Comparison of ACHILLES and GENIE observables for DUNE-PRISM and the SBN program, with new 2p2h predictions

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Abstract

The DUNE near detector LAr-TPC can be moved to different off-axis positions to sample different neutrino fluxes, which in turn will yield different cross section distributions for observables. Several DUNE ND off axis locations were simulated using GENIE and ACHILLES, and generator differences and FSI contributions were examined for various observables. Additionally, the predictions were compared with those of existing experiments, and it is shown that the DUNE ND 20m off axis predictions are similar to that of MicroBooNE for various observables. Finally, the 2p2h interaction mode was simulated for ACHILLES for the first time for ICARUS, and a preliminary comparison is made to MicroBooNE data and simulations from different event generators.

1 Introduction

1.1 Overview about the Experiments

The Deep Underground Neutrino Experiment (DUNE) is a long baseline neutrino experiment currently being developed at Fermilab. Protons from PIP-II will be launched into a graphite target, and will travel through both a near detector (ND) and a far detector (FD) 1,300 km away in Lead, South Dakota. These detectors employ Liquid Argon Time Projection Chambers (LAr-TPC), allowing them to detect neutrinos at lower energies and higher statistics than previously possible. As such, DUNE has the potential to provide the data necessary to answer some of the important questions surrounding neutrinos, such as the amount of CP violation in neutrino oscillations.[1] Since neutrinos are light and neutral, they must be detected through the particles produced when they interact with a nucleus. In the case of LAr-TPC, these are Argon nuclei.

LAr-TPC are already being utilized in the Short Baseline Neutrino (SBN) program at Fermilab. This program consists of three experiments that all lie on the same neutrino beamline, the Booster Neutrino Beam, such that they experience similar fluxes. The SBND experiment is 110 meters from the target, and acts as the near detector for the experiment. MicroBooNE is another experiment 470 meters from the target, and was designed to investigate the low energy excess of electron neutrino events observed by its predecessor, MiniBooNE. Both SBND and MicroBooNE are expected to have almost identical fluxes. Finally, ICARUS is an experiment which was recently moved from CERN to Fermilab. It is 800 meters from the target and acts as the far detector.[2]

1.2 On axis versus Off axis Event Rates for DUNE ND

Unlike previous experiments, the DUNE ND will be able to sample multiple different neutrino fluxes through a function known as DUNE-PRISM. The LAr-TPC will be able to be moved moved to various off-axis positions. This means the neutrino flux can be sampled at different neutrino energies, which means the kinds of neutrino-nucleus interactions will be different.[1]

Such neutrino-nucleus interaction modes can be classified into two types, charged current (CC), where a lepton corresponding to the flavor of the neutrino is produced, and neutral current (NC), which does not depend on the flavor of the neutrino at all. For example, in charged current quasielastic (CCQE), the neutrino interacts with a single nucleon and emits a charged lepton and a single nucleon.[3]

The neutrino nucleus interactions are nontrivial, and experimental results must be backed up by simulations. Since it can be difficult to determine the true interaction mode without relying heavily on simulations, results are often labeled as what they appear to be in the detector, for example CC0π, also called (CCQE-like), which are events with a charged lepton and no pions in the final state. The main contributions for these events are from CCQE and 2p2h, but also from events where a pion is produced and then absorbed by the nucleus.[4]

1.3 Event Generator Overview

Monte Carlo (MC) event generators are often used to provide predictions for the observables in the detectors. These can then be compared to the actual data, to test how accurate the predictions are and make adjustments as necessary. However, since there are many ways to model the various processes, the predicted results can have “generator dependencies,” where the predicted results are different depending on the generator used. Since neutrino detection experiments are always statistics limited, large error bars can make it difficult to discern whether the prediction for one generator is more realistic than the prediction for another, even if they are noticeably different.

For predictions for the DUNE experiment, the ”default” event generator is the GENIE event generator. This generator contains many interaction modes, and has versions with different models for the final state interactions (FSI), the interactions the resulting particles have with the nucleus after the primary interaction. For example, the hA2018 model approximates the final state interactions as a single interaction that has been tuned to fit the data, whereas the hN2018 model is a cascade with multiple steps.[3]

A somewhat more recent generator is the ACHILLES generator. ACHILLES was designed to have a completely theoretical backing, unlike previous event generators which are much more reliant on fitting to the data.[5] At the time of writing ACHILLES has implemented only few interaction modes, although more are being developed as presented in this paper.

1.4 Previous Work and Objective of this Research

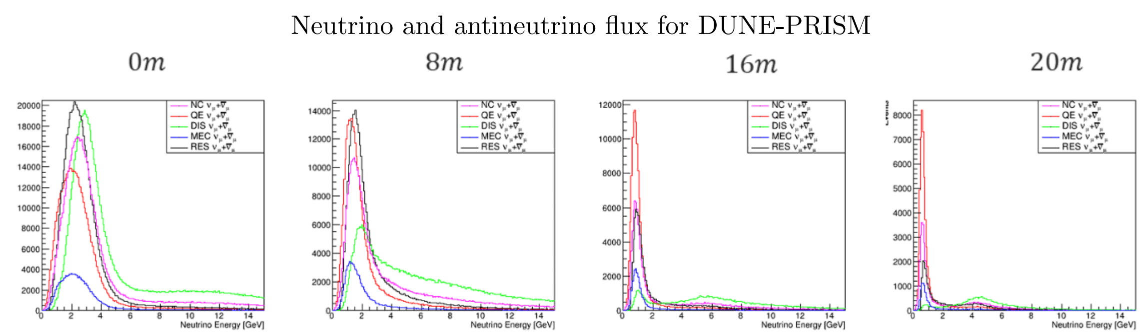

Figure 1: Combined neutrino and antineutrino flux for different positions of the DUNE ND. The y axis is counts and the x axis is neutrino energy in GeV. Figure taken from [6].

Previous research [7] compared ACHILLES vs. GENIE predictions for simulations of different off-axis positions of the DUNE ND. Only CCQE events were studied, generator differences were observed for variables such as proton kinetic energy and muon momentum. Interestingly, many of the predictions for the DUNE 20m off axis position were found to be similar to MicroBooNE predictions, allowing for the potential to easily apply analysis techniques from one experiment to the other.

This current research seeks to expand on this research. Additional observables such as the opening angle between two protons, the angle between two protons for events with two protons, and δp_T, were studied and compared with existing data. Finally, the intention is to make predictions for the more experimentally relevant cc0pi events. This is dependent on receiving ACHIlLES predictions for 2p2h, a relevant component in these events. Nonetheless, a prediction was received for ICARUS.

In this research simulations were run for GENIE and ACHILLES at 1 million events. These were converted into the nuisance flat tree format and analyzed with Python.

1.5 Neutrino energy flux for different DUNE PRISM locations

Different off axis positions have a different neutrino energy flux, and thus different relative contributions from each interaction mode. The farther off axis positions mainly have contributions from CC0π modes, such as CCQE, which merits the specific focus on them in this study.

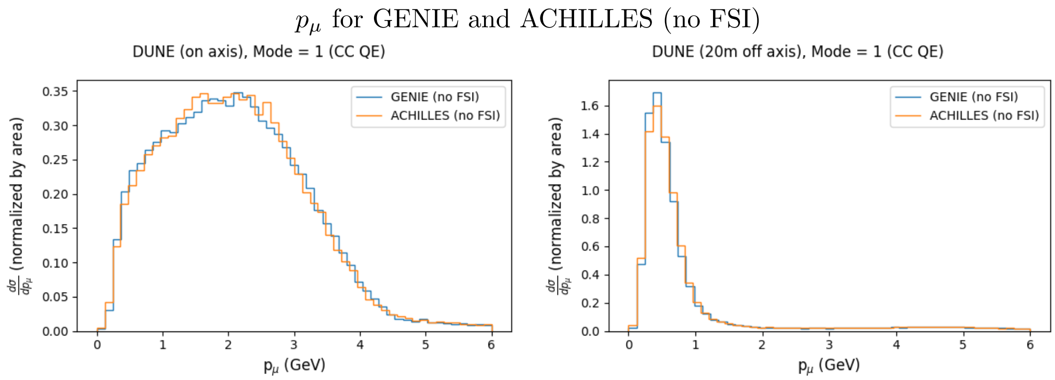

Figure 2: p_μ for GENIE vs. ACHILLES at different DUNE ND positions.

The muon momentum for GENIE vs. ACHILLES is shown in Figure 2, in the absence of FSI. The distributions look very similar between the two generators, suggesting that there is fairly good agreement between them for muon momentum.

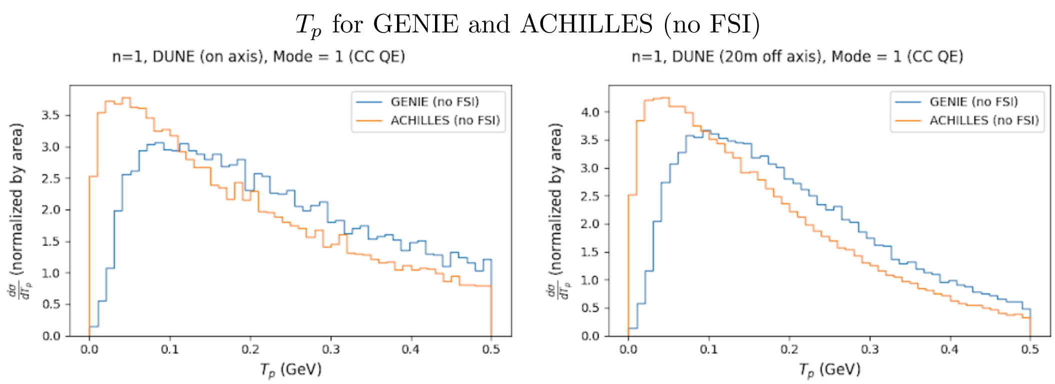

Figure 3: T_p for GENIE vs. ACHILLES at different DUNE ND positions.

The proton kinetic energy is shown in Figure 3. These distributions are noticeably different. Since FSI is not present, this suggests that ground state Monte Carlo for GENIE and ACHILLES are different. Thus we observe a significant generator difference.

2 Results

2.1 Exploring GENIE vs. ACHILLES with and without FSI for DUNE

Muon momentum distributions for GENIE (left) and ACHILLES (right) are shown in Figure 4 for on axis, 10m off axis, and 20m off axis for FSI present and FSI absent. While the muon momentum differs depending on the off axis position, it is unaffected by whether FSI is present or not.

The proton momentum is shown in Figure 5. In this case, every final state proton has been included, which means that events with more protons will inadvertently have more of a contribution. A notable

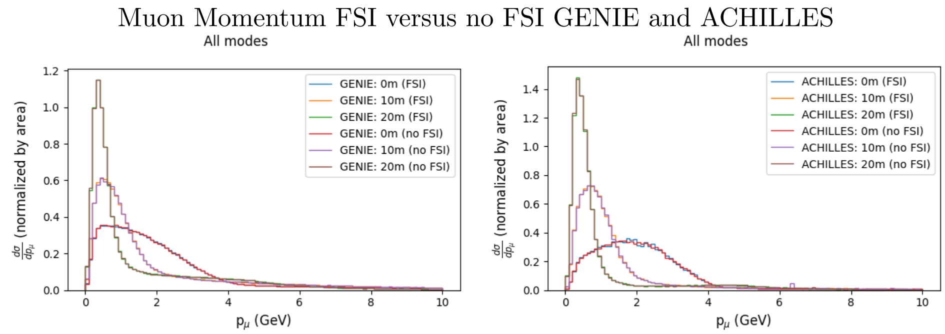

Figure 4: Muon momentum for DUNE ND positions for GENIE (left) and ACHILLES (right).

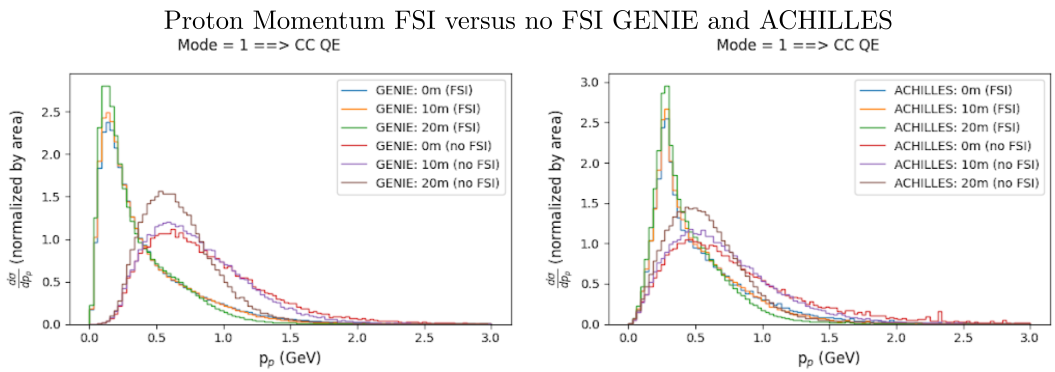

Figure 5: Proton momentum (all protons) for DUNE ND positions for GENIE (left) and ACHILLES (right).

feature is that the proton momentum peaks in nearly same place when FSI is present, resulting in similar distributions regardless of the position of the ND.

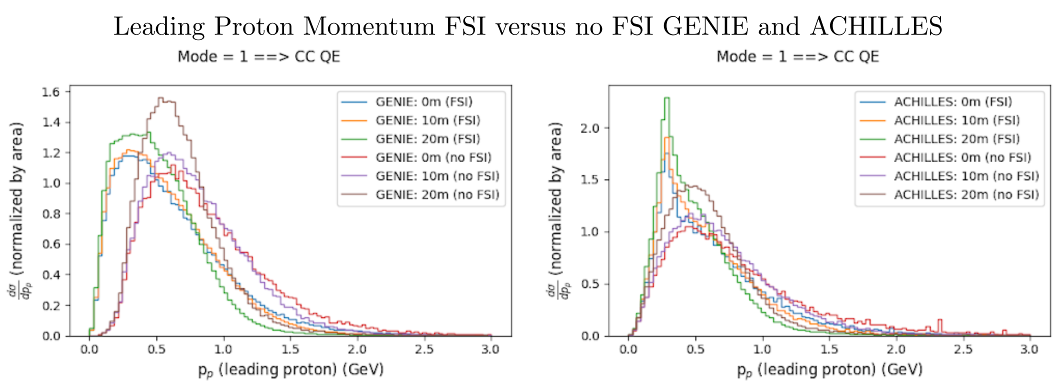

Figure 6: Leading proton momentum for DUNE ND positions for GENIE (left) and ACHILLES (right).

If we look at the case where FSI is turned off, or if we look at the leading proton only, as in Figure 6, we do see clear differences in proton momentum based on the ND position. In general, we expect the muon distributions to depend largely on the flux, whereas proton distributions are much more sensitive to the specific interactions modeled and FSI. Here FSI seems to smooth out the different proton momentum distributions such that they all appear similar. Since the FSI case better represents the results we will get from the actual DUNE experiment, this means that we may not be able to take advantage of DUNE-PRISM to get different proton momentum distributions. However, this potentially means that results from one position can be generalized to any position, since we know the distribution doesn't depend on the position.

δp_T FSI versus no FSI GENIE and ACHILLES

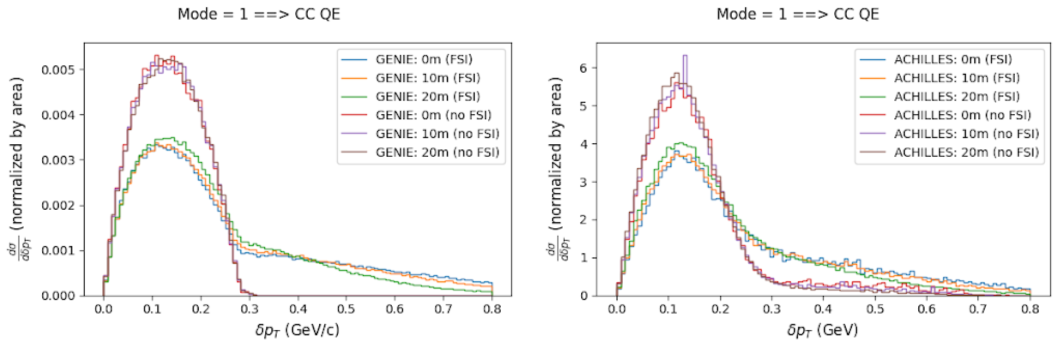

Figure 7: δp_T for DUNE ND positions for GENIE (left) and ACHILLES (right).

In Figure 7, we can see that for δp_T the distributions are similar for GENIE and ACHILLES. They both have a peak in the same place. In general, adding FSI for both GENIE and ACHILLES appears to increase the low δp_T events, meaning that the peak is higher. The same can be said for moving to increasingly off axis positions. δp_T above 0.3 GeV/c appears to be entirely the result of FSI for GENIE.

2.2 GENIE vs. ACHILLES comparison for different experiments

In this section the predictions for GENIE and ACHILLES (with FSI) will be compared with DUNE PRISM and different experiments such as MicroBooNE. If the results are found to be similar, this suggests that analyses used for one experiment can easily be applied to the other.

Angle between the protons for SBN and DUNE off axis GENIE and ACHILLES

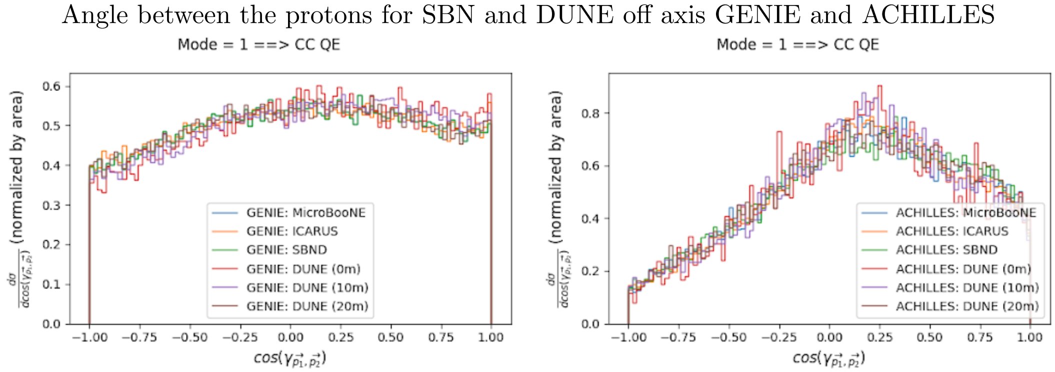

Figure 8: Opening angle cross sections for each experiment, for GENIE (left) and ACHILLES (right).

Here the opening angle between two protons is defined as the angle between the momentum of two protons in events with only two protons. In Figure 8, we can see that GENIE and ACHILLES have noticeably different predictions. The distributions appear to depend on the generator, not the experiment, since the predictions for a single generator look relatively similar regardless of the experiment. The ACHILLES prediction peaks around 0.25, whereas the GENIE distribution is much more flat.

In Figure 9, we see that the proton momentum distributions are pretty similar for both the different DUNE positions and the other experiments, likely due to the smoothing effect by FSI. However, the DUNE ND at 20m is very similar to MicroBooNE/SBND, compared to the other DUNE ND positions which don't peak as high, Interestingly, ICARUS matches the other sbn experiments well in GENIE, but not in ACHILLES.

Figure 10 shows that the leading proton momentum is also very similar for DUNE 20m off axis and MicroBooNE/SBND, although ICARUS is different for both generators. Since the leading proton momentum is less dependent on FSI, this may reflect a generator difference between GENIE and ACHILLES, which seem to predict either a higher or lower peak for ICARUS. This is inconsistent with

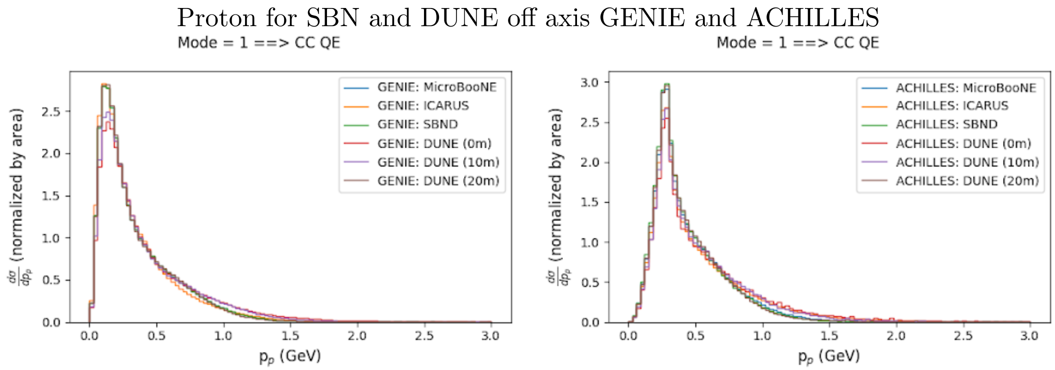

Figure 9: Proton momentum cross sections for each experiment (all protons), for GENIE (left) and ACHILLES (right).

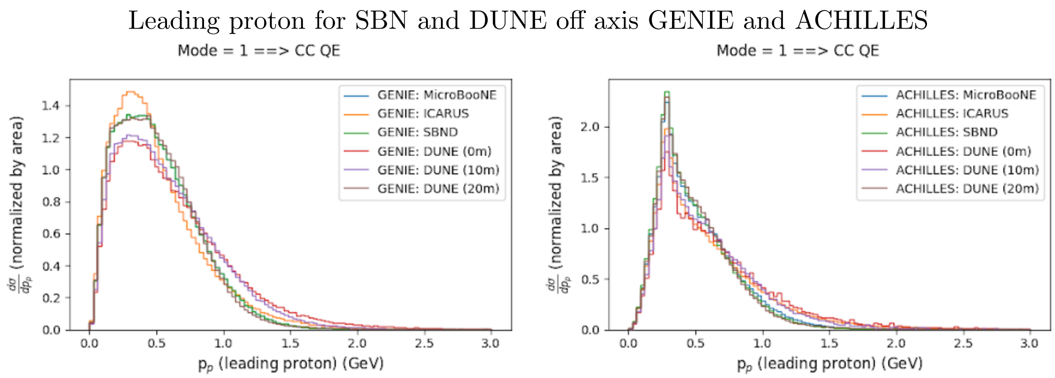

Figure 10: Leading proton momentum cross sections for each experiment, for GENIE (left) and ACHILLES (right).

the other experiments, where the generators agree on the relative ordering of the peak heights.

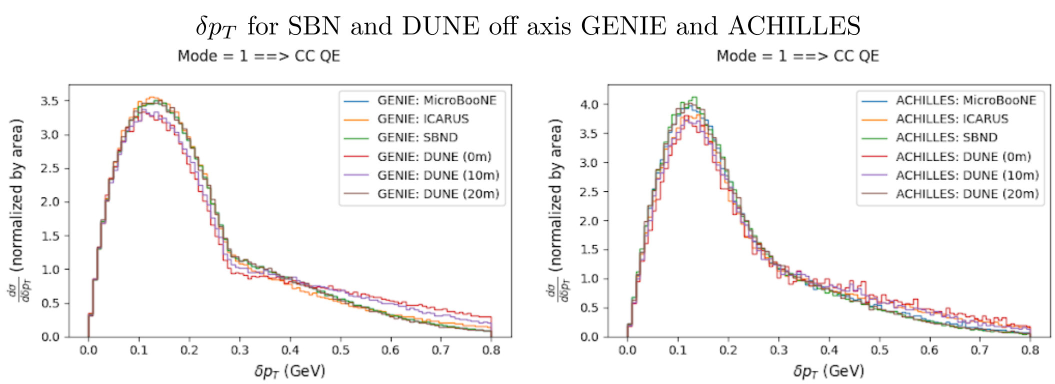

Figure 11: δp_T cross sections for each experiment, for GENIE (left) and ACHILLES (right).

As shown in Figure 11, GENIE and ACHILLES give similar predictions for δp_T regardless of the experiment, with the GENIE prediction slightly more rounded. Again, the ICARUS predictions are different, although it is clear that the δp_T prediction for 20m off axis is similar to MicroBooNE and SBND, which is interesting.

Overall the DUNE ND at 20m off axis appears to have similar physics to MicroBooNE and SBND, which is advantageous since it means analyses that were previously applied to them can easily be applied to DUNE at 20m off axis.

2.3 2p2h prediction for ACHILLES with ICARUS flux

p_μ for GENIE and ACHILLES (no FSI)

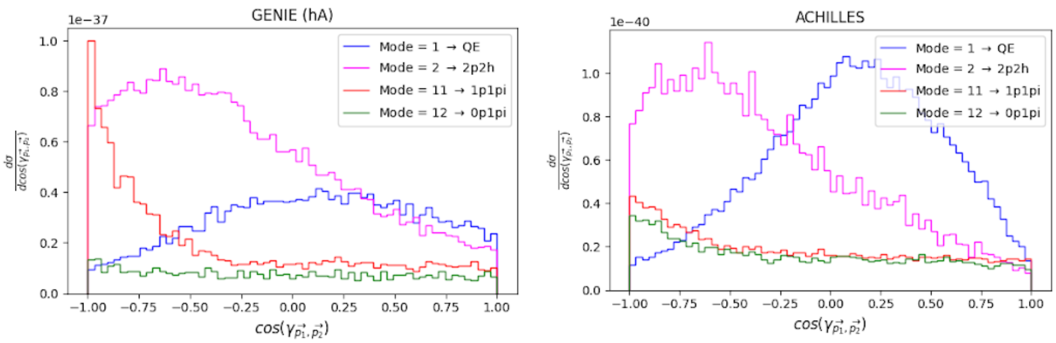

Figure 12: p_μ for GENIE vs. ACHILLES at different DUNE ND positions.

For the first time, a prediction for the 2p2h mode for ACHILLES was generated for ICARUS flux. The four modes in ACHILLES and the corresponding modes in GENIE are shown for ICARUS flux in Figure 12. As at the time of writing nuisance did not yet have ICARUS cuts, the following MicroBooNE cuts were applied (CC1Mu2p): 1 muon (0.1 < Pmu < 1.2 GeV/c), 2 protons (0.3 < Pp < 1 GeV/c), no neutral pions (any momenta), no charged pions above 65 MeV/c.

Notably, the QE components are significantly different between GENIE and ACHILLES. The 2p2h predictions are consistent between the two generators, although scaling for the ACHILLES prediction is a rough estimate and the actual scaling may be different.

Another significant difference between the two generators is the large peak observed for mode 11 in GENIE, but not ACHILLES. Overall, these results motivate the study of different FSI models in GENIE, such as hN, which may not have these features.

2.4 Data versus Event Generators Comparisons

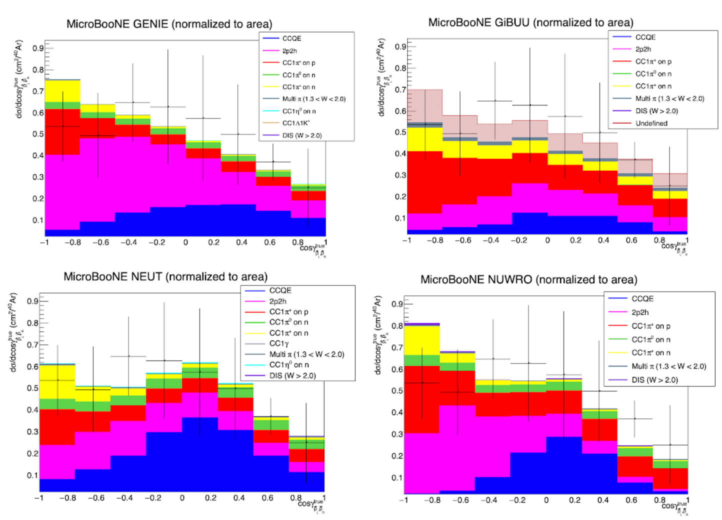

Figure 13: Opening angle cross sections with MicroBooNE cuts for each generator broken down by interaction mode.

Finally, MicroBooNE cuts were applied to generator simulations of MicroBooNE for GENIE, NEUT, NUWRO, and GiBUU, as shown in Figure 13. These all have a variety of generator differences, which is expected since the high uncertainty in measurements means there is no agreed-upon standard for generating the predictions, since it is difficult to know what the shape should actually be. Hopefully the increased precision from DUNE will help resolve this uncertainty.

The peak for CCQE seen in ACHILLES is also present in NEUT and NUWRO. It will be interesting to check if the same can be said for GENIE with hN, which was unable to be analyzed with nuisance at the time due to an error in labeling the modes.

3 Conclusions

The CC interactions for off axis DUNE ND positions are CCQE dominated, motivating the specific study of them. DUNE ND off axis cross section predictions for CCQE have been compared between GENIE and ACHILLES for the first time for observables such as proton momentum, the opening angle between two protons, and δp_T.

With FSI, the proton momentum for all protons looks similar and peaks in the same location, for both GENIE and ACHILLES. This could mean that DUNE PRISM will not be able to provide diverse distributions for proton momentum, unlike muons for example. (However, leading proton momentum distributions do look different between positions). However, it could also mean that analyses applied to one position can easily be extended to other positions.

Overall the 20m off axis position for DUNE has very similar predictions to the SBN experiments, especially SBND and MicroBooNE. This means previous analysis techniques on these experiments can be easily applied to DUNE 20m off axis.

For the first time, 2p2h predictions have been simulated for ACHILLES. These predictions are similar to GENIE (hA), though it remains to be seen if the same can be said for other GENIE FSI models like hN.

In the future, we plan to extend comparisons to CC0π events with ACHILLES and GENIE. This depends on receiving the 2p2h predictions for ACHILLES, since the primary contributions to CC0π are CCQE and 2p2h[4]. Finally, we plan to study additional FSI models for GENIE, such as hN2018.

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