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[5]. 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[6]. 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 Methods

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 Monte Carlo Generators - GENIE[1] version 2.10, using an RFG model, NEUT[2] version 5.3.6, using Nieves et. al RPA+2p2h/MEC $M_A = 1.01$, and NuWro[3] version 11, using LFG + RPA + Nieves et. al - according to the 2015 DUNE CDR fluxes. The ν_μ Near Detector and Far Detector fluxes used in this work are showin in Figure 1. 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.

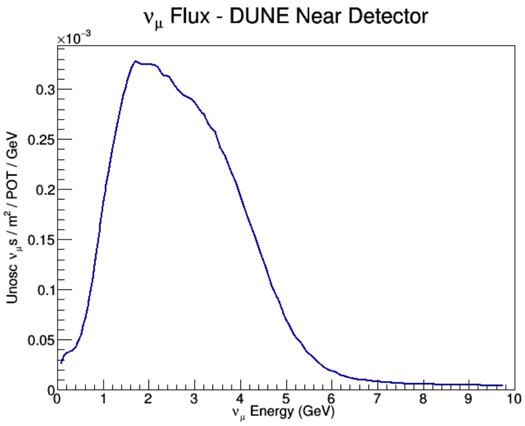

Figure 1: ν_μ flux at DUNE ND (Left) and FD (Right)

Each particle is then randomly accepted or rejected by throwing a random number and checking against the efficiency according to the particle and its momentum. Currently, only a robust description of the FGT efficiency is available. An example of the efficiency for protons in the FGT is given in Figure 2. Simple thresholds for protons are applied for the GAr - 100 MeV/c - and LAr ND and FD - 200 MeV/c. 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.

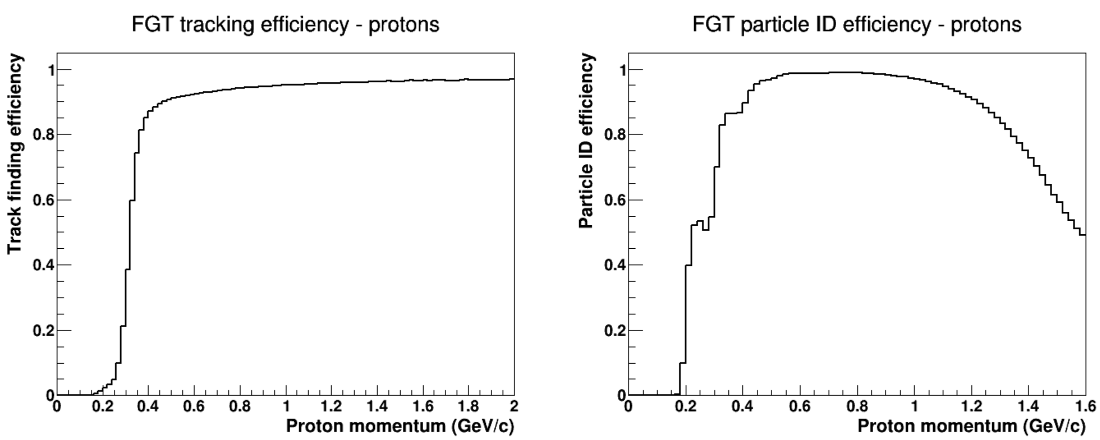

Figure 2: Left: Tracking efficiency for protons in FGT. Right: PID efficiency for protons in FGT. Total efficiency for a given proton momentum is given by the product of the two efficiencies.

3 Reconstructed Energy

A framework for investigating variations 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. This can be summed up in Equation 1:

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

where E_{lep} is the energy of the outgoing lepton, E_{pi} is the energy of the charged pion, and E_{prot} (M_{prot}) is the energy (momentum) of the proton.

3.1 Difference from True Neutrino Energy

To investigate these variations, the difference between true and reconstructed neutrino energy from each generator - where NuWro and NEUT distributions have been normalized to GENIE - are plotted for each near detector configuration as well as the far detector, and for different reaction types. The reaction types considered are true-CCQE, true-2p2h, CC0π, CC1π, and CCOther. True-CCQE and true-2p2h are both defined as MC-level CCQE/2p2h interaction with 1 reconstructed lepton. CC0π is defined as 0 charged π, 1 lepton, and any number of protons and π^0 after reconstruction. CC1π is defined as 1 charged π, 1 lepton, and any number of protons and π^0 after reconstruction. Finally, CCOther is defined as any final state with 1 lepton and any number of hadrons reconstructed.

In ν_μ mode: for all reaction types except CCOther, all three generators seem to have similar differences in all detector configurations. This is evident in Figure 3 and the figures in appendix (ref appendix). For CCOther, all three generators appear to have a long tail extending to high discrepancy regions - well past that of CCQE for example - though NuWro has a higher amount of events in the $\Delta E = .5$ GeV to 2 GeV region.

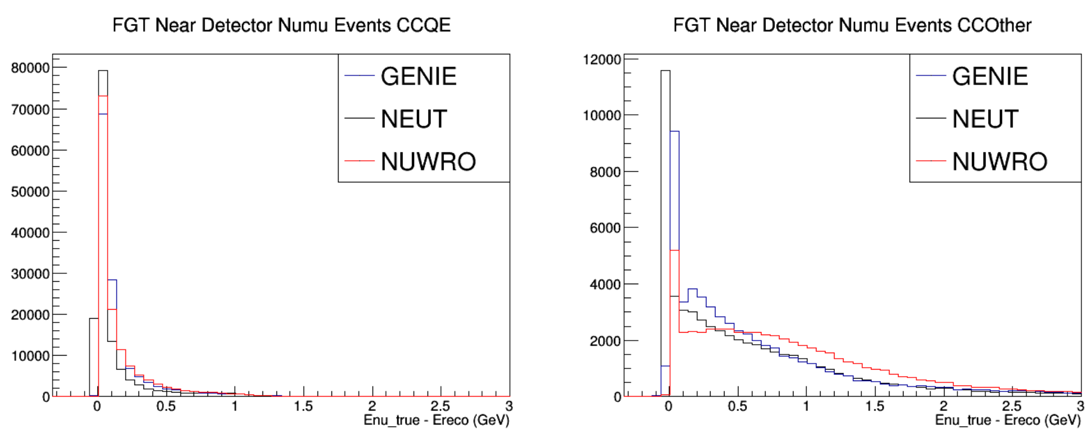

Figure 3: Difference between true and reconstructed Neutrino Energy in the FGT ND. CCQE events seem to have similar discrepancies, while CCOther mode has large tails in all three generators with NuWro having more events with higher discrepancy than the other two.

Meanwhile, for $\bar{\nu_\mu}$ CCQE, 2p2h, and CC1π events NuWro consistently has ΔE closer to 0 than the other generators as shown in Figure 4. In CC1π and CCOther NuWro again has more events with higher discrepancies, shown in Figure 5. Additionally, a large difference in the distribution of events from NEUT and NuWro between the FGT and LAr FD, which is slightly better in the LAr ND, as can be seen in Figure 6.

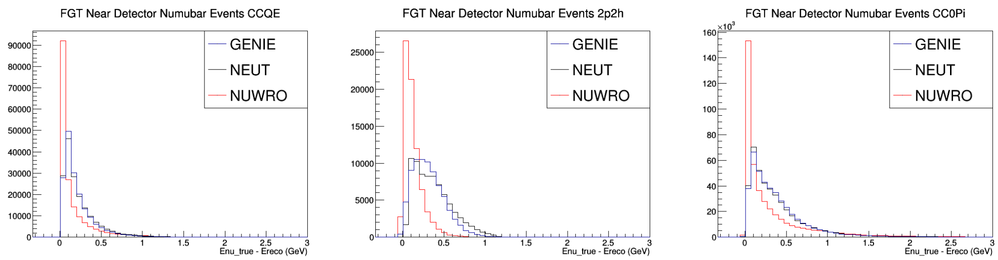

Figure 4: NuWro can be seen to have consistently less discrepancy in reconstructed energy than NEUT and GENIE in CCQE, 2p2h, and CCOπ.

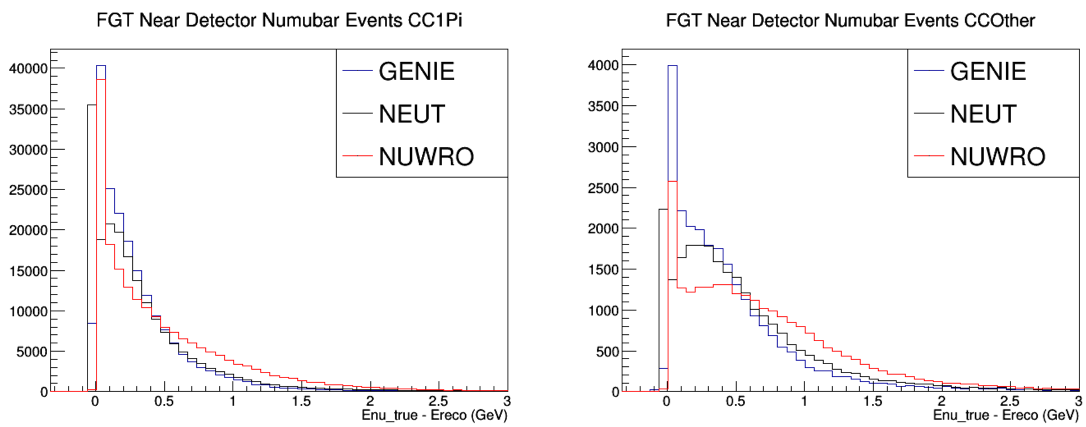

Figure 5: NuWro has higher discrepancy in reconstructed energy than NEUT and GENIE in both CC1π and CCOther.

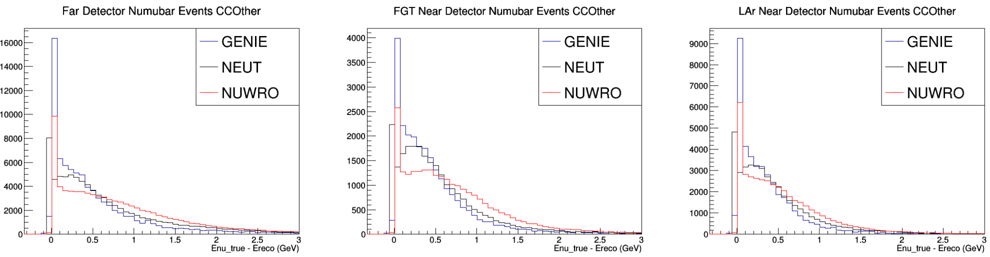

Figure 6: NuWro CCOther events have differences in shape between the Far Detector and LAr FD. The LAr ND matches more closely.

3.2 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 7 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 8. 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 9, 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.

3.3 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)

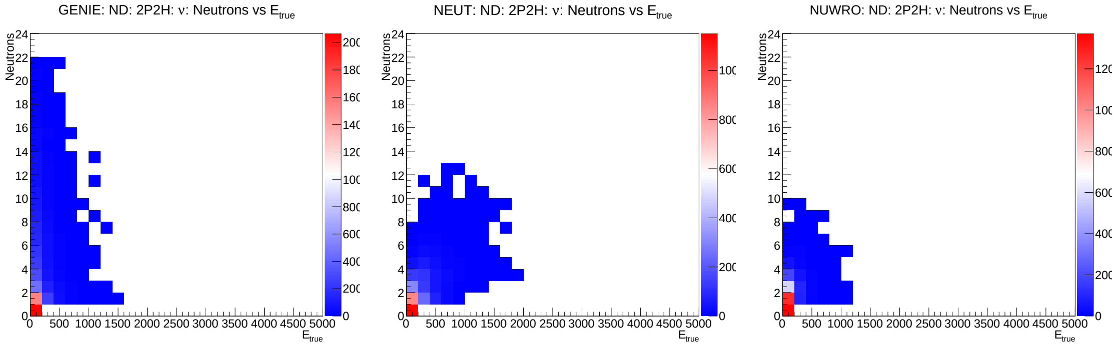

Figure 7: The neutron multiplicity vs total neutron energy for 2P2H interactions for GENIE, NEUT, and NUWRO, respectively. Even though they do show a different phase-space for the neutron multiplicity, they all agree where most of the energy lost to neutrons should be. This is similar for other interaction types as well.

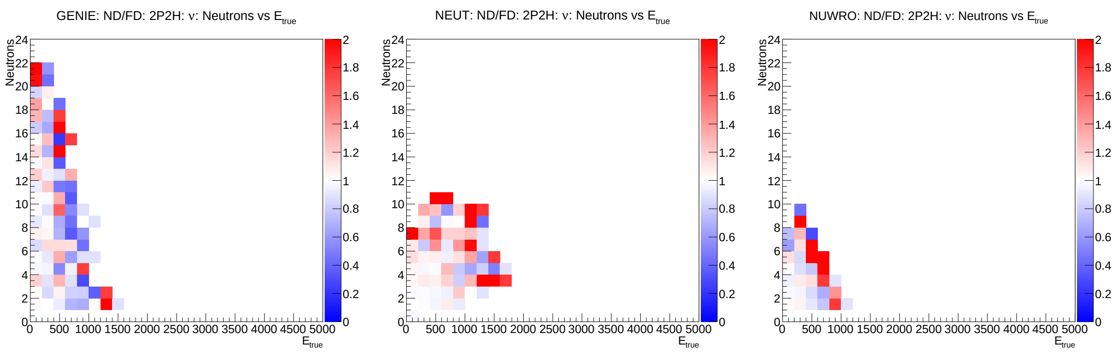

Figure 8: The ratio of the ND to the FD for neutron multiplicity vs total neutron energy for 2P2H interactions for GENIE, NEUT, and NUWRO, respectively. In the area where the largest amount of energy is lost to neutrons, low multiplicity and low energy, the agreement between the ND and FD is almost perfect.

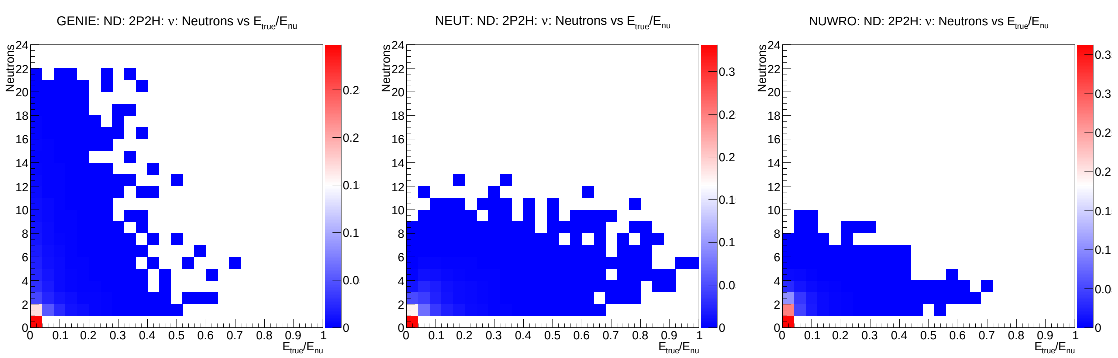

Figure 9: Neutron multiplicity vs total neutron energy divide by the neutrino energy for 2P2H interactions from GENIE, NEUT, and NUWRO, respectively. For low multiplicity, the neutron carries away a significant fraction of the neutrino energy.

protons or charged pions are summed. The magnitude is then plotted against the multiplicity for the specific particle type.

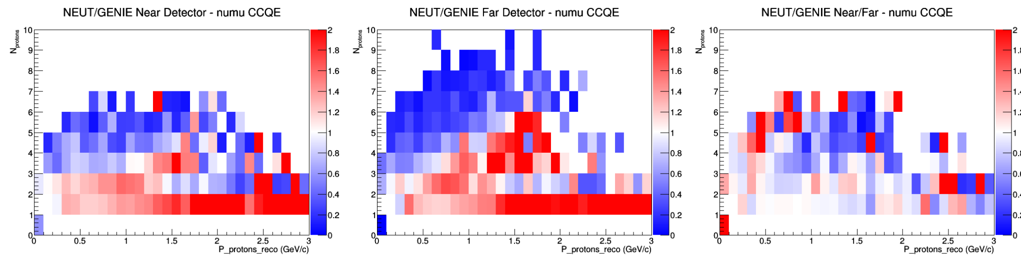

Figure 10: Nprotons vs. P protons distributed events using DUNE flux. Left: Ratio of NEUT to GENIE output at ND with FGT efficiencies, Mid: Ratio of NEUT to GENIE output at FD with LAr efficiencies, Right: Double ratio of NEUT to GENIE, Near to Far

4 Parameterization

4.1 Q^2 studies

Currently, a 3-bin Q^2 parameterization (edges: 0, 0.20, 0.55, 1000 GeV^2) has been suggested by VALOR(DO I NEED A REF FOR THIS?) for CCQE analysis. The first study to be considered is the sufficiency of this purely Q^2 parameterization 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).

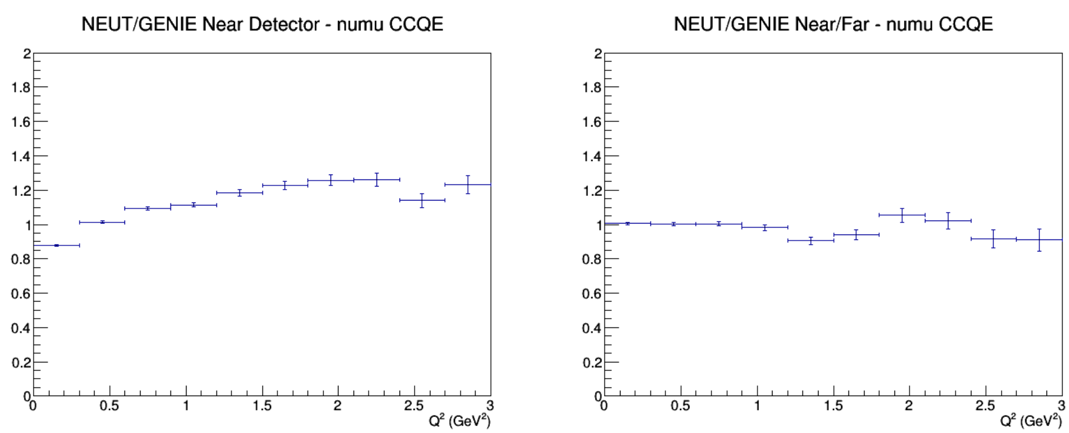

Figure 11: Q^2 distributed events using DUNE flux, no efficiencies applied. Left: Ratio of NEUT to GENIE output at ND, Right: Double ratio of NEUT to GENIE, Near to Far. Of note is the relative flatness in the low-Q^2 region in the double ratio, becoming less flat toward the higher end.

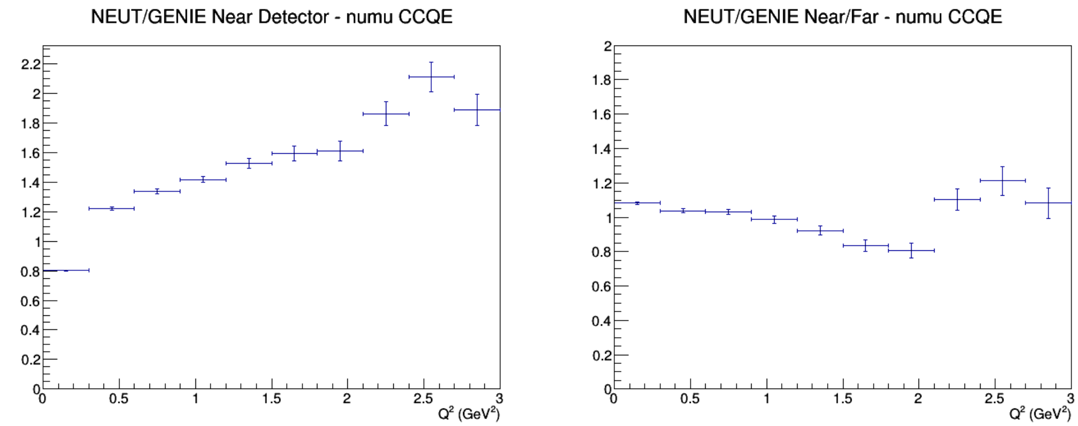

Figure 12: Q^2 distributed events using DUNE flux, FGT efficiencies applied to ND and LAr effiencies applied to FD. Left: Ratio of NEUT to GENIE output at ND (high Q^2 region out of bounds of plot), Right: Double ratio of NEUT to GENIE, Near to Far. Flatness is generally lost throughout double ratio, 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.

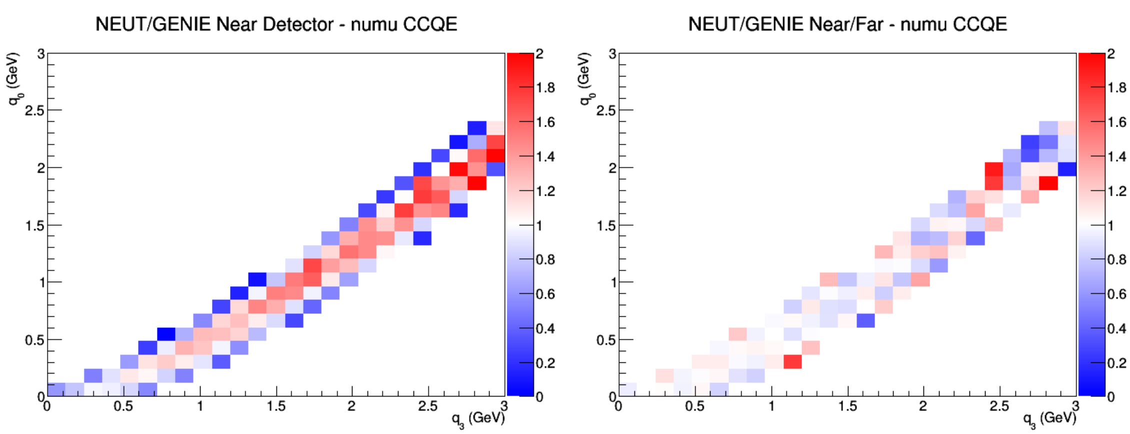

Figure 13: q3 vs. q0 distributed events using DUNE flux. Left: Ratio of NEUT to GENIE output at ND, Right: Double ratio of NEUT to GENIE, Near to Far

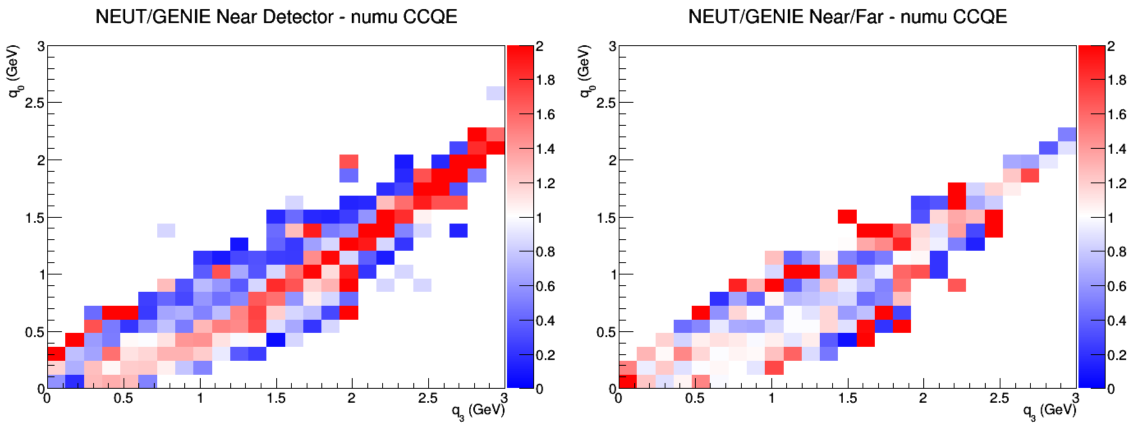

Figure 14: q3 vs. q0 distributed events using DUNE flux, FGT efficiencies applied to ND and LAr effiencies applied to FD. Left: Ratio of NEUT to GENIE output at ND, Right: Double ratio of NEUT to GENIE, Near to Far.

4.3 Nucleon multiplicity vs. W

Differences in mapping from E_{reco} to true variables can arise from shape differences in nucleon multiplicities vs. W distributions. These distributions can also show where in the phase space most of the events shown in Section 3.2 and Section 3.3 exist. A first look of this is shown in this section.

4.3.1 Neutrons vs W

Apart from the difference in neutron multiplicity discussed in Section 3.2, the exact phase space of these event in the neutron/W plane is slightly different. This is most pronounced for 2P2H events, as can be seen in Figure **??**. The width of NEUT's peak is broader then GENIE's or NUWRO's while NUWRO allows for much higher W's.

However, Figure 16 shows that the differences are not so important if a near to far extrapolation is used, as both the ND and FD have simular responses. To see if the different models could have a larger affect on the physics results, we have taken a double ratio of the ND/FD and the different generators to GENIE. Interestingly, Figure 17 indicates that there would not be large affect if a few perecent difference between the models is acceptable.

These results are also true for protons and pions, though pions have a much lower multiplicity. Those results, along with other interactions can be found in Appendix **??**.

4.3.2 Protons vs W

In the last section we saw a differnce in the phase space between the different generators. Now we will show an instance where the phase space is almost the same but there is a large difference between the ND and FD. Though here we are only showing the results for CC1π via protons, the results are the same for CC-Other (anything

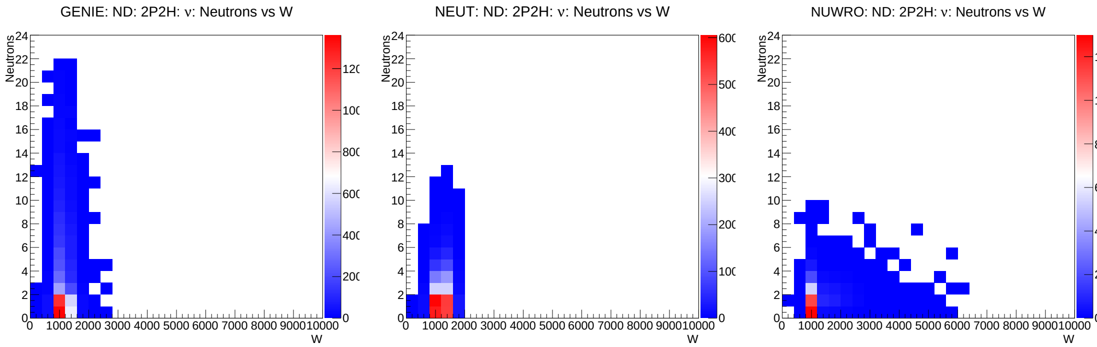

Figure 15: The neutron multiplicity vs W for 2P2H interactions from GENIE, NEUT, and NUWRO, respectively. It can be seen that all three event generators have the peak of the distribution at the same place, but NEUT's peak is much broader while NUWRO allows for much higher W's.

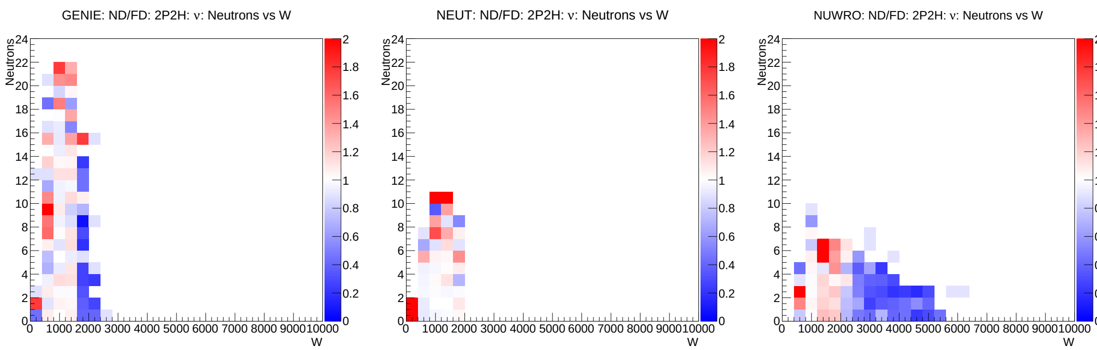

Figure 16: The ND/FD ratio of neutron multiplicity vs W for 2P2H interactions from GENIE, NEUT, and NUWRO, respectively. The effects of the different phase space seen in Figure 15 is not great if a ND ro FD extropolation is used. This can be seen by the ratio being very close to one at the peak of Figure 15 distribution.

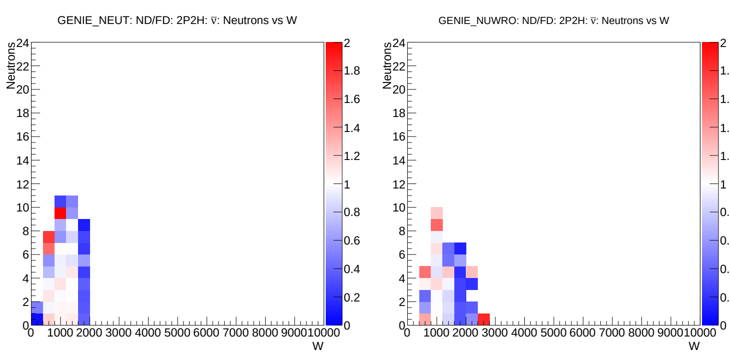

Figure 17: The double ratio of ND/FD and the event generators to GENIE of the neutron multiplicity vs W for 2P2H interactions. Despite the differences seen in the W distributions, the double ratio shows suprisingly good agreement between the generators, indicating that the different models should not have a large impact on the final results.

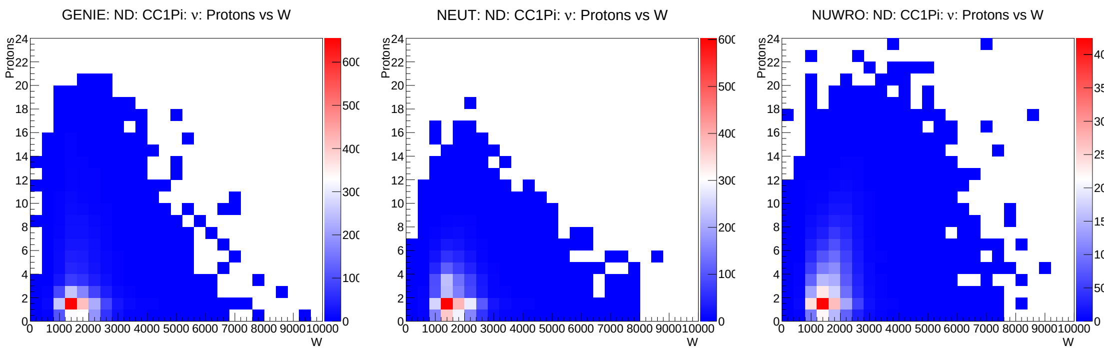

Figure 18: The proton multiplicity vs W for CC1π interactions from GENIE, NEUT, and NUWRO, respectively. It can be seen that all three event generators have the peak of their distribution at the same place and are almost identical

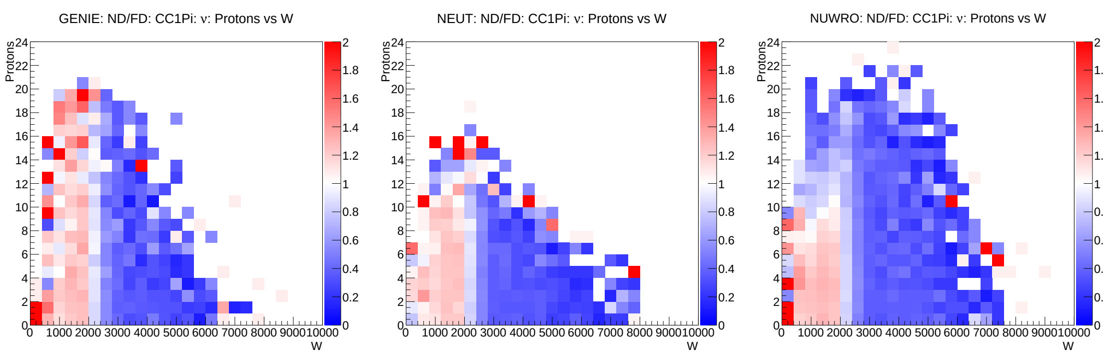

Figure 19: The ND/FD ratio of the proton multiplicity vs W for CC1π interactions from GENIE, NEUT, and NUWRO, respectively. Unlike with 2P2H events shown for neutrons, there are clear differences between the ND and FD. At the peak of the distribution this is between 20% and 40%. Furthermore, there is a clear difference between W values below 2000 and ones above it.

not CCQE, CC1π, or 2P2H), and neutrons along with pions. Figure 18 shows that GENIE, NEUT, and NUWRO have very similar distributions.

If a near to far detector extrapolation is used, however, there are much larger differences in region of most interest. Figure 19 shows that there is a difference between the two detectors between 20% and 40% at the peak of the distribution. There is also a clear difference in lower W values compared to higher W values.

We can again see if the different models could have a larger affect on the physics results, by taking the double ratio as we did before. Simular to before, Figure 20 indicates that there would not be large affect if a few perecent difference between the models is acceptable. In the region of interest, the difference between GENIE and NEUT is negligable while it is small compared to NUWRO.

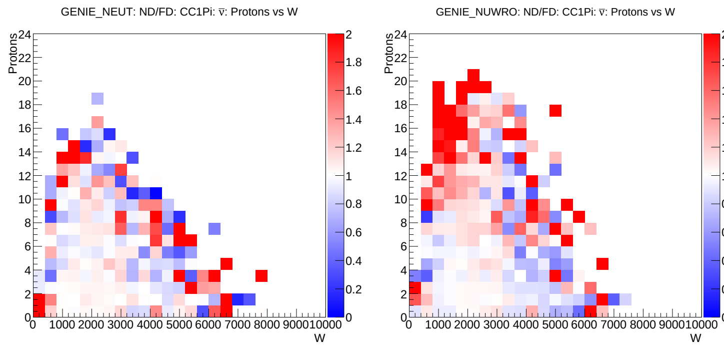

Figure 20: The double ratio of ND/FD and the event generators to GENIE of the proton multiplicity vs W for CC1π interactions. Despite the differences seen in the single ratio, the double ratio shows suprisingly good agreement between the generators

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 and acceptance information when available.
- Include a mapping of E_{true} to E_{reco} along with y_{true} to y_{reco} and investigate differences between configurations.

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