Feasibility Study For Neutrino-Argon Interaction Measurement in ANNIE

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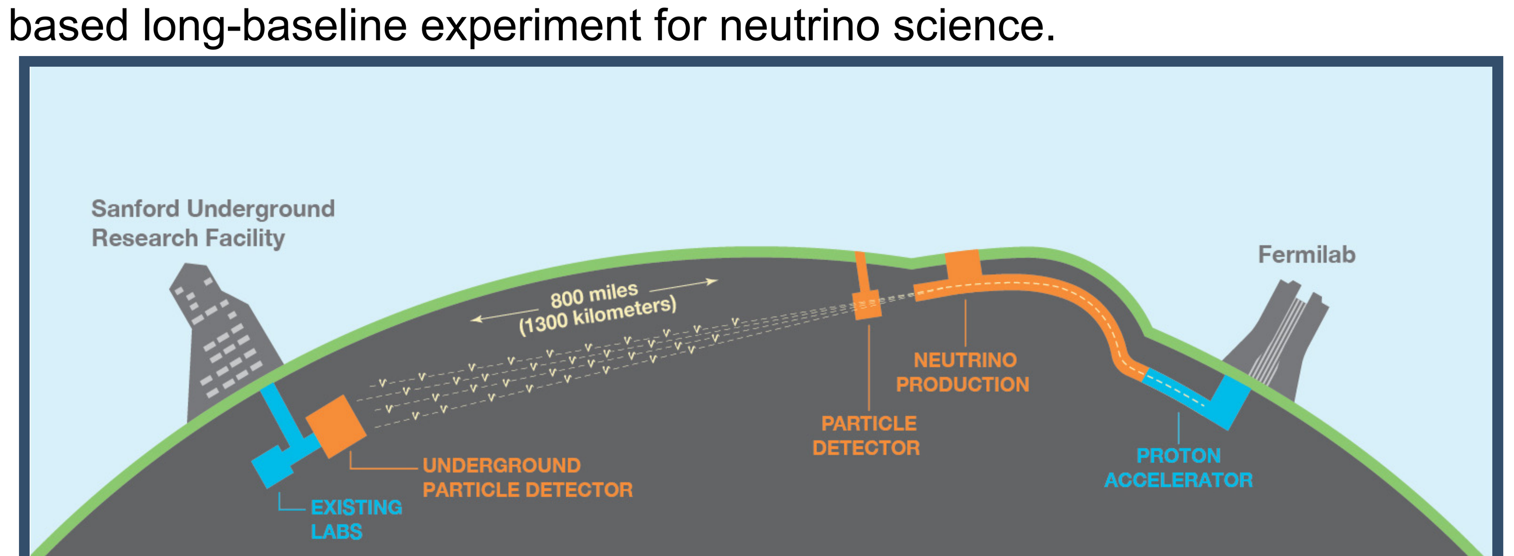
Abstract

The Deep Underground Neutrino Experiment (DUNE) aims to measure the neutrino CP-violating phase and determine the mass ordering, using the Liquid Argon Time Projection Chamber (LArTPC) technology. These measurements rely on the precise reconstruction of the incoming neutrino energy. However, the nuclear effects on neutrino-nucleus interactions are not well understood in argon, which could affect the precision of the experiment. Of particular interest, the measurement of the number of final-state neutrons from neutrino interactions can help constrain the theoretical neutrino-nucleus interaction models. To study neutrino-argon interactions, we propose to use the currently existing Accelerator Neutrino Neutron Interaction Experiment (ANNIE) at the Booster Neutrino Beam (BNB) at Fermilab. ANNIE is currently a water-based neutrino detector but can be modified to study neutrino-argon interactions such as those in DUNE. A feasible experimental strategy is to deploy a liquid argon target at ANNIE's fiducial volume location.

Motivation

The Deep Underground Neutrino Experiment (DUNE) is an upcoming US-based long-baseline experiment for neutrino science.



DUNE is the flagship experiment of the Department of Energy. It will send a neutrino beam from Fermilab in Illinois to Sanford Underground Research Facility in South Dakota [1]

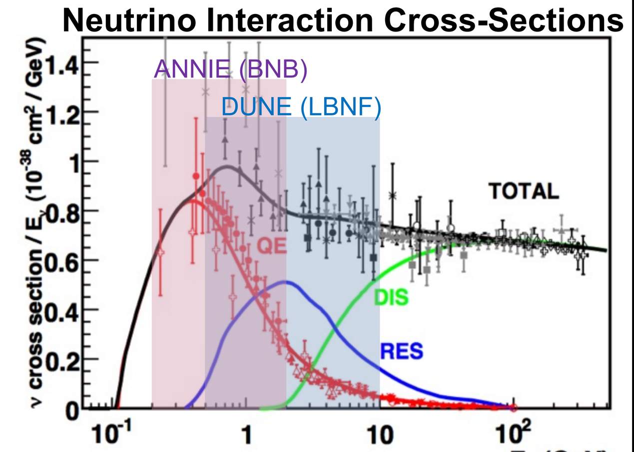
- To turn neutrino physics into a precision science, we need to understand the complex neutrino-nucleus interaction
  - Dominant source of uncertainty on energy reconstruction
  - Neutrino-nucleus interaction is hard to model
  - Need comprehensive measurements of number of final-state neutrons/ protons for a variety of materials, and neutrino energy (E_ν)
- Measurement of final-state neutrons can help constrain the theoretical neutrino-nucleus interaction models, but neutrons are quite elusive in most large-scale detectors
- A small-scale experiment measuring neutrons from neutrino-argon interactions in a well-known neutrino beam is needed

Introduction to Neutrino Interactions

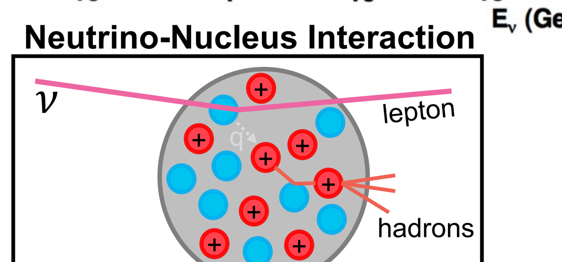
Modes of neutrino interactions with nucleons:

- Quasi-elastic scattering (QE)
  - No neutrons produced
  - E_ν can be calculated analytically
- Resonant pion production (RES)
  - A resonant delta baryon is produced which decays into other particles
  - Neutron could be produced
- Deep inelastic scattering (DIS)
  - E_ν is very high
  - Interaction knocks off a quark
  - The knock-off quark can further interact to produce a hadronic shower
  - Multiple neutrons produced

Neutrino Interaction Cross-Sections



Neutrino-Nucleus Interaction



How can ANNIE help?

ANNIE: Accelerator Neutrino Neutron Interaction Experiment [2]

- 26-ton gadolinium-loaded water Cherenkov detector placed downstream of the Booster Neutrino Beam (BNB) at Fermilab
- Measure the number of final-state neutrons from neutrino-nucleus interactions in water
- Demonstrate the use of Gd-loaded water and fast-timing LAPPD photodetectors

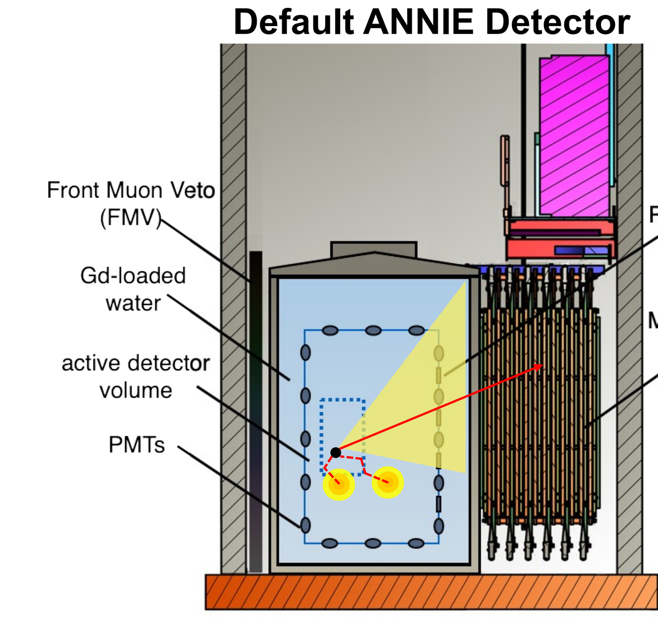
How does ANNIE work?

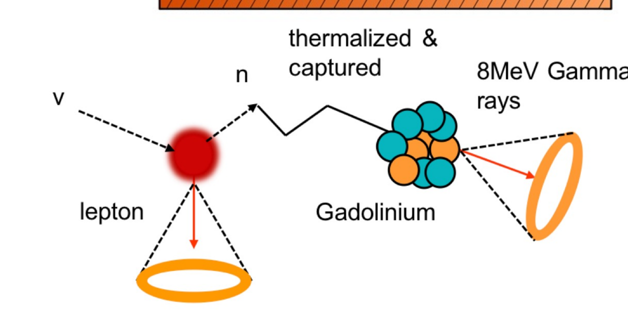
- Muon neutrino from BNB interacts with nucleus in target volume and stops in MRD
- Neutrons produced (if any) are captured in gadolinium producing Cherenkov light
- Using MRD and photodetector data, the energy and final-state neutrons can be reconstructed

ANNIE detector can be modified to study neutrino-argon interactions

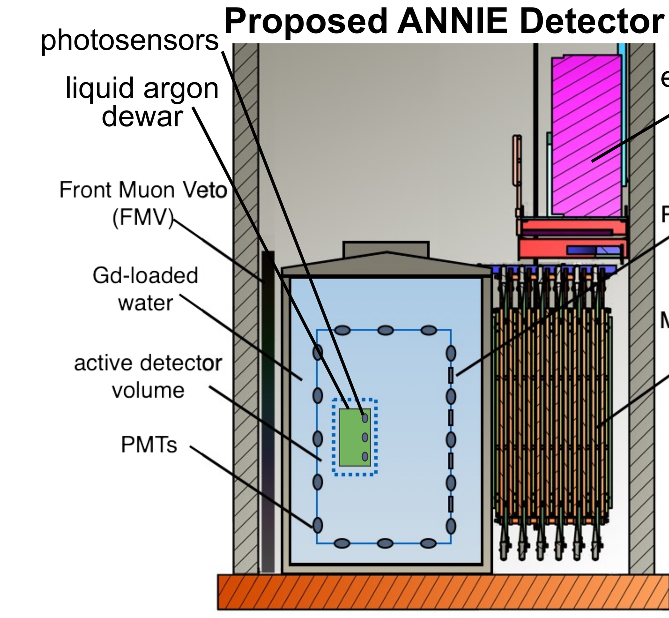
- Add a small liquid argon target into the fiducial volume
- Install photodetectors inside the target which will be used to identify neutron interactions in target
- Leptons and neutrons can be reconstructed using the existing ANNIE infrastructure

Default ANNIE Detector





Proposed ANNIE Detector



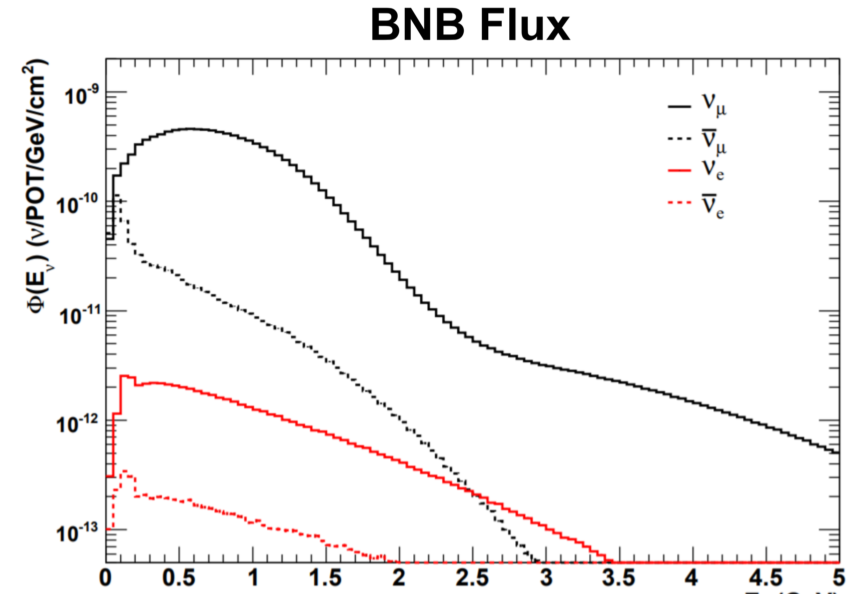
Simulation of Neutrino-Argon Interactions

GENIE [3], which stands for Generates Events for Neutrino Interaction Experiments, is a Monte Carlo event generator that is used by nearly all modern neutrino experiments. GENIE's predictions serve as standard reference points for the neutrino community.

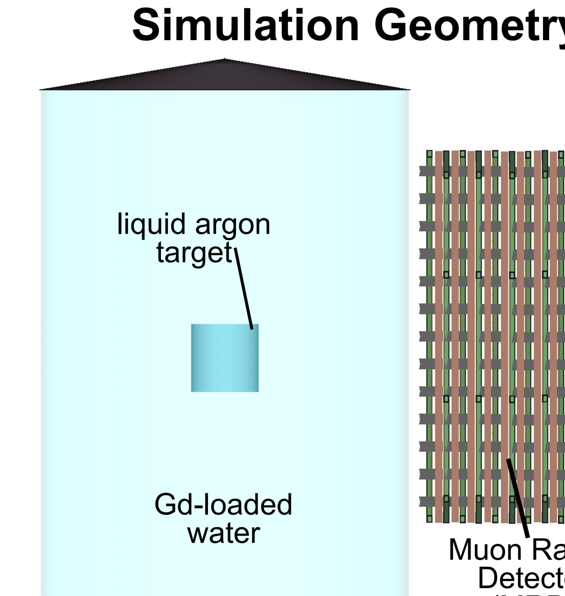
GENIE Generator parameters:

- **GEOMETRY** is modified by adding a cylindrical liquid argon volume at the center of the ANNIE water tank
- **TOP VOLUME** is defined as the added liquid argon volume
- **FLUX FILES** are pre-simulated for the BNB neutrino beam at Fermilab
- **CROSS-SECTIONS** (xsec) are from precomputed data files. The xsec file contains approximations for different types of interactions between multiple neutrino flavors and isotopes, and at many energies
- **TUNE** specifies the comprehensive model configuration the generator will use. The preliminary results used G18_10a_02_11a

BNB Flux



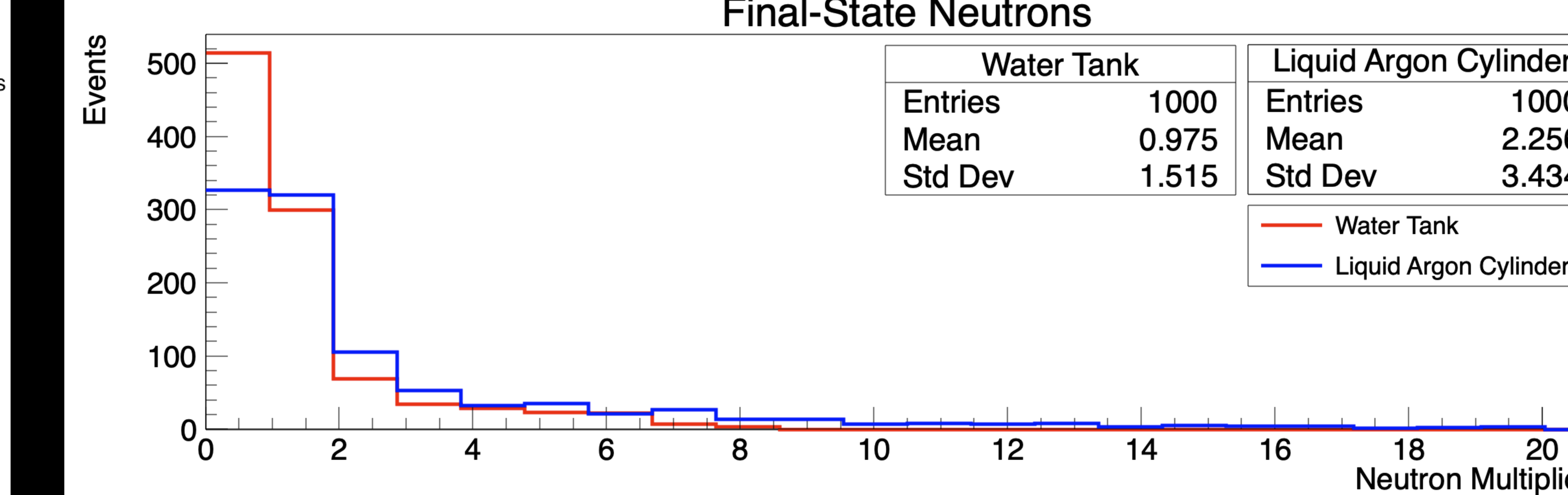
Simulation Geometry



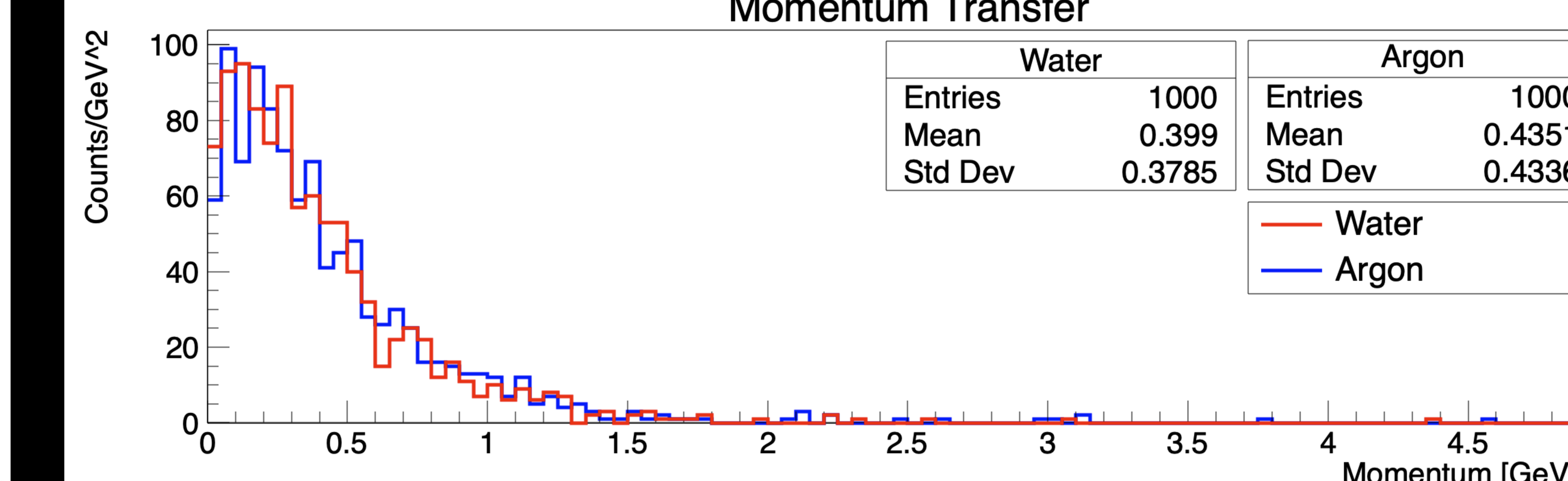
First Simulation Results

GENIE Generator simulated 1000 neutrino-argon interactions in ANNIE's main water tank and proposed liquid argon target. The following are **preliminary** results:

Final-State Neutrons



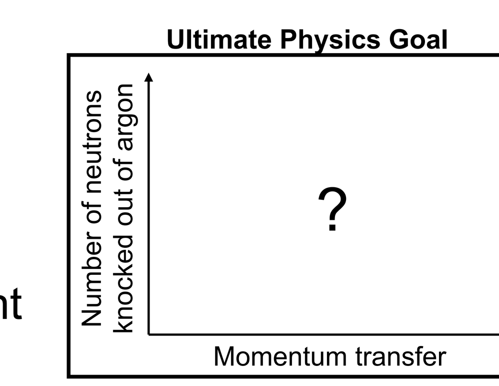
Momentum Transfer



Future Work

- Perform simulations on other well-measured targets to verify the preliminary results for liquid argon target
- Modify the ANNIE detector geometry used for GENIE Generator simulations to more closely represent the realistic experimental conditions:
  - Add an actual liquid argon dewar
  - Add photodetectors into the dewar
  - Optimize the size and location of the target
- Use ANNIE's official simulation software WCSim/RATPAC to propagate final-state particles to obtain detector responses
- Run default ANNIE event reconstruction to count the number of neutrons and reconstruct the lepton kinematics

Ultimate Physics Goal



Summary

- Measuring the number of final-state neutrons from neutrino-argon interactions could help constrain the neutrino-nucleus interaction models, thus improving the energy reconstruction precision in DUNE
- Existing ANNIE detector can be modified to study neutrino-argon interactions by adding a liquid argon target into the water tank
- The first GENIE Generator simulation has been preformed, and more work is underway

References

[1] http://www.dunescience.org
[2] A. Back et al., arXiv preprint arXiv:1707.08222, 2017.
[3] http://www.genie-mc.org

Acknowledgements

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