Comparisons of Neutrino Event Generators from an Oscillation-Experiment Perspective

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Abstract. Monte Carlo generators are crucial to the analysis of high energy physics data, ideally giving a baseline comparison between the state-of-art theoretical models and experimental data. Presented here is a comparison between three of final state distributions from the GENIE, Neut, NUANCE, and NuWro neutrino Monte Carlo event generators. The final state distributions chosen for comparison are: the electromagnetic energy fraction in neutral current interactions, the energy of the leading π^0 vs. the scattering angle for neutral current interactions, and the muon energy vs. scattering angle of ν_μ charged current interactions.

Keywords: neutrino-nucleus scattering, monte carlo generators, final state interactions
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INTRODUCTION

Monte Carlo (MC) generators are important tools used in facilitating the interpretation of observed data in neutrino experiments. MC generators simulate the dominant neutrino-nucleon and neutrino-nucleus interaction final states. The relative importance of the various underlying physical processes varies depending on the experimental design and the phenomenon that is being measured. For example, the final state interactions (FSI) that are a primary concern for a neutrino interaction experiment may be of lesser importance to a neutrino oscillation experiment. The purpose of the this document is to examine the differences among final state observables from current neutrino MC generators, the generators examined are: GENIE [1], NUANCE [2], NEUT [3], and NuWro [4]. The distributions examined in this document are important for determining the background and baseline behavior in the next generation of neutrino oscillation experiments such as T2K and NOvA. The electromagnetic energy fraction, and the π^0 kinematical distribution are important for characterizing the background to ν_e appearance measurements; these are the topics of the first and second comparisons. The third comparison focuses upon the kinematics of the final-state muon, which is crucial to characterizing the behavior of the signal in a ν_μ disappearance measurement.

There are a number of independently crafted neutrino event generators which are available to researchers. Roughly speaking, the generators invoke a common set of generic processes, each or which is characterized by a coded model, for the purpose of describing neutrino interactions. One such process is quasi-elastic scattering which gives rise to a charged lepton plus a recoiling nucleon in the final state. (The scattering is truly elastic when the final- state lepton is a neutrino.) [5] Another dominant process results in single pion production, usually as the result of $\Delta(1232)$ resonance or other low-lying N* resonances. Most generators use the Rein-Sehgal model to describe such reactions [6]; NuWro however uses an isobar model and includes a non-resonant contribution. The third process is inelastic scattering both shallow, and deep inelastic scattering, usually characterized by multiple pions in the final state. The final process which has the smallest contribution to the total cross section is coherent scattering, characterized by a lepton and a single pion in the final state. The impulse approximation is assumed for all but the coherent scattering, thus the scattering occurs on an individual nucleon within the nucleus. Particles created in the primary interaction are then propagated through the nucleus using an intra-nuclear cascade model [7][8].

GENERATOR COMPARISONS

Electromagnetic Energy Fraction of Final-State Visible Energy

The incident neutrino energy was set to 2.0 GeV and carbon was chosen as the target medium. Neutral current (NC) events were selected and events with zero electromagnetic energy were excluded. Distributions were normalized to

100 events. The electromagnetic energy fraction is defined as the ratio of electromagnetic (EM) energy (electrons and gammas) to the total visible energy in the event. The EM energy fraction for three of the generators is plotted in Figure 1. The generators exhibit a similar response over most of the fraction range, however there are notable differences at the range endpoints. A large peak appears near 0.0 which is an artifact of the NUANCE generator. Recall that zero EM energy events are excluded. A smaller peak appears near 1.0 which is due to the NuWro generator.

The spike which appears at very small EM fraction is the result of large numbers of de- excitation photons produced by NUANCE. These are produced from the neutrino interaction. They represent EM energy but they contribute very little to the experimentally detectable ("visible") final state energy. This outcome reflects the fact that NUANCE was tuned to reproduce as much of the light (γs) produced in the event as possible, as was motivated by the design needs of the MiniBooNE experiment.

The NuWro spike near 1.0 indicates differences in its modeling of single pi0 coherent scattering compared to the other generators. NC coherent π^0 production is a likely culprit because the π^0 decays predominantly into $\gamma\gamma$, and coherent scattering NC(π^0) produces a single π^0 in the final state. If this spike is due to the NuWro coherent model we would expect that there would be an excess of π^0s in the forward going direction.

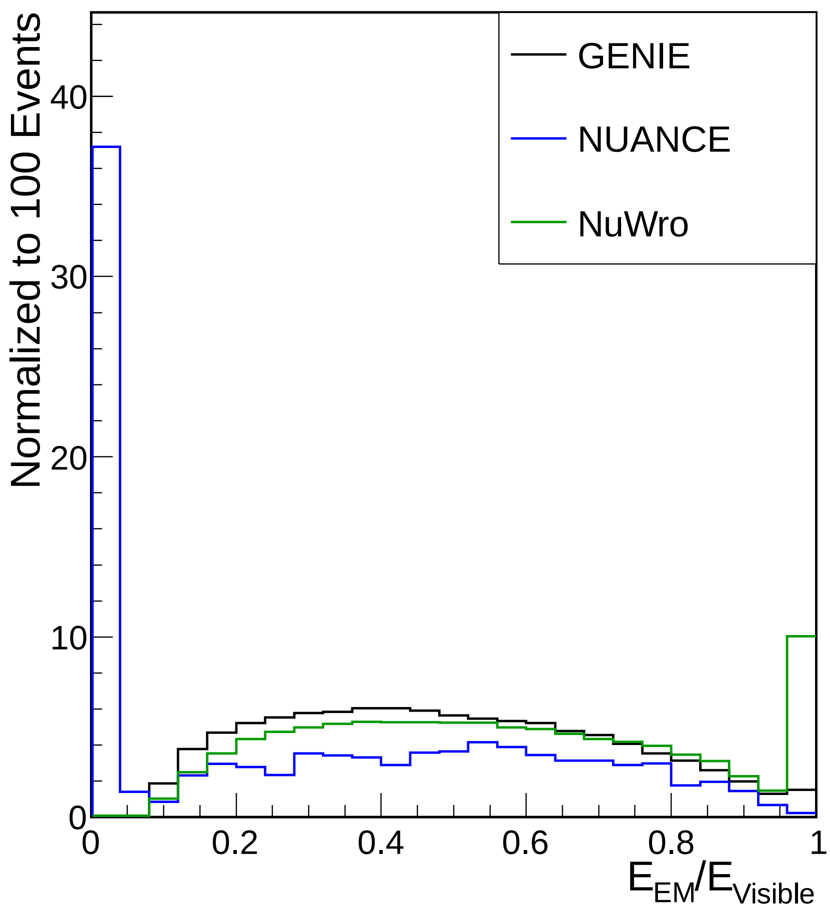

FIGURE 1. The electromagnetic energy fraction in NC final states as generated by GENIE (black), NUANCE (blue), and NuWro (green). The generators exhibit a similar response over most of the EM fraction, however differences are apparent near 0.0 and 1.0.

Kinematics of Leading π^0 in NC Events

The initial neutrino energy was set to 2 GeV with a carbon interaction target and leading π^0's were selected from the NC interactions. The behavior of these π^0's is of interest because π^0's which are forward-going in the Lab comprise a background to a $\nu_\mu \rightarrow \nu_e$ oscillation appearance measurement. The distributions of Figure 2 exhibit two aspects of generator response which are of particular interest.

The top-right plot of Figure 2 shows that the GENIE simulation gives π^0's with much broader distributions in both energy and in production angle, with more of the higher energy π^0's appearing in the backward hemisphere than occurs with the other generators. This broadness is exclusively due to intranuclear inelastic scattering of the produced π^0's. Every one of the pions in the dark red region of the top-right panel in Figure 2 reinteracted in the nucleus and underwent an inelastic interaction.

A second feature is discernible in the bottom-right panel of Figure 2, which shows the ratio of the NuWro 2D pion kinematic distribution to the average of all the generators examined. There is an excess of pions at the highest energies and most forward-going angles. This is indicative of a significant difference between NuWro's model of coherent scattering versus those of other neutrino generators.

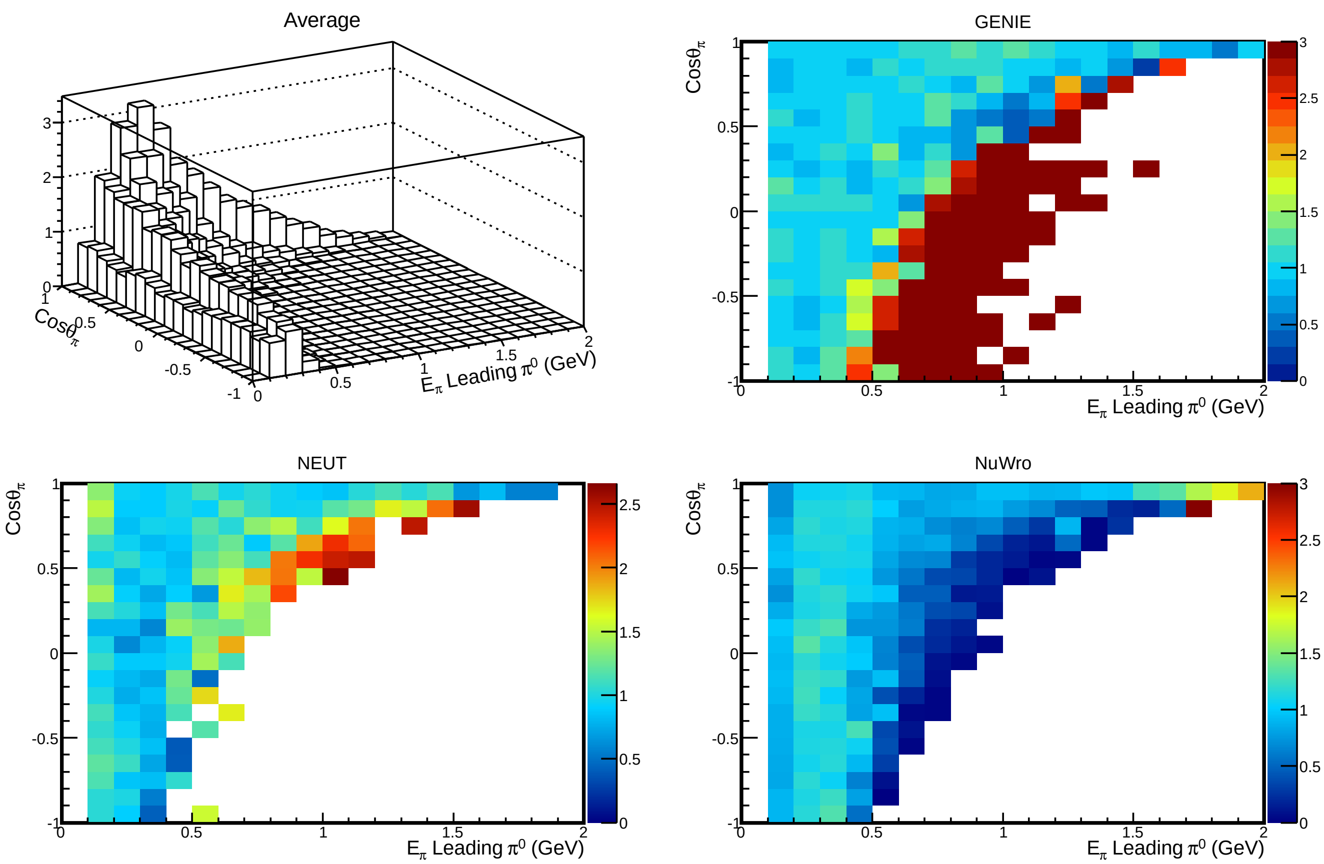

FIGURE 2. Leading π^0 vs. scattering angle for 2 GeV NC interactions on a carbon target normalized to 100 events. Upper left: The average 2D distribution for the three generators considered (GENIE, NEUT, NuWro). Upper right: The ratio of the GENIE distribution to average. Lower left: The ratio of the NEUT distribution to the average. Lower right: The ratio of the NuWro to the average.

Kinematic Localization of Muons in ν_μ + CH_2

Figure 3 shows the muon kinetic energy, T_μ, vs. the muon scattering angle with respect to the beam direction, $cos(\theta_\mu)$, for neutrino energies of 0.8 GeV and scattering on a CH_2 interaction target. Here, charged current (CC) events were selected. Proceeding similarly as in Figure 2 the average of the muon distribution over the plane of the T_μ vs. $cos(\theta_\mu)$ was calculated using the three generators, and then the ratio of the distribution for each generator was taken with respect to the average. These distributions are shown in Figure 3. The distribution of the muon kinematics are noticeably broader for the GENIE neutrino generator than the other generators under consideration. GENIE uses the relativistic Fermi gas (RFG) with the Bodek-Ritchie tail spectator momentum distribution [9]. The Bodek-Ritchie high momentum tail increase the number of high momentum nucleon within the nucleus. The momentum distribution of the nucleons has a smearing effect on the momentum of the final state lepton.

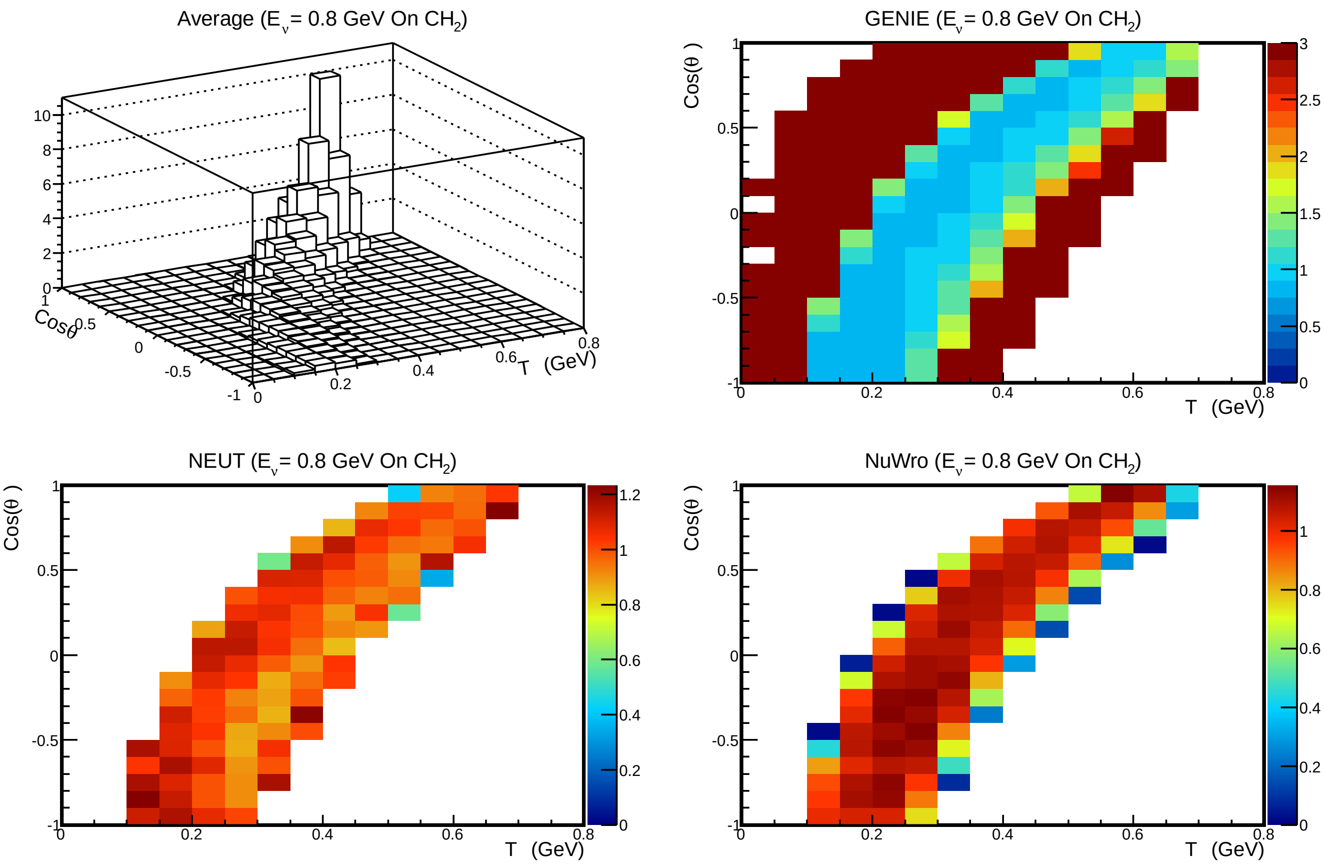

FIGURE 3. Muon kinematics for 0.8 GeV neutrinos in CH_2. Distributions are plotted over the plane of T_μ versus $cos(\theta_\mu)$. Top left: Average of the three generators under consideration. Top right: ratio of the GENIE distribution to the average. Bottom left ratio of the NEUT distribution to the average. Bottom right ratio of the NuWro distribution to the average. The GENIE distribution is discernibly broader than the distributions from NEUT and from NuWro.

CONCLUSION

This document compares observable final state distributions from four different neutrino event generators. The distributions relate to important contributions to the systematic uncertainties that are anticipated for ν_e appearance and for ν_μ disappearance oscillation measurements. Figures 1 and 2 explore the leading π^0 kinematics and show intriguing differences between the examined generators. Notable are the apparent differences in implementation of the NC coherent model among the generators. Examination of the final state muon kinematics also shows significant differences among the compared generators; these differences can be attributed to differences in the nuclear models used.

Neutrino generators are an essential tool for the data analysis of neutrino experiments. The comparisons of this work using four event generators which are currently used by ongoing experiments show that, while there are overall similarities among the predictions, some noteworthy differences currently exist. The variations among simulation outcomes may perhaps be viewed as a "good thing" in as much as the more accurate ingredients thet presently used can be identified and then integrated into a new and better generator. Eventually there may be convergence to a single neutrino generator which can describe most any aspect of neutrino scattering. In the meantime, work of the kind reported here is needed to develop and refine the current crop of event generators. Continued progress is needed in order that accelerator long baseline experiments such as T2K and NOvA will not be compromised by large or unknown systematic uncertainties.

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