Semester Report – 3nd 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

Building upon the foundation established in previous semesters, where the NuMI on-axis flux prediction was reproduced and systematic uncertainties were characterized using the Package to Predict the Flux (PPFX) [1] with a 100 universe approach for systematic error variations, this semester's work focused on developing a unified PPFX framework that integrates recent improvements from multiple collaborators. The PPFX provides data driven corrections to hadron production uncertainties, but different experiments have developed independent versions optimized for their specific needs. Maintaining separate versions leads to duplicated effort, inconsistent systematic treatments, and difficulty comparing results across experiments.
The primary goal this semester was to merge two key PPFX developments: (1) the MicroBooNE version, which provides Geant4.10.4 compatibility for modern DUNE flux simulations, and (2) the NOvA version, which incorporates NA61/SHINE hadron production data with improved numerical methods. Successfully integrating these versions will reduce neutrino flux systematic uncertainties for the DUNE ND 2×2 detector and establish a unified framework applicable to multiple experiments.

2. Description of Research in the Current Semester

2.1 Motivation for PPFX Unification

PPFX corrects simulated neutrino flux predictions by reweighting hadron production based on external experimental measurements. Different versions of PPFX have been developed independently: the MicroBooNE version ensures compatibility with Geant4.10.4 simulations used for current flux ntuples, while the NOvA version incorporates measurements from NA61/SHINE [2], a fixed target experiment at the CERN Super Proton Synchrotron that measures hadron production cross sections relevant for neutrino flux predictions. Specifically, the NA61/SHINE collaboration has published measurements of π^++C interactions at 60 GeV,[3] which directly constrain secondary hadron production in the NuMI beamline. Integrating these versions is both necessary and beneficial: the NA61 60 GeV pion data improves flux predictions for any experiment where this energy range is relevant, which includes the DUNE ND 2×2.

2.2 Technical Integration Work

The integration required modifications across multiple components of the PPFX and the analysis framework.

Adding NA61 output branches: To access the new reweighting information, the output structure was extended to include dedicated variables for the NA61 based reweighter, storing both central values and universe variations for downstream uncertainty analysis.
Integrating the NA61 reweighter: The NOvA version introduced a dedicated reweighter that applies NA61 data specifically to π^++C interactions. To avoid double counting, the π^+ incident channels were carefully partitioned: the NA61 reweighter handles π^+ interactions producing π^+, π^-, K^+, K^-, K^0_S, Λ^0 and protons, while the general meson incident reweighter retains K^0_L and neutron production channels, as well as all other meson incident channels. This separation was validated by confirming that the product of individual component weights equals the total PPFX weight, ensuring no overlap or missing coverage.
SVD decomposition for covariance matrices: The NOvA version replaced Cholesky decomposition [4] with Singular Value Decomposition (SVD) [5] for generating correlated systematic error variations from the hadron production covariance matrices. This change was necessary because Cholesky decomposition failed for the NA61 60 GeV pion data covariance matrix, which was not strictly positive definite. SVD provides a more numerically stable approach that can handle such matrices.

2.3 Fractional Uncertainty Analysis

A ROOT analysis macro was developed to evaluate the impact of the integrated NA61 reweighter on flux uncertainties. The macro automatically detects whether NA61 branches are present in the input files and computes fractional uncertainties for both individual systematic components and combined effects. Since the two reweighters cover disjoint sets of interactions, their weights can be treated independently.
To evaluate the combined meson-related uncertainty, the analysis first removes both meson incident $w_{\textbf{mesonic}}$ and (π^+C$\rightarrow$ π^+X) w_{pipcpip} contributions from the total weight to obtain a base weight:

$$w_{\text{base}} = w_{\text{total}} \times \frac{w_{\text{ppfx}}}{w_{\text{mesoninc}} \times w_{\text{pipcpip}}} \tag{1}$$

Systematic error variations are then computed by multiplying this base weight with the corresponding systematic error weights from both reweighters. The RMS spread of these variations quantifies how the two reweighters, which handle disjoint regions of phase space, contribute to the total systematic uncertainty.

2.4 Current Status and Ongoing Investigation

After integrating the NA61 reweighter, the unified PPFX version shows improvement in the meson incident component compared to versions without NA61 constraints. However, the total flux uncertainty remains somewhat higher than the standalone MicroBooNE version, which is under investigation 1. Possible explanations include: (1) legitimate propagation of NA61 measurement uncertainties through the covariance matrix, (2) differences in the Feynman x_F binning schemes between versions, where the NOvA version uses 4 bins covering only positive x_F (0 to 1), while the MicroBooNE version uses 8 bins covering the full x_F range (-1 to 1), leading to different NucleonA uncertainty contributions, and (3) edge effects at the boundaries of NA61 phase space coverage. Further consultation with collaborators is planned to understand the expected uncertainty reduction and to determine the optimal binning scheme for the unified framework.

2.5 Summary and Outlook

This semester established the technical foundation for a unified PPFX framework combining Geant4.10.4 compatibility with NA61/SHINE hadron production constraints. The work involved configuring the reweighter execution sequence for proper NA61 integration, extending

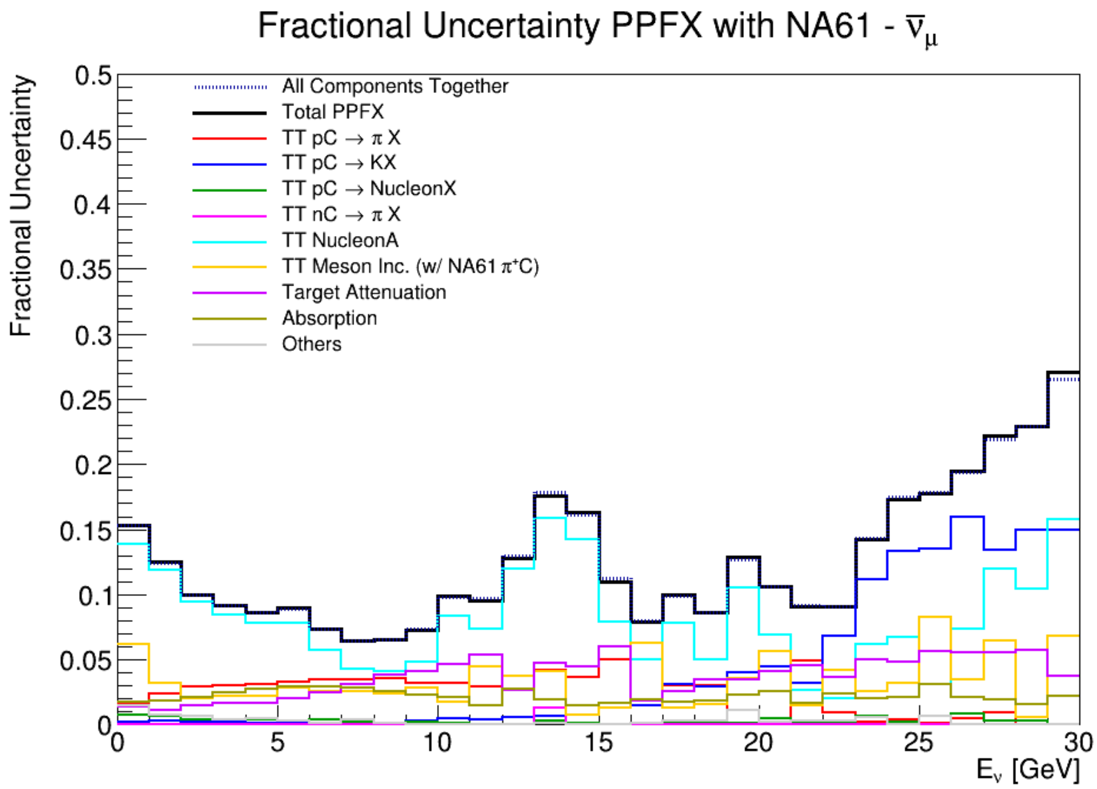

Figure 1: Fractional uncertainties of the integrated PPFX reweighted flux (anti-muon neutrino). TT stands for thin target.

the analysis infrastructure to handle new systematic components, and developing tools for evaluating the impact on flux uncertainties.

Upcoming work will focus on validating the uncertainty propagation by comparing detailed breakdowns between the original and integrated versions, understanding how correlations between reweighters should be treated in the multi universe approach, and integrating another PPFX version of The Long Baseline Neutrino Facility (LBNF) to the current integrated version. These developments will be presented at the NuFlux Workshop at the University of Notre Dame in March 2026 [6], with the goal of establishing this unified framework for broader use within DUNE and potentially other Fermilab neutrino experiments.

3. Studies in Current Semester

- **FIZ/2/004E: Experimental methods in particle physics 2.**

- **FIZ/2/081E: Weak interaction.**

- **Neutrino University, Fermilab Neutrino Physics Center Summer Lecture Series:**

4. Conferences and Workshops

Following the PPFX Working Group meeting, participating in meetings and discussions as scheduled:

- Presented a presentation titled ”PPFX for DUNE 2x2” at the the PPFX Working Group meeting, July 21, 2025.

- Attended DUNE Collaboration Meeting – CERN, 26-30 January 2026 (online)
- Planned new progress report presentation at the the PPFX Working Group meeting, Feb 2026 (date February 09, 2026).
- Will attend the NuFlux Workshop on Accelerator and Atmospheric Neutrino Flux Determination at the University of Notre Dame (USA) from March 9–13, 2026, and will present a talk entitled "Developing a Unified PPFX Framework for Neutrino Flux Predictions.

References

[1] Leonidas Aliaga Soplin. "Neutrino flux prediction for the NuMI beamline". In: (2016).

[2] András László. "The NA61/SHINE experiment at the CERN SPS". In: *arXiv preprint arXiv:0907.4493* (2009).

[3] Antoni Aduszkiewicz et al. "Measurements of hadron production in π++ C and π++ Be interactions at 60 GeV/c". In: *Physical Review D* 100.11 (2019), p. 112004.

[4] Danan S Wicaksono et al. *23 European Symposium on Computer Aided Process Engineering: Reformulation strategies for eigenvalue optimization using Sylvester's criterion and Cholesky decomposition*. Vol. 32. Elsevier Inc. Chapters, 2013.

[5] C. Farhat et al. "LINEAR ALGEBRA". In: *Encyclopedia of Vibration*. Ed. by S. Braun. Oxford: Elsevier, 2001, pp. 710–720. ISBN: 978-0-12-227085-7. DOI: https://doi.org/10.1006/rwvb.2001.0003. URL: https://www.sciencedirect.com/science/article/pii/B0122270851000035.

[6] *NuFlux: Workshop on Accelerator and Atmospheric Neutrino Flux Determination*. Accessed: 2026-01-28. Mar. 2026. URL: https://indico.fnal.gov/event/71283/.