

Overview of topics in the 2012 Generator Exercise

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Abstract. There is now a good series of exercises where the generator authors produce a series of plots so that results can be compared for important quantities. This time, each experiment was asked to suggest plots. A subset of these ideas were sent to generator authors; many of those results were shown at the conference. This talk gives an overview of the subjects covered.

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INTRODUCTION

MC neutrino-nucleus generators are an important component in the design and analysis parts of every experiment. Oscillation experiments rely on these programs for cut selection and efficiency determination, and background estimation. If different generators produce different background estimates, there is in principle a systematic error from the choice of generator made. Generators are then expected to provide a complete picture of the final state for all neutrino-nucleus interactions that are relevant to detectors. With the comparatively small set of existing data, generators must use theoretical models and data from other probes to give an idea of what might happen with neutrinos. As a result, there can be significant differences between the generators. Of course, adding to the body of neutrino-nucleus data is the major subject of this conference series.

The first exercise was led by Hugh Gallagher for NUINT04 [1]; they looked at neutrino cross sections for free protons and bound protons in oxygen. Significant differences were seen, reflecting the choices in model building. For NUINT09, direct comparisons of theory and generator results for specific cross sections were made. Steve Boyd and this author designed the study; Jan Sobczyk and Roman Tacik help organize and interpret the results [2]. This study showed there is a unified approach to many issues that is justified by older data. However, the wide range of results for the Coherent and Inclusive Pion Production shows the potential for differences in interpretation. In addition, both theory and data advances are coming more rapidly and generators must incorporate this new information. Fig. 1 shows results for coherent and 1-pion production processes. Although all generators used the same model for coherent interactions [3], differences were large. The 1-pion production models differ significantly in input choices - number of resonances used, nuclear model, FSI model - resulting in a wide range of predictions.

For NUINT12, Hugh Gallagher, Yoshinari Hayato, and Jan Sobczyk emphasized the experimental-generator interface. Each modern experiment was asked to provide a list of plots that provide important information about their experiment. Representatives from each generator group (GENIE, NEUT, NuWro, and NUANCE) provided the plots. This talk discusses the context of the results and following talks by Tomasz Golan and Nathan Meyer present the plots. For this presentation, the subjects will be oscillation backgrounds, quasielastic (QE)-like cross section, coherent cross section, final state interaction (FSI) issues, and total visible energy.

OSCILLATION BACKGROUNDS

T2K and MINOS are running experiments with an emphasis on extracting the $\nu_\mu \rightarrow \nu_e$ oscillation signal. NOvA will start taking data in summer of 2013 and LBNE is in the planning stages. Both plan to extract the same signal with ν_μ and $\bar{\nu}_\mu$. The primary known backgrounds come from neutral current electromagnetic processes and the ν_e content of the beam. Either photons or electrons in ν_μ events where there is no muon can simulate $\nu_\mu \rightarrow \nu_e$. The effect tends to give extra events at low reconstructed neutrino energy.

Isolated electromagnetic energy signals come from π^0 decays and γ 's coming from other particle and nuclear states. Nuclear states preferentially decay via γ 's if the excitation energy is below particle emission threshold, roughly 15 MeV in light nuclei and 8 MeV in heavier nuclei. None of the MC generators include these effects in a systematic

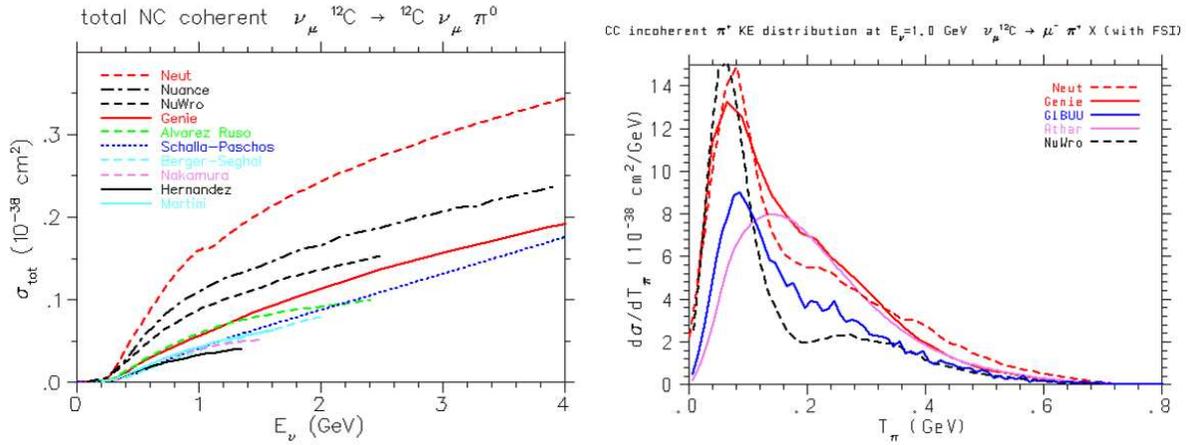


FIGURE 1. Results from the NUINT09 generator-theory comparisons. Many groups are shown for NC coherent total cross section (left) and pion kinetic energy distribution for 1-pion CC resonant processes for 1 GeV ν_μ carbon. All calculations are done for same quantity, so model dependence is directly determined.

way. There are many sources of π^0 's, especially DIS events and nucleon resonance states. All generators include these effects, but differences in implementation are known (Fig. 1).

For the T2K 2011 result [4], an alternate approach was used. Atmospheric π^0 events were grafted onto the normal MC events because the normal MC poorly describes these events.

QE-LIKE CROSS SECTIONS

Many oscillation experiments use the QE signal as a 'standard candle' to count ν_μ events. Problems come from difficulty in reconstructing the final state and masking due to Final State interaction effects. To accurately determine the final state (and measure the beam energy), detectors must be sensitive to low energy nucleons (neutral and charged) that come from FSI. Traditionally, water Cerenkov detectors only measure the muon and veto on charged pions in the final state. This creates uncertainty because the pion can be absorbed, converting its total energy to low energy nucleons. For these events, the beam energy is underestimated by $\sim 40\%$ with the normal reconstruction algorithm. A simulation of 1 GeV ν_μ Carbon events finds a roughly equal number of pion production and true QE events. About 25% of the pion production events have no pion in the final state and those events have calculated beam energy of 200-800 MeV too low. This is a hard background to identify and MC still has uncertain ability to predict it. (A new generation of pion production data will make this situation better.)

Generators all derive their pion absorption probabilities from pion-nucleus data. Although this is unlikely to be far off from reality, checks with neutrino data will be important. Even though all generators have good agreement with the pion-nucleus total absorption cross section, published data have large error bars. There is a large body of data giving information about how the pion energy is transferred to the final state, but only GENIE uses this information. Fig. 1(right) shows the differences in pion production cross sections; the π^+ kinetic energy spectrum for 1 GeV ν_μ carbon interactions is given. Some have a dip at pion energy corresponding to the peak of the Δ resonance and others don't.

An additional problem/opportunity is the recent hypothesis that roughly 20% of QE events are really Meson Exchange Current (MEC) events where the neutrino interacts with 2 nucleons while they are interacting with each. Instead of 1 nucleon in the final state when there is no FSI, there will be 2 nucleons. Therefore, the QE algorithm underestimates the neutrino energy by roughly 15% with a smaller effect in Q^2 . Fig. 2 shows a simulation of the effects MEC can have on an experiment where only the muon is detected in the final state.

Both T2K and MINERvA are actively trying to find nucleons from MEC. The new liquid argon experiments (ArgoNeut and MicroBooNe) have a strong interest in measuring the low energy nucleons.

The only generator in this study with an MEC interaction is NuWro. (Newer versions of GENIE have this, see the talk at this conference by Katori.) The larger issue of nuclear correlations has been poorly handled in the past because

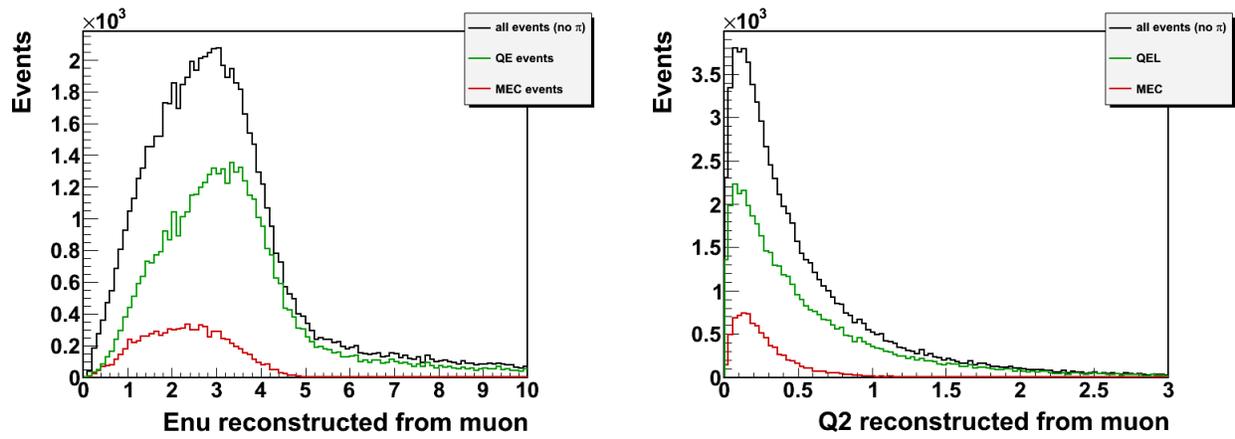


FIGURE 2. Calculations with the preliminary GENIE MEC model to show the effect on data. Plots show E_ν and Q^2 reconstructed using only the muon for NUMI ν_μ LE beam and a carbon target. The total QE strength has been matched to the MiniBooNe QE-like data [5].

all generators use the Fermi gas model to describe nucleon motion. NuWro is the only generator that includes a spectral function description.

Water Cerenkov detectors have no way to measure these low energy nucleons that become prevalent. Scintillator detectors see an energy-saturated blob known vertex energy. Liquid Argon detectors hold the promise of measuring all the energy in an event. The first results of proton multiplicity from ArgoNeut shown at this conference (see talks by Partyka and Palamara) show us the promise of this direction.

MINERvA and T2K are running experiments that are in the process of generating high quality QE-like measurements.

FSI EFFECTS

To measure the neutrino energy, a full accounting of the final state is required. In most cases, the muon energy is of great importance, but the hadronic energy is required. The hadronic energy is divided into charged and uncharged, low and high energy. Calorimeters are able to get the high energy particles well, both charged and neutral. Scintillators do well with charged particles of all energies. The new generation of liquid argon detectors potentially get all energies.

The general effect of FSI is to convert hadronic energy from single particles at higher energy to multiple tracks at lower energy. FSI can also convert charged to uncharged particles and vice versa. Therefore, FSI primarily masks the final state. The strong interaction also guarantees that FSI effects occur often, a good rule of thumb is that for neutrino interactions of about 1 GeV in carbon, 35% of the hadrons are influenced. For high energies, the fraction goes down; for higher mass, the fraction goes up as the total reaction (inelastic) cross section increases as $A^{2/3}$.

The hardest energy to recover is the hadrons with less than 50 MeV kinetic energy. These are produced by MEC events and FSI. Higher energy hadrons tend to interact with single nucleons; both the initial hadron and the struck nucleon propagate in the residual nucleus with reduced energy. When the nucleon energy is below about 80 MeV kinetic energy, the cross section for knocking out a few nucleons becomes important. It grows rapidly as the energy decreases. The best examples come from hadron-nucleus interactions where neutrons are detected in the final state. Fig. 3 shows 2 examples of neutron energy spectra coming from interactions of moderately high kinetic energy hadron probes on heavy targets. The advantage of detecting neutrons is that the spectrum can go to very low energies. For kinetic energies less than ~ 100 MeV the strength rises rapidly. There is good reason to believe that there are similar numbers of low energy neutrons and protons in the neutrino-nucleus interaction.

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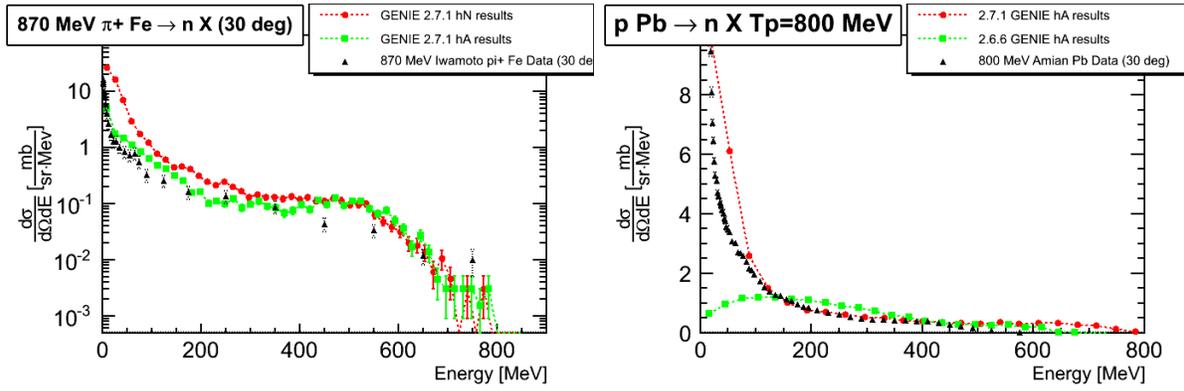


FIGURE 3. Neutron energy distribution at 30° for 870 MeV π^+ -iron with new GENIE hA and hN models. Comparisons with neutron energy distribution for 800 MeV p-Pb data for the old and new GENIE hA models. Note how many low energy neutrons come out of heavy targets for even high energy probes and the ability of the newer models to match this feature.

COHERENT CROSS SECTION

Measurements of the neutrino-nucleus coherent interaction have been limited to the total cross section. The background from inclusive pion production is large and poorly known from data. Therefore, background subtraction must come from Monte Carlo with uncertain error estimates. MINOS has recently shown preliminary results. MINERvA and T2K have strong efforts to measure this cross section in more detail.

The NUINT09 study showed how there are many differences in the generator algorithms for the coherent interaction. The original Rein-Seghal model [3] was designed for high energy (>10 GeV), making approximation in kinematics and the pion part of the interaction. The generators implement these approximations in different ways, showing up as factors of 2-3 in the total cross section. In addition, there are significant differences in the distributions in pion energy and angle (see Fig. 1).

TOTAL VISIBLE ENERGY

In CC events, the final state energy is divided between the muon and hadrons. For NC events, the undetectable neutrino complicates the final state. MINOS determines the total visible energy with a calorimeter; this becomes an important part of the estimated error for Δm_{23}^2 [6].

Many interactions contribute to the final state. Like the studies of electromagnetic energy in Oscillation Backgrounds section, this is a global property. Nevertheless, this is an excellent way to get an overall picture of what is inside the generators. For example, the mix between electromagnetic and hadronic energy and between charged and neutral particles will go into this quantity.

SUMMARY

Generator comparisons have become an important part of the NUINT series. It's a lot of work for all involved, but the results are unique comparisons of interesting quantities. These comments provide an introduction to the present study.

Every experiment must cope with inefficiencies and background. Neutrino experiments are different from collider experiments because there is no problem with angular acceptance. Since neutrinos interact very weakly, the target becomes the detector. However, the final state is a complicated mixture of leptons and hadrons, charged and uncharged particles. Therefore, the detector choice is very tricky. Water, scintillator, and calorimeter are the traditional choices; each involves a trade-off that means the MC generator is important to show what happens to particles that aren't visible. The newest detector material is liquid argon; it is then possible to get a response in the detector for all particles in the final except neutrinos. This new era will require generators to incorporate more details of the neutrino-nucleus interaction.

The experimental groups know the problems in their analysis and have made excellent choices for comparisons of existing generators. The reader should look closely for differences and can then speculate about the underlying causes.

ACKNOWLEDGMENTS

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