Current Status and Future Progess of DUNE ND studies

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1 Overview

The Deep Underground Neutrino Experiment (DUNE) is a next-generation Long Baseline neutrino experiment aimed to achieve current scientific goals set out by the High Energy Physics community. It consists of both a Near and Far Detector separated by 1300km and standing in the NuMI beam created at Fermilab[**?**]. While the design of the Liquid Argon Far Detector has been finalized, there is still ongoing effort in deciding the configuration of the Near Detector. The main near detector design includes a Fine-Grained Tracker (FGT) with possible inclusion of an upstream detector - being either a Liquid (LArTPC) or High Pressure Gaseous Argon TPC (GArTPC). DUNE's goals will require systematic uncertainties in the interaction model to be below the 2% limit after a near-to-far extrapolation[**?**]. The focus of the work described in this document is then to quantify the abilities of the standalone FGT detector and additional LAr/GAr TPC to achieve this limit in the near-to-far extrapolation. The sufficiency of current kinematic parameterization to handle model variations is also considered.

2 Motivation, Methods, and Results

As the analysis techniques for DUNE are developed, checks on the cross section model are necessary. Variations arise in the different handling of Final State Interaction (FSI) effects by Monte Carlo event generators, as well as choice of Near Detector configuration. Sets of neutrino and antineutrino events on Argon-40 are produced with the GENIE[1][1], NEUT[2][2], and NuWro[3][3] according to the 2015 DUNE CDR fluxes. The various data sets are passed through the NUISANCE[4] software to reduce the various outputs to a common format, in turn saving all final state particle information for each event. Each particle is than randomly accepted or rejected

[1]GENIE version 2.10, RFG

[2]NEUT version 5.3.6, Nieves et. al RPA+2p2h/MEC $M_A = 1.01$

[3]NuWro version (FIND THE VERSION) LFG + RPA + Nieves et. al

according to efficiencies for each detector. Currently, only a robust description of the FGT efficiency is available, and simple thresholds for protons are applied for the GAr[4] and LAr ND and FD[5]. Currently, we do not have the efficiencies for μ, $\pi^{+,-}$, and π^0 in the LAr and GAr, and so the detectors are assumed to be perfectly efficient (no rejections) to these particles. π^0 efficiency information is also currently missing in the FGT configuration, and so are assumed fully accepted.

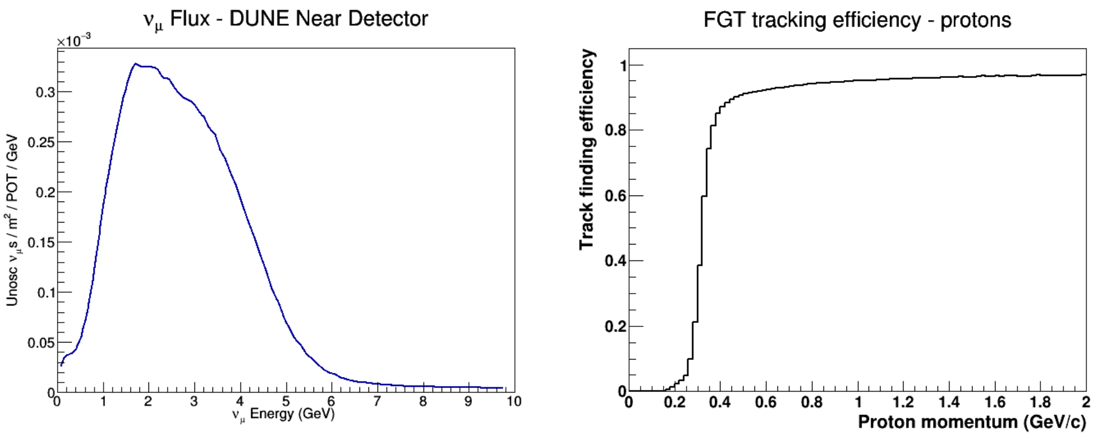

Figure 1: Left: ν_μ flux at DUNE ND used to generate events, Right: Tracking efficiency for protons in FGT.

3 Reconstructed Energy

A framework for investigating the differences in reconstructed energy calculations between different generators and ND configurations has been developed.

The current development of this work includes a calculation of the final state energy by summing the total energy from final state leptons and pions (all charges) and the kinetic energy of final state protons after passing efficiencies through the data sets. All neutrons are assumed undetectable.

$$E_{reco} = \Sigma E_{lep} + \Sigma E_{\pi} + \Sigma(E_{prot} - M_{prot}) \tag{1}$$

This is achieved by using the NUISANCE software package to reduce the output from various Monte Carlo neutrino event generators (including GENIE, NEUT, NUWRO, as well as the nuclear reaction and transport simulation software, GiBuu) into a common format that can easily be analyzed.

Work has begun to include tracking/PID efficiencies to accept or reject final state particles. So far, only the full information (barring π^0 efficiencies) for the FGT is available, but the inclusion of the LAr or GAr TPCs will be easily implemented.

[4] 100 MeV/c
[5] 200 MeV/c

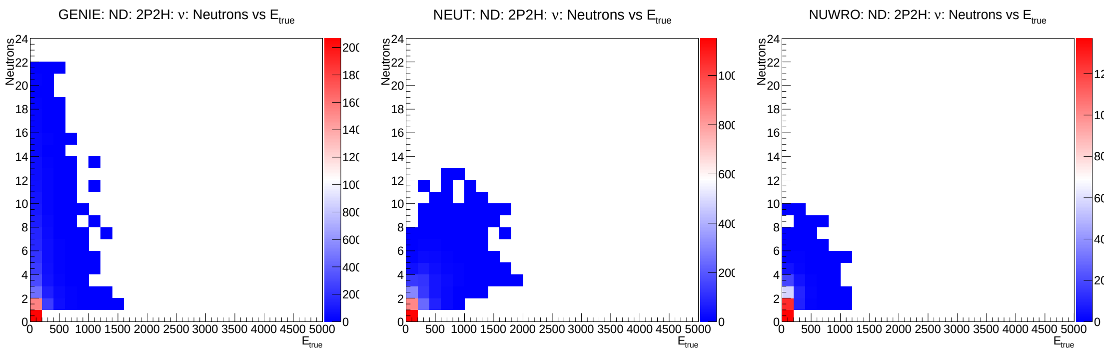

Figure 2: The neutron multiplicity vs total neutron energy for 2P2H interactions for GENIE, NEUT, and NUWRO, respectively. Even though they do show a different phase-space for the neutron multiplicity, they all agree where most of the energy lost to neutrons should be. This is similar for other interaction types as well.

3.1 Neutron Multiplicities & Energy

Differences between models in the number of final state neutrons and the total energy into FS neutrons can largely affect reconstruction of neutrino energy. Large variations in reconstructed energy can arise due to missing energy caused by the inability to detect neutrons in the various models.

To investigate this, we have looked at GENIE, NEUT, and NUWRO to see if the different models showed a large difference in the neutron energy and multiplicity. This was done for CCQE-like, CC1π, 2P2H, and everything else ("Other") interactions and neutrinos as well as anti-neutrinos. In all cases, the generators agreed rather well with each other even though there were some differences in the neutron multiplicity. These differences only account for a small fraction of the events. Figure 2 shows an example of this for 2P2H neutrino events, while the other interaction modes can be found in Appendix **??**

Further more, the difference in the multiplicities between the generators becomes irrelevant after a ND to FD extraction, as can be seen in Figure 3. Here, the region where the most energy is lost agrees very well between the ND and FD for all generators and interaction types. The areas with low statistics do show a disagreement, but very few events fall into this area.

Care should still be taken when calculating the total neutrino of the event if only a calorimetric approach is used, as is the case in this document. This is because as much as 50% of the energy can be taken away by the neutron in CCQE-like events. Even for 2P2H events, as shown in Figure 4, it can be as much as 30%. The other interaction modes and anti-neutrino events can also be found in Appendix **??** and have a smaller fraction.

Additionally, investigations in the ability for errors in GENIE to cover the differences between models have been started.

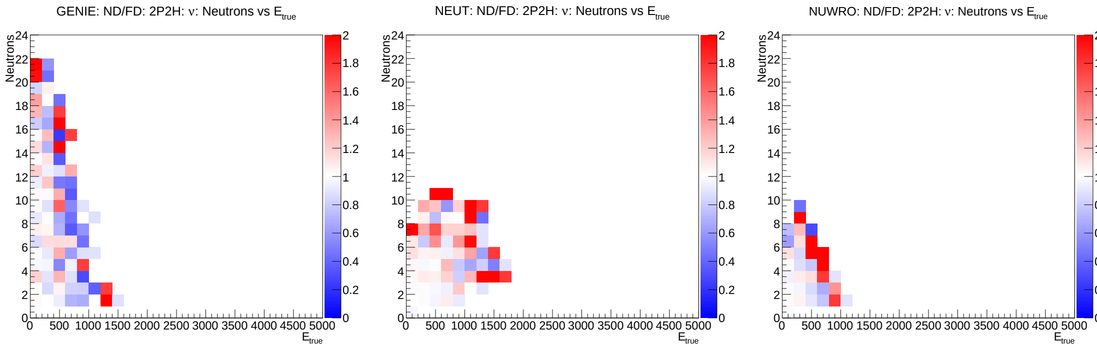

Figure 3: The ratio of the ND to the FD for neutron multiplicity vs total neutron energy for 2P2H interactions for GENIE, NEUT, and NUWRO, respectively. In the area where the largest amount of energy is lost to neutrons, low multiplicity and low energy, the agreement between the ND and FD is almost perfect.

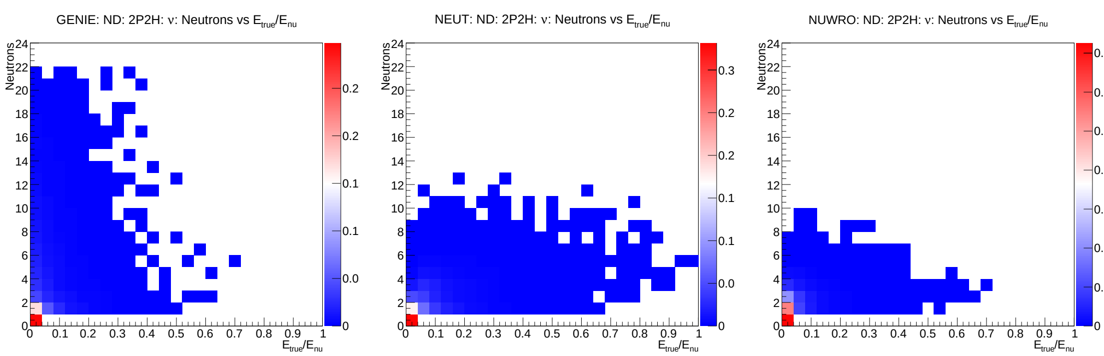

Figure 4: Neutron multiplicity vs total neutron energy divide by the neutrino energy for 2P2H interactions from GENIE, NEUT, and NUWRO, respectively. For low multiplicity, the neutron carries away a significant fraction of the neutrino energy.

3.2 Particle Multiplicity and Momentum

Nucleon multiplicity and momentum distributions offer similar information as do N vs. E distributions, while specifically looking at protons and charged pions along with detector thresholds can enlighten the ability of the detectors' reconstruction capabilities. For these studies, the 3-momentum of the final state (after efficiencies) protons or charged pions are summed. The magnitude is then plotted against the multiplicity for the specific particle type.

4 Parameterization

4.1 Q^2 studies

The first study to be considered is the sufficiency of a purely Q^2 parameterization (a la VALOR) in treating the uncertainties for CCQE. To be considered is the relative change between the models (displayed as a single ratio of Other/GENIE separately at the near and far detectors) and this change as it is extrapolated between the near and far detector (as a double ratio of Other/GENIE,Near/Far).

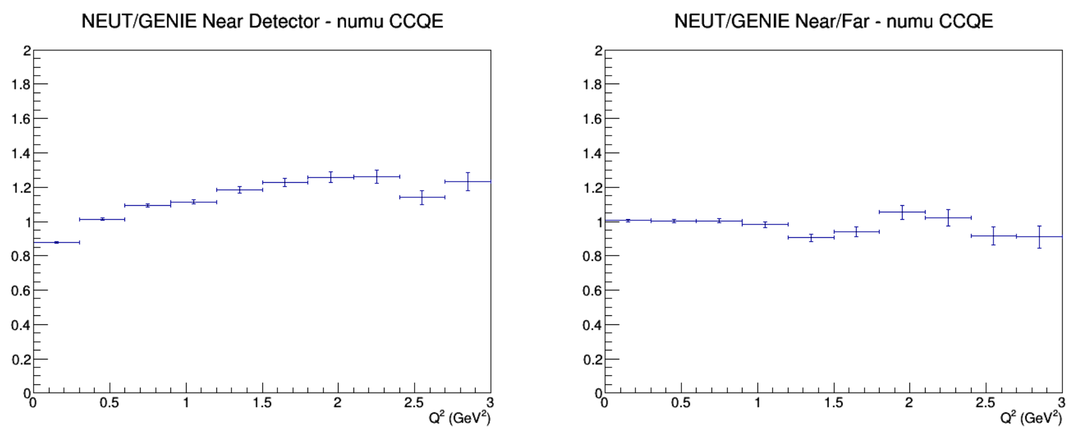

Figure 5: Q^2 distributed events using DUNE flux, no efficiencies applied. Left: Ratio of NEUT to GENIE output at ND, Right: Double ratio of NEUT to GENIE, Near to Far. Of note is the relative flatness in the low-Q^2 region in the double ratio, becoming less flat toward the higher end.

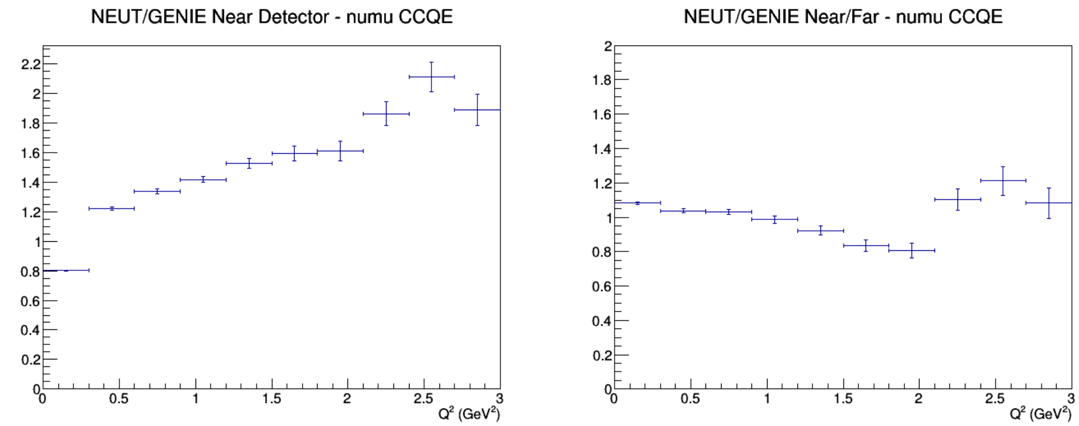

Figure 6: Q^2 distributed events using DUNE flux, no efficiencies applied. Left: Ratio of NEUT to GENIE output at ND (high Q^2 region out of bounds of plot), Right: Double ratio of NEUT to GENIE, Near to Far. Flatness is generally lost throughout double ratio, particularly made worse in higher end.

4.2 $q_0 vs. q_3$ studies

In comparison to the purely Q^2 parameterization, a simple $q_0 vs. q_3$ parameterization was also considered. One concern is the possibility of inconsistency between the two parameterizations in variations between models.

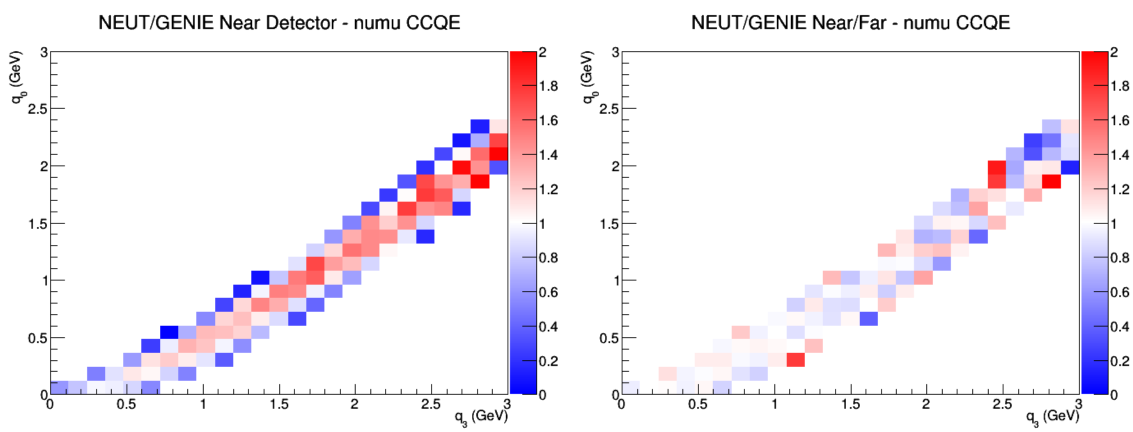

Figure 7: q3 vs. q0 distributed events using DUNE flux. Left: Ratio of NEUT to GENIE output at ND, Right: Double ratio of NEUT to GENIE, Near to Far

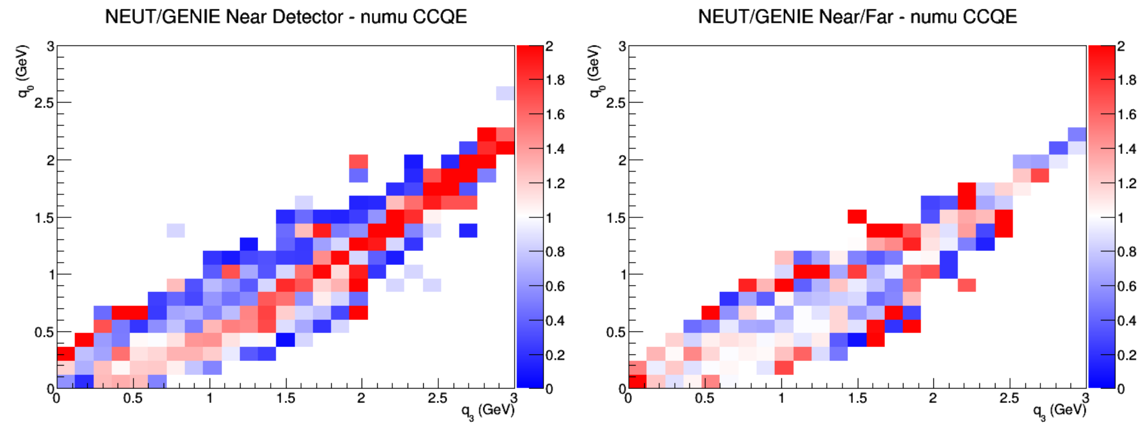

Figure 8: q3 vs. q0 distributed events using DUNE flux. Left: Ratio of NEUT to GENIE output at ND, Right: Double ratio of NEUT to GENIE, Near to Far. Much of the FD has a tighter phase space due to being generator-level truth information, so a good deal of the ND-with-efficiency phase space is lost. Within the FD-covered phase space in the double ratio, flatness seems to be lost in the lower region, and much more bin-to-bin variation is present in the upper region (possibly need more statistics?).

4.3 Nucleon multiplicity vs. W

Differences in mapping from Ereco to true variables can arise from shape differences in Nucleon multiplicities vs. W distributions. The first foray into these studies have been started, and need to be fleshed out for meaningful results.

5 Future Work

The above studies need to be furthered and expanded upon to successfully arrive at useful conclusions on ND configuration choice.

- Extend studies to include LAr and GAr efficiency information when available
- Map from Ereco, yreco into true variables and investigate differences between configurations

References

[1] Andreopoulos, C. *et al.* *The GENIE Neutrino Monte Carlo Generator*. Nucl.Instrum.Meth. A614 (2010) 87-104 arXiv:0905.2517 [hep-ph] FERMILAB-PUB-09-418-CD

[2] Hayato, Yoshinari *A neutrino interaction simulation program library NEUT*. Acta Phys.Polon. B40 (2009) 2477-2489

[3] T. Golan, J.T. Sobczyk, J. Zmuda *NuWro: the Wrocaw Monte Carlo Generator of Neutrino Interactions*. Nuclear Physics B - Proceedings Supplements 229 (2012) 499

[4] P. Stowell, C. Wret, C. Wilkinson, L. Pickering, S. Cartwright, Y. Hayato, K. Mahn, K.S. McFarland, J. Sobczyk, R. Terri, L. Thompson, M.O. Wascko, Y. Uchida *NUISANCE: a neutrino cross-section generator tuning and comparison framework* arXiv:1612:07393v2