Semester Report – 1st Semester

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PhD Thesis Title:
Measurements of Neutrino Charged-Current Interactions
in Liquid Argon Using a Multi-GeV Neutrino Beam

1. Introduction

Neutrinos are fundamental, electrically neutral, and exceedingly light particles that primarily interact via the *weak interaction*. Their non-zero masses, confirmed by observations of neutrino oscillations at experiments such as Super-Kamiokande and the Sudbury Neutrino Observatory [1, 2], provide direct evidence of physics beyond the Standard Model. Understanding neutrinos' properties and interactions remains a major goal in modern particle physics.

The Deep Underground Neutrino Experiment (DUNE) aims to precisely measure neutrino oscillation parameters, investigate leptonic CP violation, and search for physics beyond the Standard Model. Its near detector (ND) complex will play a pivotal role in reducing systematic uncertainties related to neutrino flux predictions and cross-section measurements.

Within the DUNE ND, the **ND 2×2** is a technology demonstrator for ND-LAr, which is a modular liquid-argon time projection chamber (LArTPC) that serves as the near detector for DUNE, the **ND 2×2** is the first DUNE detector receiving ν beams, and it will provide $\nu - Ar$ measurements. Accurate flux predictions are essential for quantifying cross sections and reducing key uncertainties in these measurements.One strategy to validate the flux modeling tools that will be used for DUNE **ND 2×2** is not only to produce MINERvA flux—the measured energy distribution of neutrinos at the MINERvA detector but also to improve with available external hadron production data (NA61). In particular, the dk2nu ntuples, which store detailed neutrino production information, and the PPFX (Package to Predict the Flux) framework, which reweights the simulated flux using external hadron-production data, form the foundation for this approach [3], [4]. This semester, my work centered on setting up PPFX and dk2nu within Fermilab's computing environment, retrieving the relevant MINERvA Geant4 based flux simulation samples, and reproducing the MINERvA flux distributions as a validation exercise. Achieving consistency with MINERvA's known flux results confirm that the tools and workflows function correctly. The successful reproduction of MINERvA's flux thus provides a reliable starting point for generating precise flux predictions for the DUNE ND 2×2 detector. The reason for emphasizing the MINERvA flux is the DUNE **ND 2×2** is running at the NuMI beamline where MINERvA experiment used to be.

2. Description of Research in the Current Semester

2.1 Accessing `dk2nu` Ntuples

I accessed `dk2nu` ntuples from Fermilab's servers, which reflect the NuMI beamline configuration [5]. Documentation on these ntuples can be found in [3].

2.2 Setting up the PPFX Framework

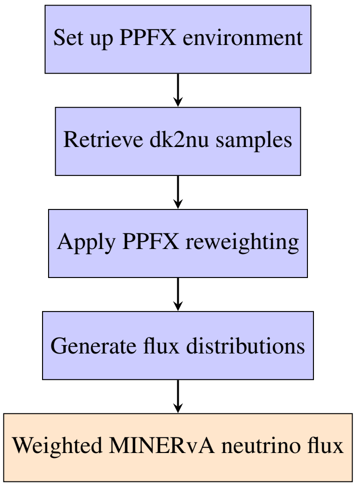
The PPFX framework applies external hadron-production data to reweight the raw flux predictions from dk2nu. More detailed discussions of PPFX and its role in MINERvA flux predictions can be found in Refs. [6], [7]. This semester, I focused on the Geant4 10.4-compatible PPFX branch [8].

2.3 Reproducing the MINERvA flux

To confirm that PPFX works correctly on modern computing systems:

1. I installed PPFX on Fermilab nodes and loaded Geant4 10.4 environments.
2. Retrieved the MINERvA `dk2nu` samples.
3. Ran the PPFX reweight procedure and produced flux distributions.

All of these is shown clearly in the following flowchart:



Figures 1 and 2 illustrate the neutrino energy spectra for MINERvA, showing good agreement with known results [9], especially ν_μ, $\bar{\nu}_\mu$.

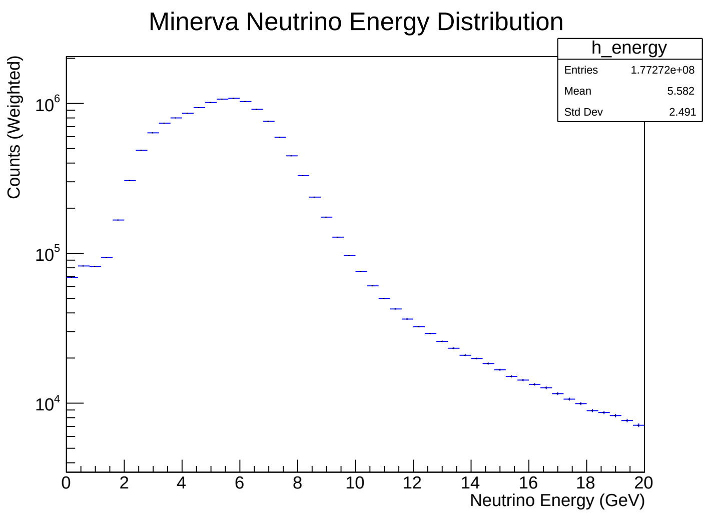


Figure 1: MINERvA neutrino energy distribution. Mean ≈ 5.58 GeV, Std. Dev. ≈ 2.49 GeV.

2.4 Conclusion and Next Steps

By reproducing the MINERvA flux distributions from existing dk2nu ntuples via PPFX, I have validated the core software setup and gained familiarity with essential reweighting methodologies. These achievements form a strong basis for upcoming work:

1. Improving systematic uncertainties using NA61 hadron production data.
2. Extending the setup to produce flux predictions for the DUNE ND 2×2 detector.

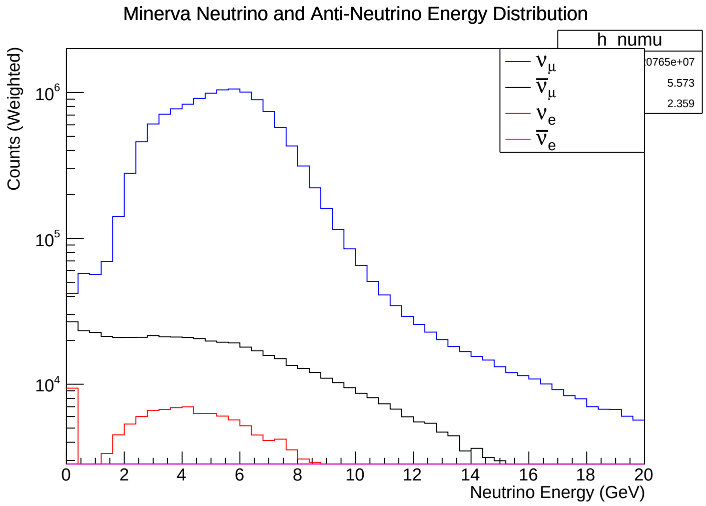


Figure 2: Neutrino and anti-neutrino energy distribution (NuMI). Mean ≈ 5.57 GeV, Std. Dev. ≈ 2.36 GeV.

3. Studies in Current Semester

- **FIZ/2/022: Experimental Methods of Nuclear Physics.**
- **FIZ/2/083E: Quantum Chromodynamics.**
- **FIZ/2/117: Selected Chapters from Experimental High-Energy Physics.**

4. Conferences in Current Semester

Joint ND Prototypes + Sim/Reco Workshop
Dates: January 24–25, 2025, CERN (Geneva, Switzerland)
Purpose: Focuses on the development and simulation of near-detector prototypes essential to DUNE's experimental setup.
Personal Goal: To gain insights from experts and familiarize myself with the concepts and methodologies discussed at the workshop.

DUNE Collaboration Meeting
Dates: January 27–31, 2025, CERN (Geneva, Switzerland)
Purpose: Gathers DUNE collaborators to discuss progress, coordinate efforts, and plan future activities.
Personal Goal: To network effectively with collaborators, with a particular focus on connecting with young scientists, including fellow PhD students.

LArSoft Workshop
Dates: February 3–7, 2025, CERN (Geneva, Switzerland)
Purpose: Provides training and updates on LArSoft, the software toolkit for liquid argon TPC experiments.
Personal Goal: To strengthen and expand my knowledge of LArSoft, ensuring its effective application in my future research.

References

[1] Y. Fukuda et al. Evidence for oscillation of atmospheric neutrinos. *Physical Review Letters*, 81:1562–1567, 1998.

[2] A. W. P. Poon. Neutrino observations from the sudbury neutrino observatory. *AIP Conference Proceedings*, 631:31–42, 2002.

[3] MINERvA Collaboration. Flux ntuple. Technical report, Fermilab Indico, 2012. Event #5499, Session #9700.

[4] DUNE Collaboration. DUNE for PPFX. Technical report, Fermilab Indico, 2016. Event #12458.

[5] Ralf-Hendrik Menk, Archana Sharma, Andrea Vacchi, Hans Juergen Besch, and Albert Walenta. Nuclear instruments and methods in physics research, section a: Accelerators, spectrometers, detectors and associated. 2003.

[6] MINERvA Collaboration. *Measurement of the Neutrino and Antineutrino Energy Dependent Cross Sections on Carbon Using the NuMI Beam and the MINERvA Detector*. PhD thesis, Fermilab, 2016.

[7] L. Aliaga and others [MINERvA Collaboration]. Neutrino flux predictions for the numi beam. *Physical Review D*, 94(9):092005, 2016.

[8] N. Nayak. PPFX for Geant4 10.4, 2025. Accessed January 2025.

[9] S. Henry et al. Measurement of electron neutrino and antineutrino cross sections at low momentum transfer. *Physical Review D*, 109(9):092008, 2024.