SOUTH DAKOTA MINES
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Physics Topics about the Neutrons in DUNE

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

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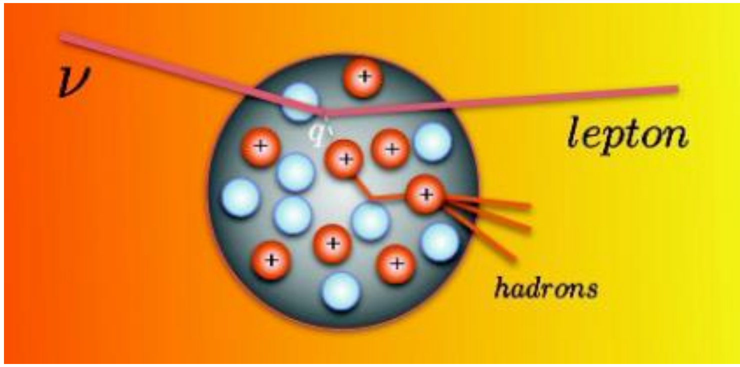
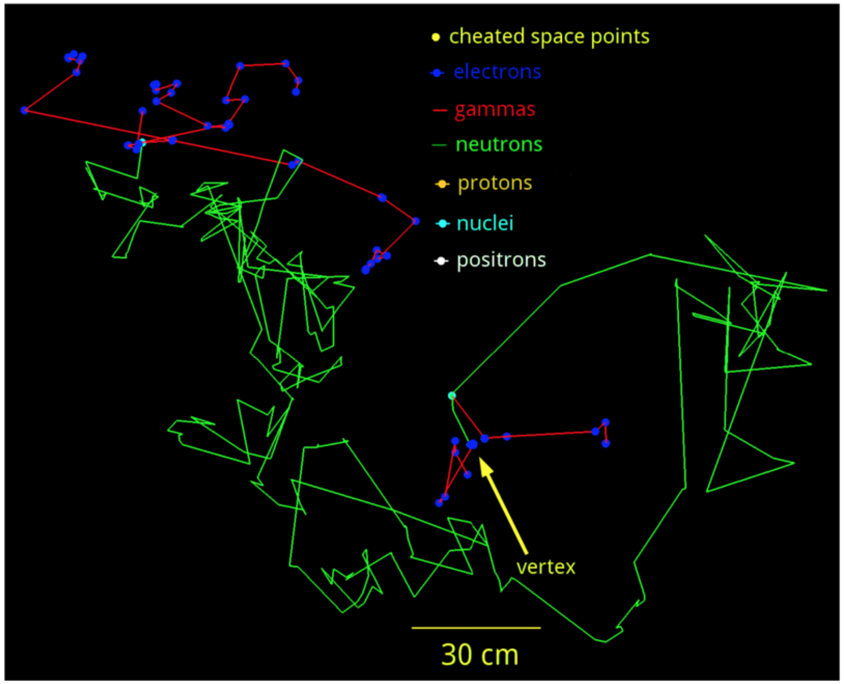
Pulsed Neutron Source Working Group Meeting

Neutrons are Important

- To turn neutrino physics into precision science, we must understand the neutrino-nucleus interactions
  - Neutrons carry away a large fraction of energy
  - Neutron yield is model dependent
  - Very hard to detect in liquid argon
- Understanding the neutrons are also important for low-energy physics
  - Part of the signals for supernova/solar neutrino event
  - Dominant background



Particle trajectories from a simulated SN event in DUNE



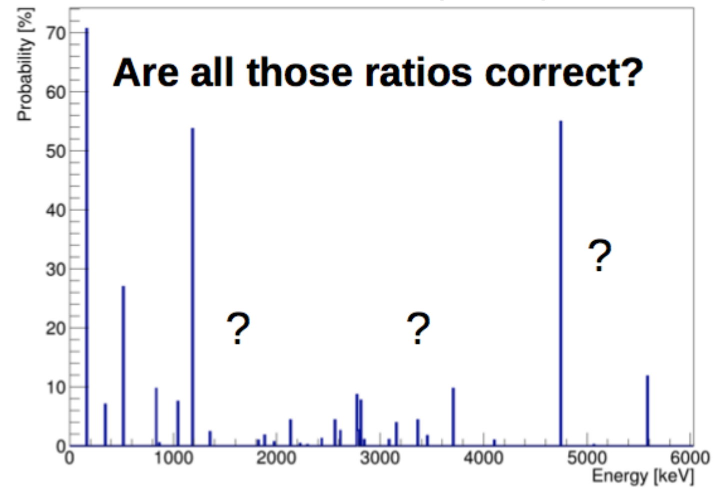
Neutron Cross Section Measurements

- **ACED (LANL):** Measured neutron capture cross sections at thermal energies
- **ARTIE-I (LANL)**: Measured neutron total cross section for 20-70 keV
- **ARTIE-II (LANL)**: Measure neutron total cross section from 0 to 200 keV; Proposal approved by LANL.
- **MArEX@n-TOF (CERN)**: Multiple experiments planned to measure neutron total cross section, neutron capture cross section from 0 to 500 MeV. LOI approved by CERN.
- **Near detector 2x2 Demonstrator**: inelastic cross sections at several hundred MeV
- **ProtoDUNE-I and II:** inelastic cross sections at several hundred MeV
- **Question: How are the neutron cross sections going to affect the physics simulation and data analysis?**

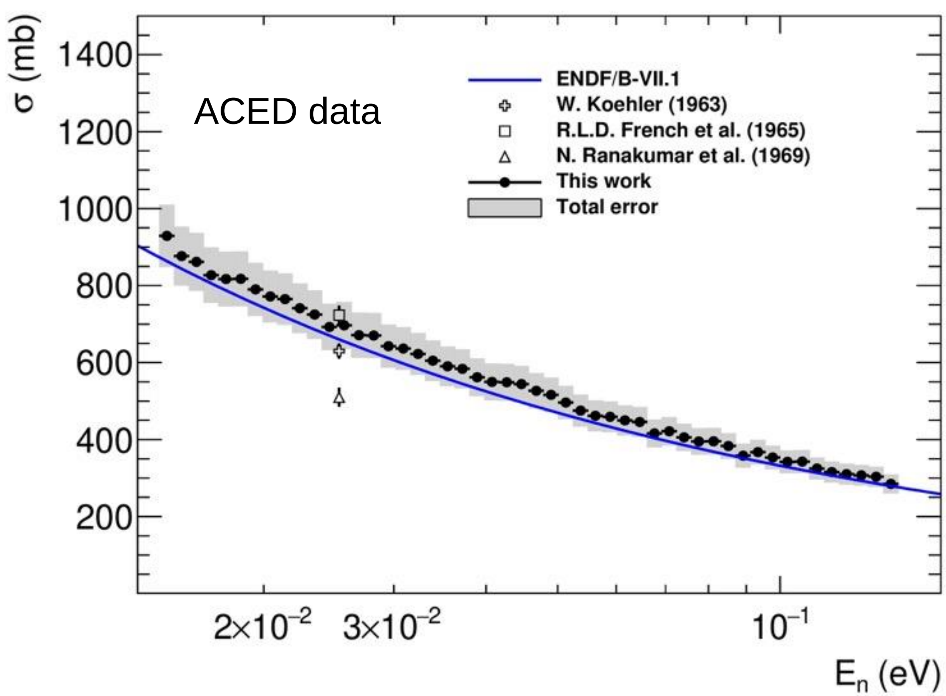
ACED Neutron Capture Result

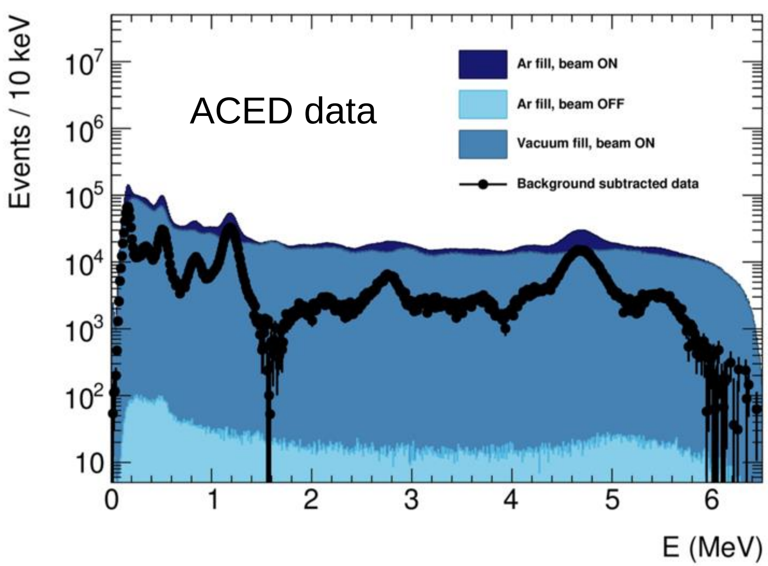
- ACED experiment measured capture cross sections at thermal energies
- Gamma cascade measured but data not analyzed

Gamma emitted after capture (from NNDC)



Phys. Rev. D 99, 103021 (2019)

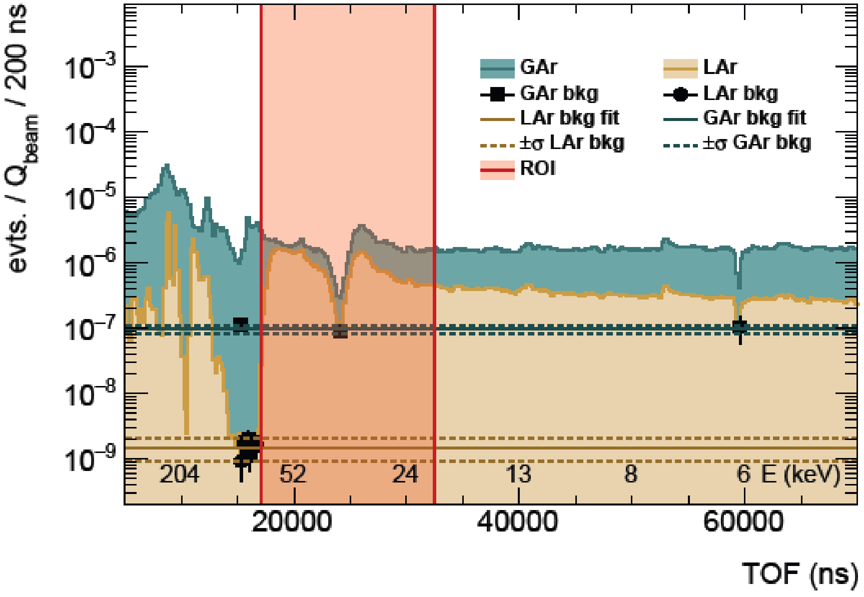




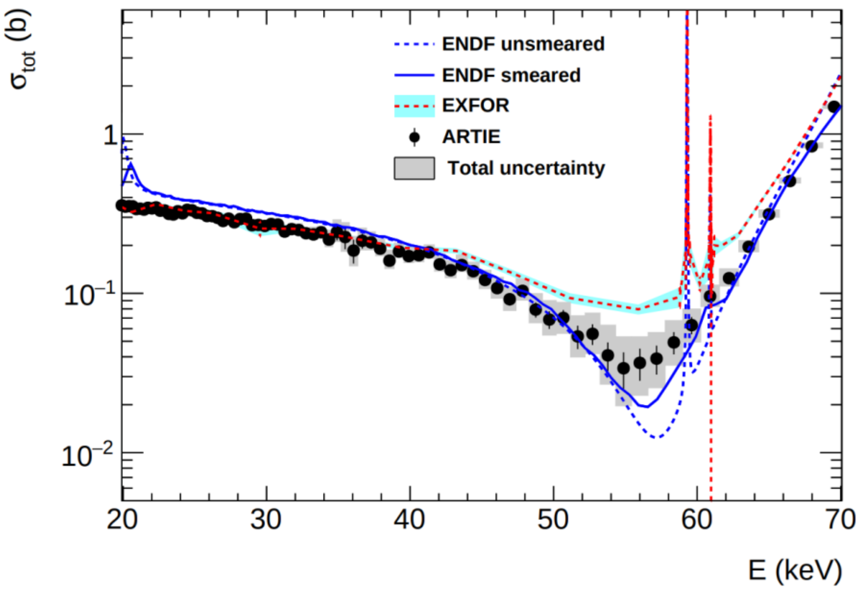
ARTIE Neutron Transmission Result

- ARTIE experiment confirmed the existence of the cross section dip around 57 keV
- Paper draft available on arXiv (https://arxiv.org/pdf/2212.05448.pdf)
- Submitted to PRC

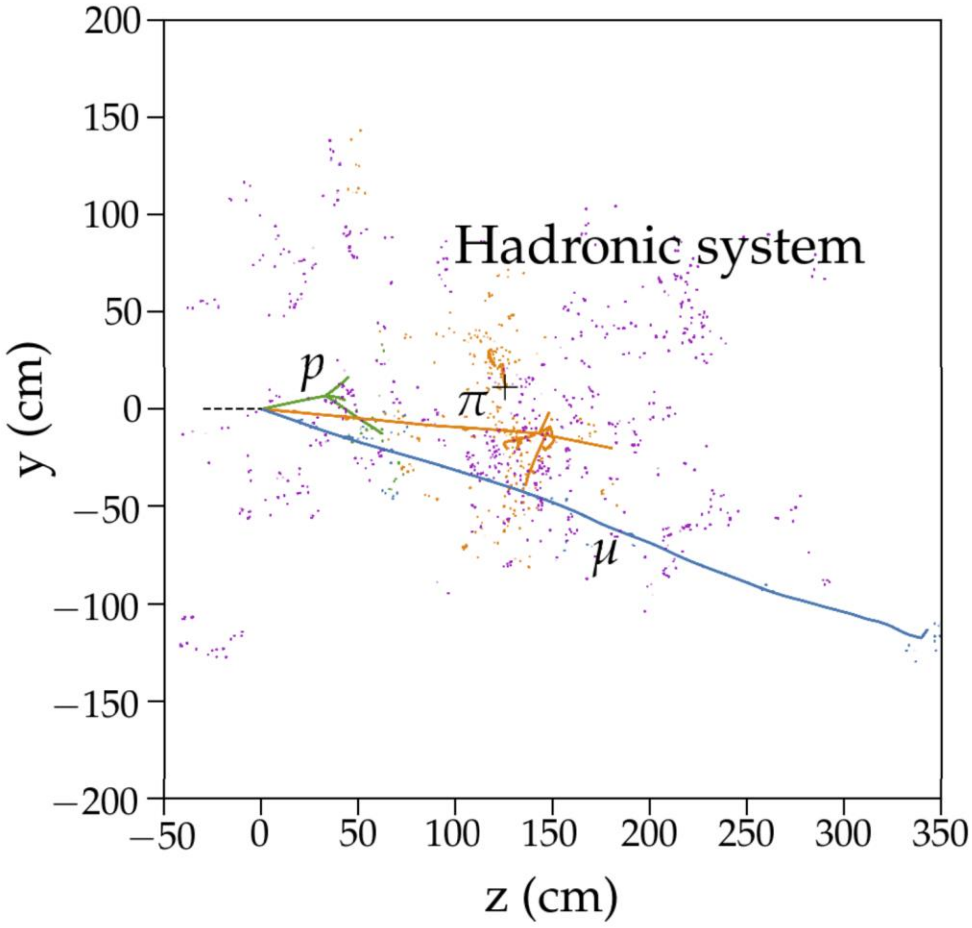
Background measurement using "black resonance" filters



ARTIE total cross section result



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

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

Missing Energy Problem

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

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

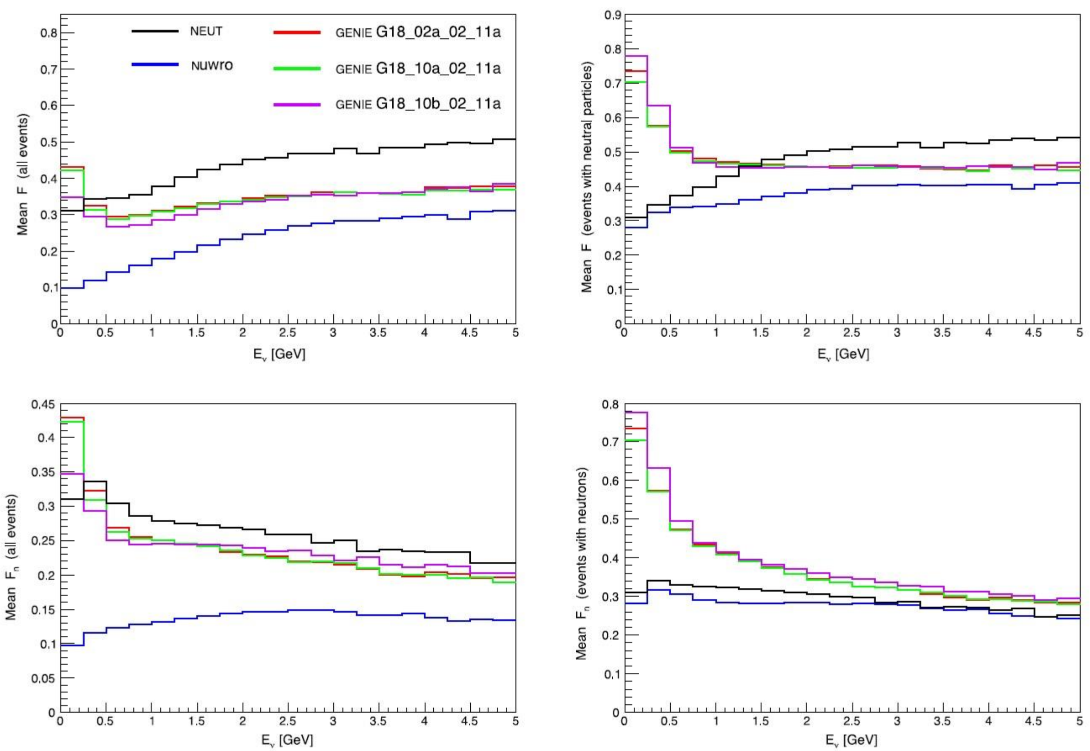


FIG. 37. Mean fraction of the leptonic energy transfer imparted to final-state neutral particle species. All panels show distributions calculated for charged-current ν_μ interactions on ^{40}Ar. Top left: Predictions including all neutral particles and all events in the sample. Top right: Predictions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

Neutron Multiplicity Simulations

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

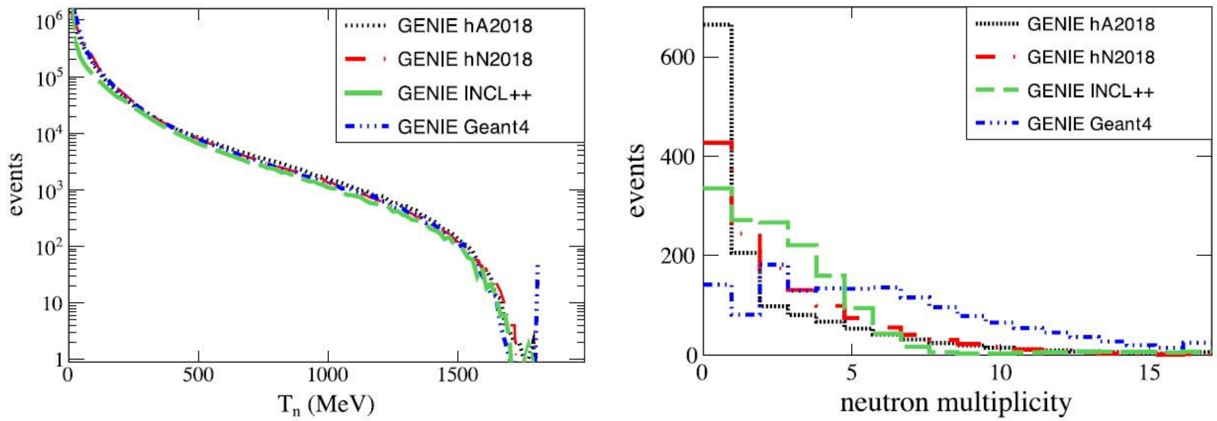


Fig. 8 Neutron distributions from a simulation of 2 GeV ν_μ ^{40}Ar, kinetic energy (left) and multiplicity (right). In each case, results from all 4 models described in the text are shown

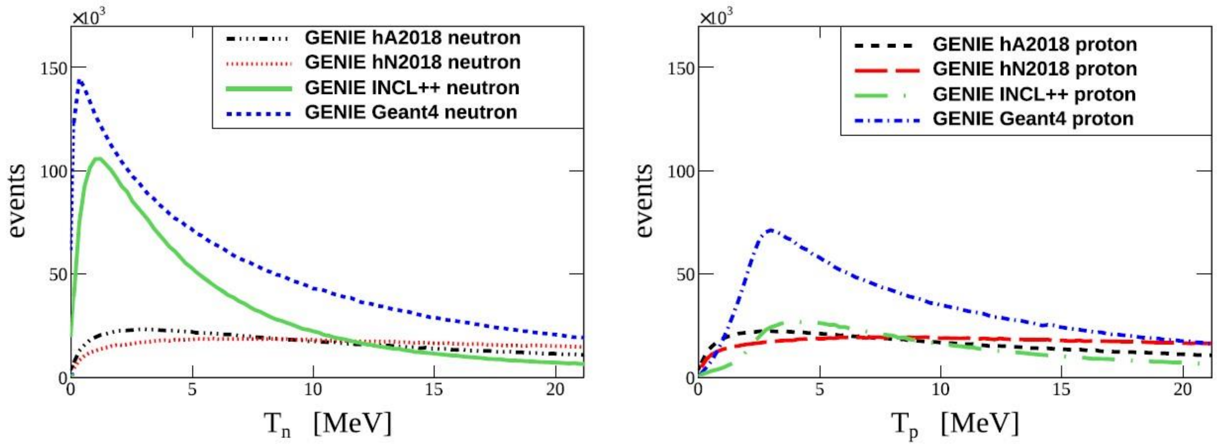
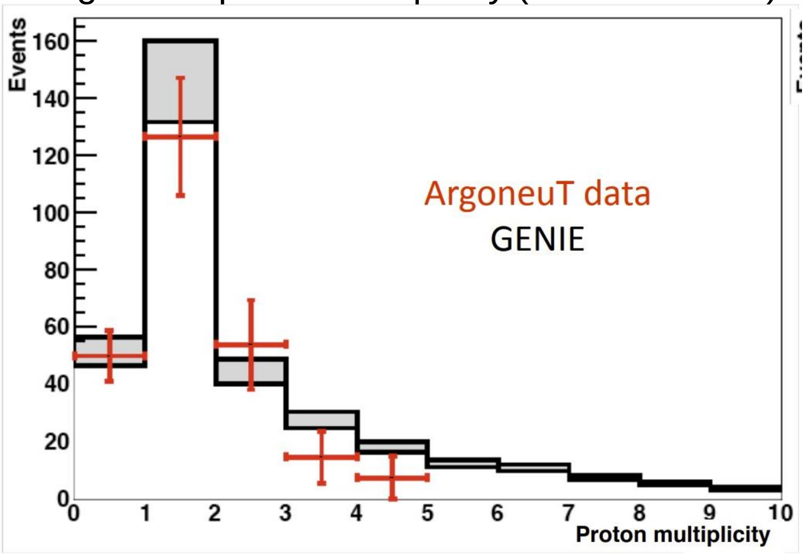


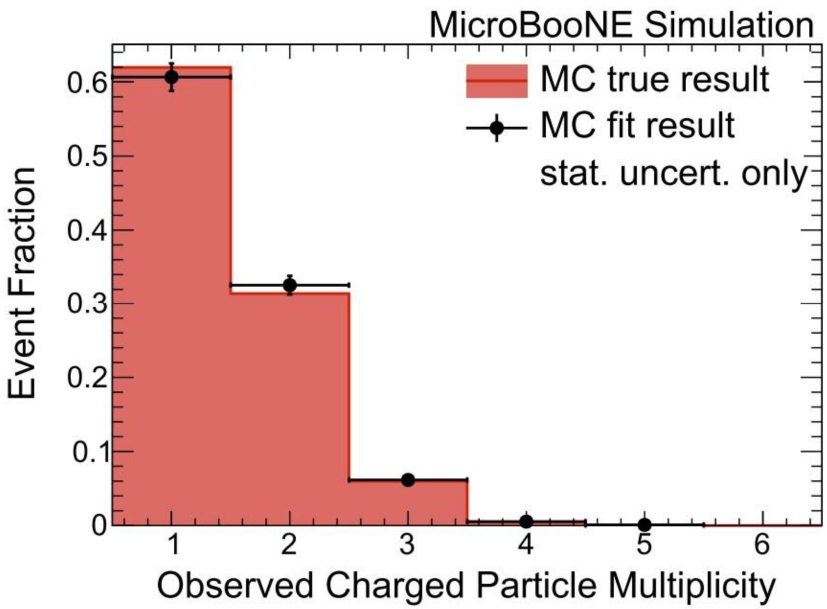
Fig. 9 Left: Neutron (left) and proton (right) kinetic energy distributions from a simulation of 2 GeV ν_μ ^{40}Ar focusing on low energy responses, in each case, results from all 4 models described in the text are shown. Results from INCL++ and Geant4 models described in the text are shown

Existing Measurements

- 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

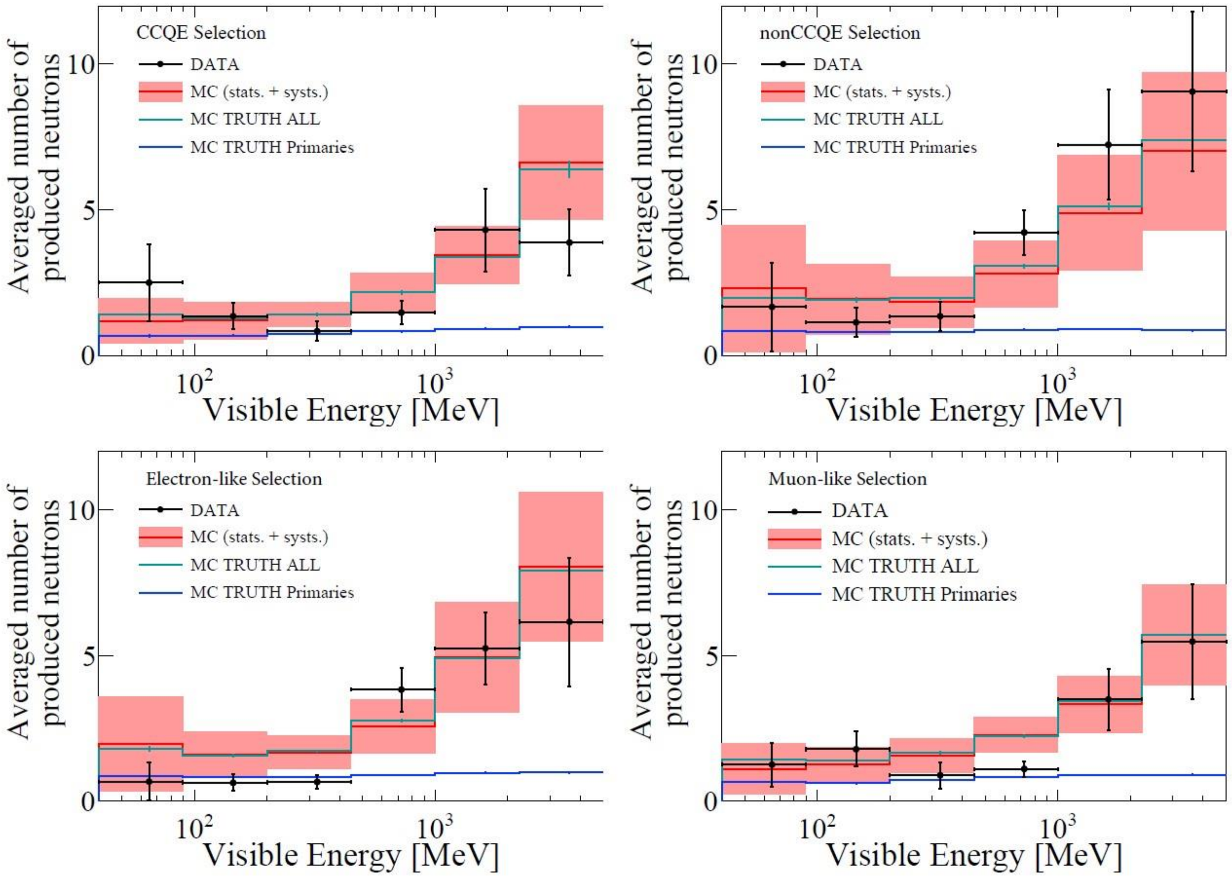


FIG. 15. Averaged number of produced neutrons vs visible energy for both phases together. We show the different selections: CCQE (top left), nonCCQE (top right), electronlike (bottom left) and muonlike (bottom right). The points represent data with statistical uncertainties. The reconstructed MC is shown 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

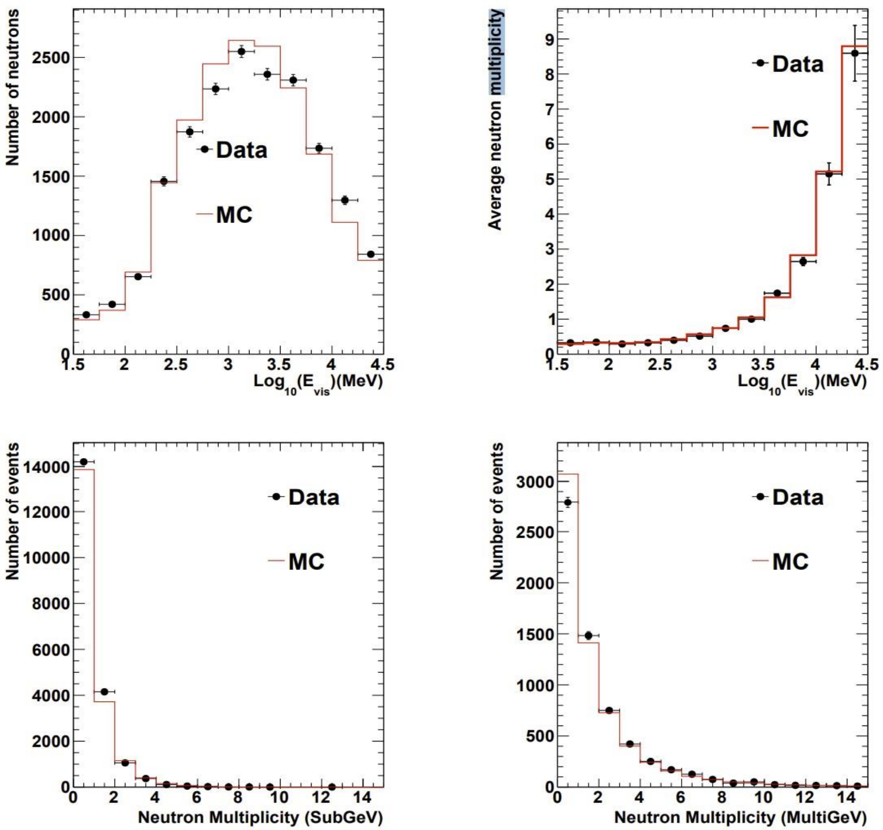


Figure 13. Comparison of data and MC for tagged neutrons in the SK-IV atmospheric neutrino data. The top left (right) plot shows the total number of neutrons (average neutron multiplicity) as a function of visible energy (E_{vis}). The bottom left plot shows the neutron multiplicity for sub-GeV events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

K. Abe et al 2022 JINST 17 P10029

Minerva Measurement

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

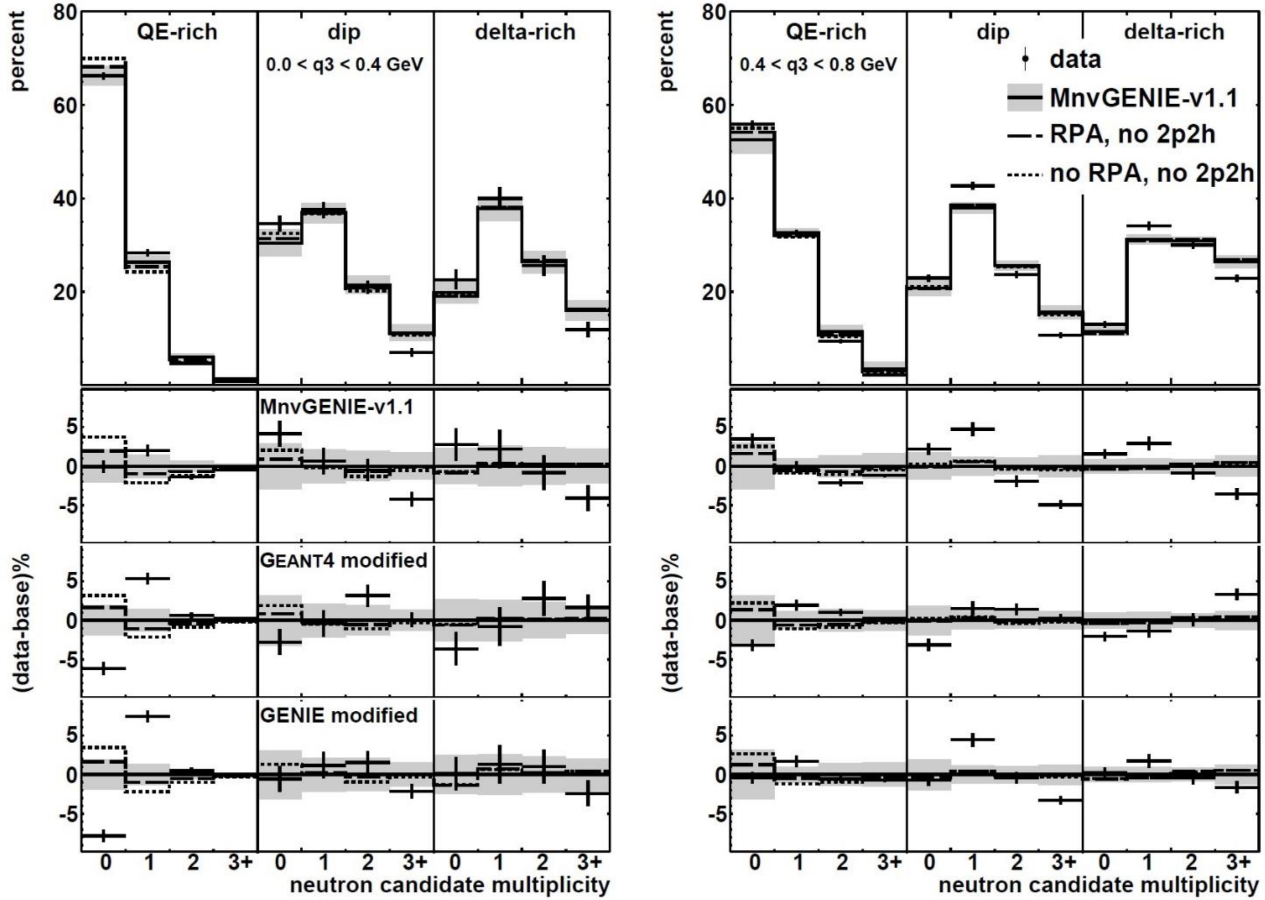


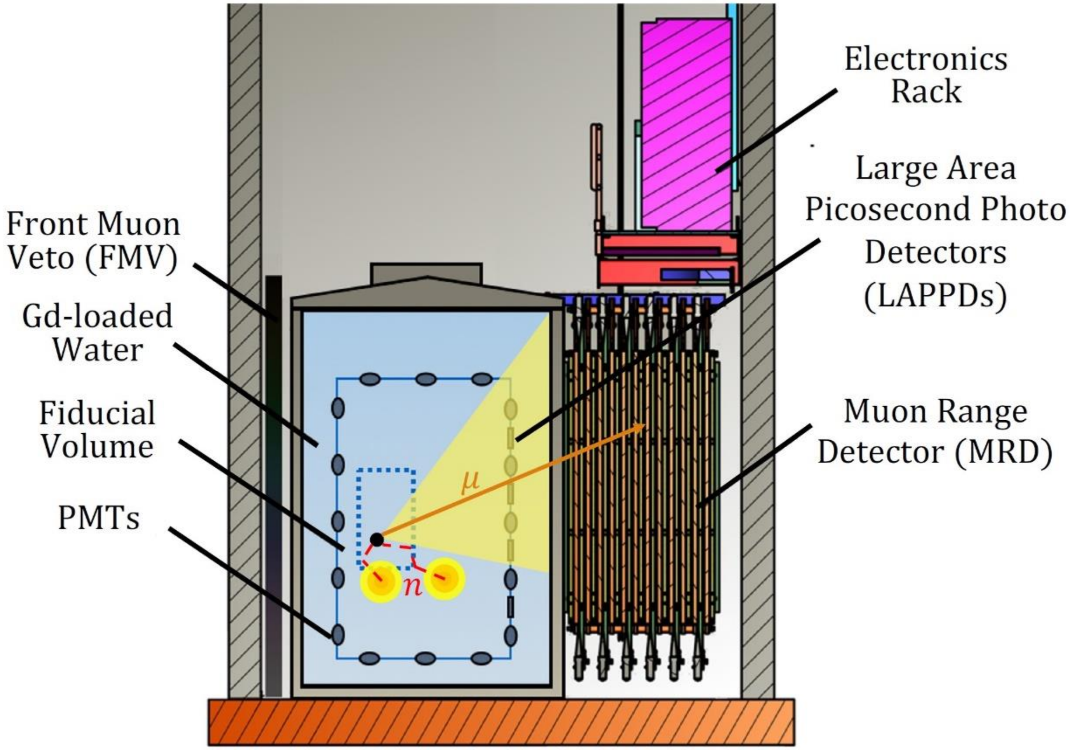
FIG. 10: Candidate multiplicity distribution for all six subsamples, $0 < q_3 < 0.4$ (left) and $0.4 < q_3 < 0.8$ GeV/c (right), with subpanels for the QE-rich, dip, and Δ-rich regions. The top plot shows the reference MnvGENIE-v1.1 simulation with a solid line and error band, and two variations that 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.

Possible to measure in ANNIE?

- Accelerator Neutrino Neutron Interaction Experiment (ANNIE) is a 26 ton Gd-loaded water detector at the BNB beam

- Possible to deploy an argon target
  - Vacuum-insulated liquid argon target, or
  - High-pressure gaseous argon target at the fiducial volume location
- Need small-size photodetectors inside the target to trigger.
- Neutrons can go through the target to get captured by Gd-water
- Neutrons are counted by existing ANNIE detector

ANNIE Detector Layout



Interesting Topics to Discuss

- Measure total/inelastic/capture cross sections over all energy ranges through many experiments
- Recover missing energy by measuring the neutron activities
- Identify neutrino beam wrong sign contamination by counting neutrons
- Test/model the light response from neutron interactions in argon
- Test supernova trigger efficiency with the PNS runs.
- Test neutron capture identification on different materials with PNS data at ProtoDUNE
- Test supernova/solar neutrino event selection algorithms with PNS data at ProtoDUNE
- Perform muon capture analysis in existing liquid argon TPCs or propose new experiments.
- …