Current status of final-state interaction models and their impact on neutrino-nucleus interactions

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Abstract. Hadrons produced in neutrino-nucleus interactions may re-scatter while propagating through the nuclear medium. Such re-scatters, often called Final State Interactions (FSI), can change the charge and multiplicity of the outgoing hadrons, as well as altering their final state kinematics. A good description of these processes is crucial for accurate measurements of the neutrino energy spectra – a key part of neutrino oscillation analyses.

We present the comparison of predictions from various neutrino interaction event generators (NEUT, GENIE, Geant4, NuWro and FLUKA) with thin-target pion/nucleon scattering data. The FSI model used in NEUT is a microscopic cascade where the hadrons are propagated semiclassically through a nuclear medium in finite steps. A new tune of the cascade model has been performed for improvements from the current NEUT parameters using external data, and is presented.

1. Introduction

To improve our understanding of neutrinos and how neutrinos oscillate we have to study how neutrinos interact with matter. Accurate measurements of neutrino flux is essential for precise measurements of oscillation parameters. Since the hadrons produced from a neutrino interaction must propagate through the nucleus before being observed in a detector, they can re-interact inside the nucleus. Such re-interaction, which we call final state interactions (FSI), can affect the reconstruction of final state particles. Secondary interactions (SI) can occur when particles interacts with materials inside a detector, which could also affect the kinematics of observed particles.

Pion and nucleon FSI/SI are one of the dominant detector systematics in the near detector of T2K. The current treatment of systematic uncertainties of FSI/SI are uncorrelated, and different models of FSI/SI are used for near and far detector. Unifying treatment of FSI/SI in T2K near and far detectors for nucleons and pions allows us to have a consistent way of retuning free parameters in order to evaluate correlations between them. Comparison using current NEUT parametrisation is presented in section 3, section 4 shows the improved method of tuning pion FSI parameters.
2. Cascade Models in NEUT and other generators

NEUT [1] is a neutrino interaction event generator used primarily in T2K. It simulates FSI using a semi-classical cascade model. Nucleons inside a nucleus are assumed to have a Fermi Gas momentum distribution. For pion, the maximum momentum is determined by the density (Local Fermi Gas model) and is constant parameter for the other particles (Global Fermi Gas model). After the hadrons are produced at the neutrino interaction vertex, they propagate through the nucleus step-by-step. For pion momentum less than 500 MeV/c, momentum and density dependence of the mean free path (MFP) is calculated based on the Delta-hole model from Oset et. al. [2]. For higher momentum, MFP is calculated from free π-p scattering data from SAID. For nucleon FSI, MFP is calculated from free nucleon-nucleon cross-section using MECC-7 parametrisation [3]. There are seven scaling parameters for the pion FSI model: three each for low-energy and high-energy region for Quasi-Elastic (QE), Absorption (ABS) and Charge Exchange (CX) microscopic scattering probabilities, and one parameter for overall scaling. For nucleon FSI model there are four scaling parameters: Quasi-Elastic, single/double pion production interaction probabilities, and one parameter for overall scaling.

Models used in other generators include GENIE hA/hA2014 model [4], NuWro [5], FLUKA, Geant4 (Bertini and Binary) models are used for comparison with NEUT. The GENIE hA/hA2014 models are effective cascade models, while the other generators all use semi-classical cascade model but are tuned by different cross-section data. Geant4 models use a more recent Local Fermi Gas (LFG) model to describe nucleons inside nucleus.

3. Comparing generator predictions with external data

Comparing different generators with external scattering data for different nuclei allows us to quantify uncertainties of FSI models. NEUT MC are generated by simulating large number of π⁺ or proton on a carbon target with uniform energy spectrum. Interaction channels are defined based on outgoing particles for each event. The cross-section for each channel can be calculated using total number of events and target area. Figure 1 shows proton-Carbon scattering cross-section predictions from different generators for three interaction channels. We defined elastic channel if we observe only one nucleon in the final state, but because in NEUT and NuWro the target nucleon always got knocked out, there are no separate elastic channel for both generators. All other processes are counted as reactive channel. An estimated uncertainty band of 30% is added to NEUT prediction, the uncertainty can be quantified after finalising nucleon fitting result. While NEUT prediction for total cross-section agrees well with data, there is a discrepancy for reactive cross-section in particular at low momentum.

Figure 1. Proton-Carbon scattering cross-section predictions from different generators for total (left), elastic (middle) and reactive (right) interaction channels. There are no elastic interaction process in NEUT and NuWro.

Figure 2 shows the same comparison for π⁺-Carbon scattering for five interaction channels. The comparison has been improved by including new external data such as the DUET pion scattering data [6]. Most data points are within the 1σ band of current NEUT predictions.
4. Fitting FSI parameters

Current pion FSI parameter tuning procedure [7] can be improved by including new external data, more freedom with more fit parameters, and including final-state kinematics. Proton and $\pi^+$ beam scattering data from various experiments are used for tuning FSI parameters as they isolate the hadronic processes involved in FSI. Examples of external data used can be found in [8,9]. Best-fit points for each free parameter in pion/nucleon FSI model are found using minimum $\chi^2$ method. Different sets of MC are generated using different combination of FSI parameters. $\chi^2$ values for each set of MC are calculated by comparing NEUT $\pi^+$/proton scattering MC with external data. Initial data fit was performed using 3D grid scan for 3 low-energy pion parameters and 3 nucleon parameters. To get a smooth $\chi^2$ function, two methods of interpolation (polynomial or spline) are used to find best-fit points. The difference in the obtained minimum $\chi^2$ using the two methods is about 0.05 which is comparable to the size of the error of the parameters (see Table 1), so we will combine the two methods. Results are compatible with previous fitting work. The nucleon parameters do not allow NEUT to model the low momentum region, as no tuning can result to a good fit to all the data, so reactive cross-section data points below 500 MeV/c are excluded for fitting.

| Pion           | Nucleon         |
|----------------|-----------------|
| **Best-fit point** | **Best-fit point** |
| QE 0.936        | Reactive 1.229  |
| ABS 1.241       | Elastic 1.140   |
| CX 0.790        | Total 0.857     |
| Error 0.068     | Error 0.075     |
| Error 0.080     | Error 0.078     |
| Error 0.091     | Error 0.044     |

Table 1. Best-fit points for pion (left) and nucleon (right) FSI parameters found using minimum $\chi^2$ method.

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