscopic Approach with LAPPDs

- 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)

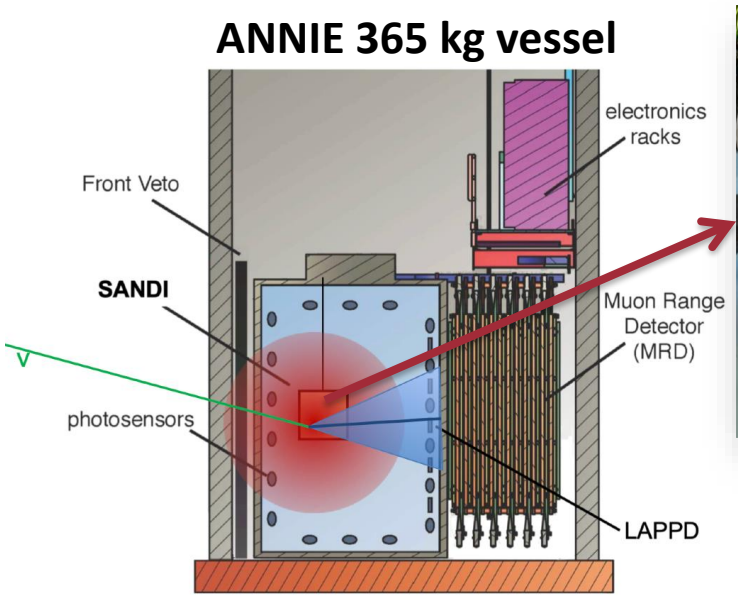


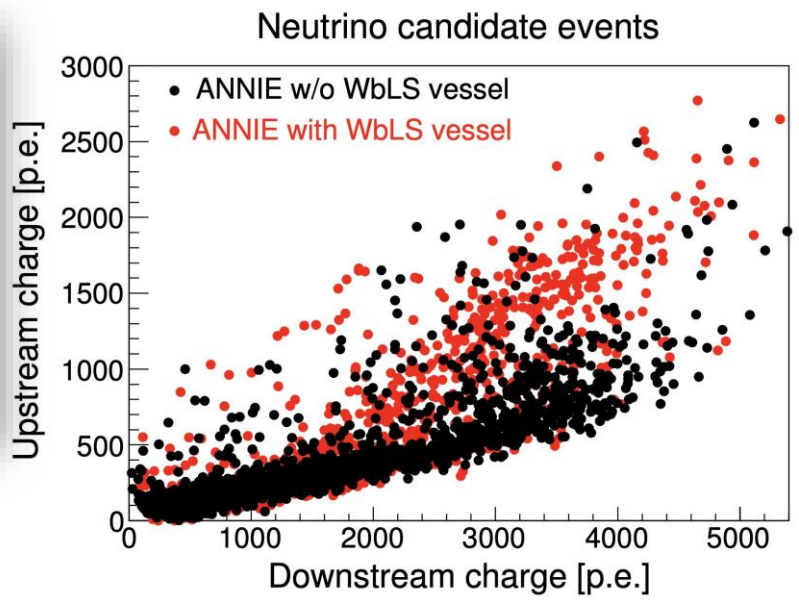




Water-based Liquid Scintillator

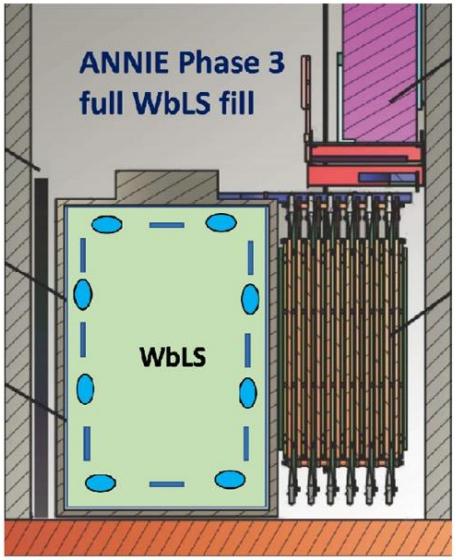
- **Water-based Liquid Scintillator:** novel detection medium combining advantages of both scintillation and Cherenkov light
  - Enhanced neutrino energy reconstruction, background rejection and neutron detection
- SANDI test: ~3'×3' acrylic vessel containing 356 kg of 0.5% LS water-based liquid scintillator (WbLS), deployed in March 2023
- 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 by JINST)

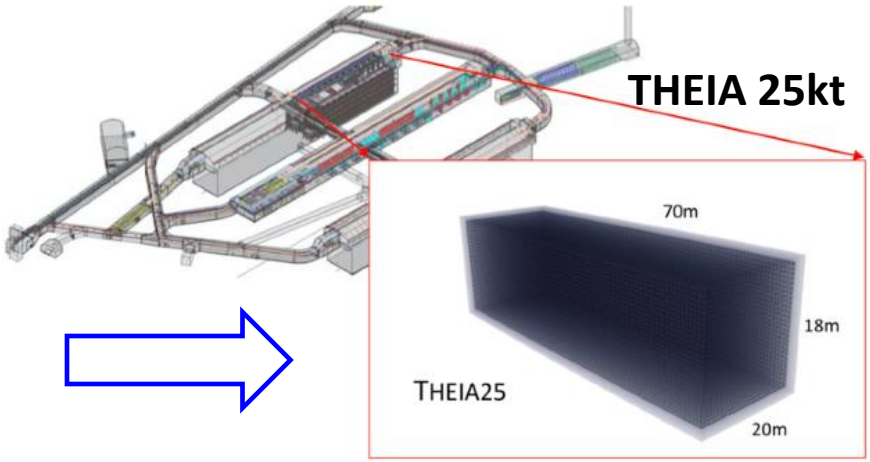




Future WbLS Study

- WbLS is the candidate technology for building the fourth far detector in DUNE (Module of Opportunity)
- **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”
- ANNIE is performing new deployment with SANDI+LAPPDs. A future full WbLS-filled phase is planned.

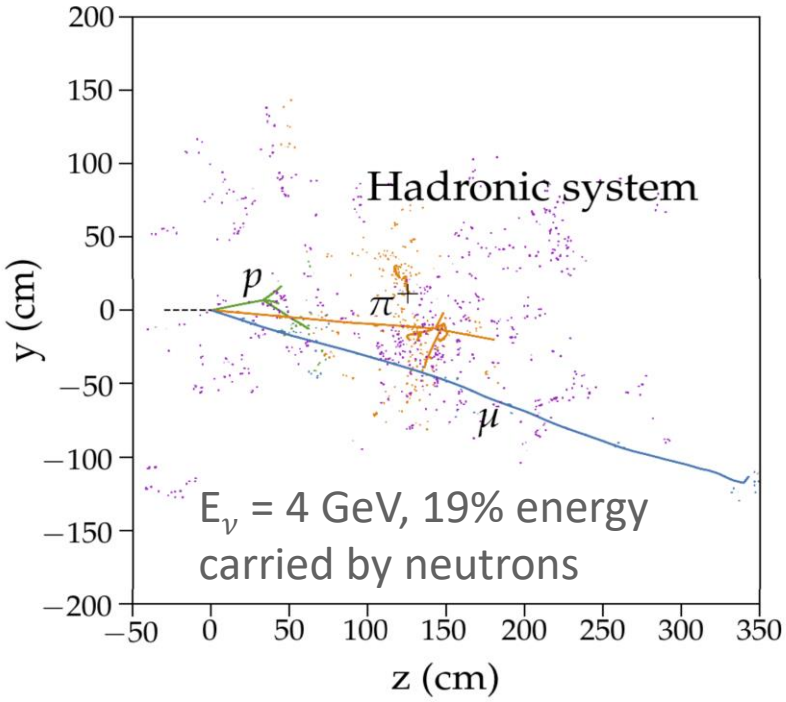




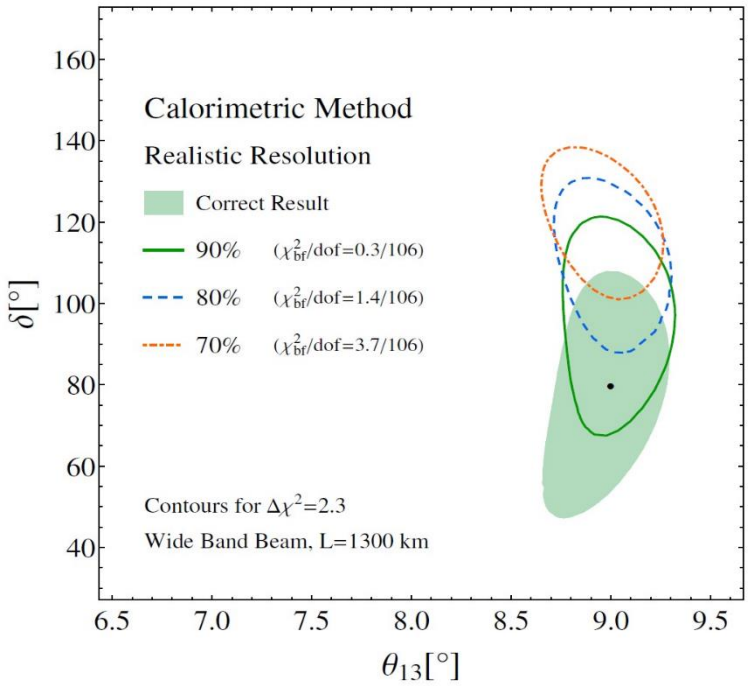
Neutrons in DUNE

- ~20% of neutrino energy is carried by the neutrons.
- Missing neutrons may result in large bias in CP violating angle measurement.

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



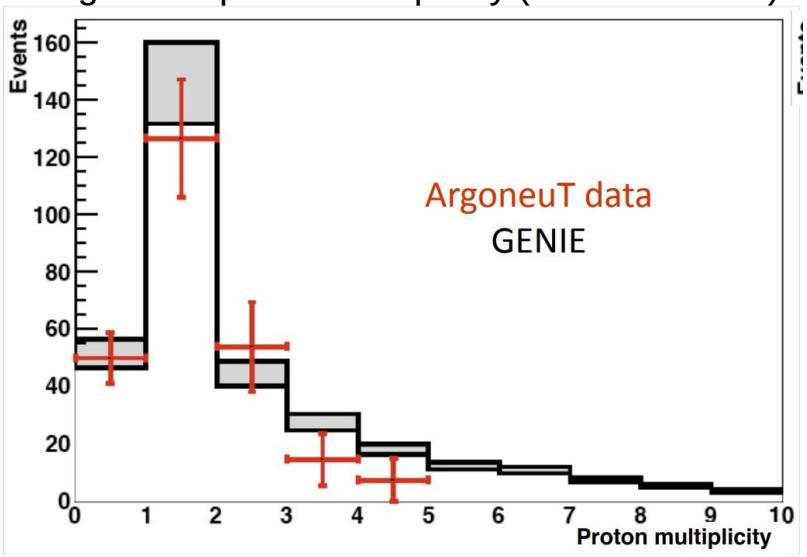
A. M. Ankowski, et. al., Phys. Rev. D **92**, 091301(R)

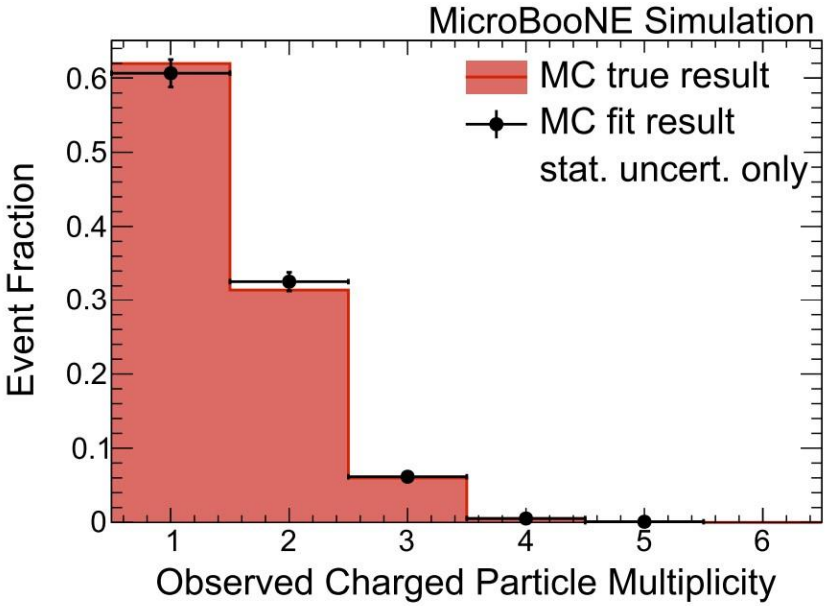


No neutron measurement with Ar

- 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 (MicroBooNE, ArgoNeuT) measured protons (or charged particles), but **no neutron measurement exists in argon**

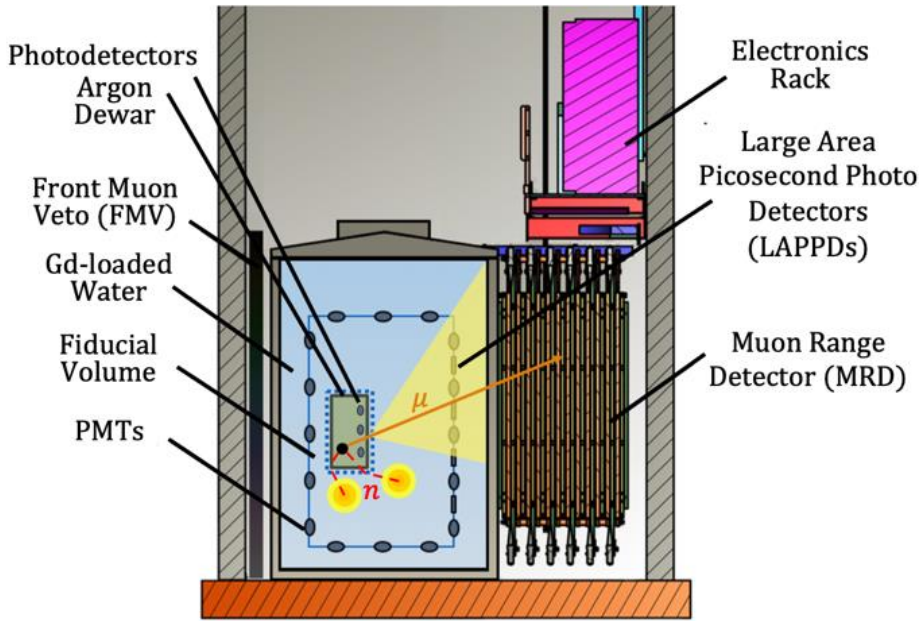
ArgoNeuT proton multiplicity (neutrino beam)

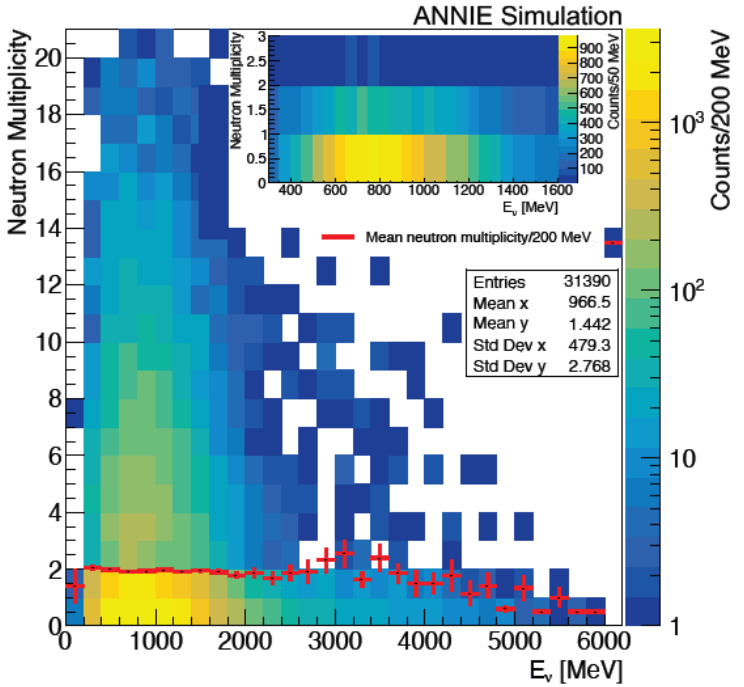




Neutron Production in Argon

- ANNIE will perform joint analysis with SBN to constrain the hadron production model for neutrino-argon interactions.
- Or, perhaps perform a direct neutron multiplicity measurement with argon target deployment 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 goals:**
  - Neutron multiplicity and Cross section measurements in water
  - Demonstrate enabling technologies: Gd-loaded water, fast-timing LAPPDs, WbLS
- **ANNIE main achievements:**
  - High statistic neutron multiplicity analysis with Gd-loaded water in a neutrino beam
  - First LAPPD test with neutrinos
  - First WbLS test with neutrinos
- **DUNE related:**
  - Joint cross section and hadron production analysis with SBN program
  - LAPPDs as candidate for ND-GAr
  - Demonstration of WbLS technology for DUNE far detector module
  - Potential neutron multiplicity measurement with an argon target
- Future talks about specific topics will be given

Backup

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