Neutrino Flux Predictions for Cross Section Measurements

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Abstract. Experiments that measure neutrino interaction cross sections using accelerator neutrino sources require a prediction of the neutrino flux to extract the interaction cross section from the measured neutrino interaction rate. This article summarizes methods of estimating the neutrino flux using in-situ and ex-situ measurements. The application of these methods by current and recent experiments is discussed.

Keywords: Neutrino flux prediction, Hadron production
PACS: 14.60.Lm, 24.10.Lx, 13.85.-t

INTRODUCTION

Modern neutrino oscillation experiments require measurements of the interaction cross section of neutrinos scattering off of nucleons bound in a nucleus. The interaction cross sections of neutrinos of energy $\mathscr{O}(1)-\mathscr{O}(10)$ GeV are typically measured with muon neutrinos (ν_μ) produced at accelerators by colliding a proton beam with a fixed target. Charged mesons produced in the collisions are typically focused by magnetic horns, and a ν_μ beam is produced, predominantly from the decays of charged pions. Measuring the interaction cross sections of these ν_μ requires an absolute prediction of the neutrino spectrum that is determined independently of the interaction process being measured. The configurations of beam lines for some current experiments (MINERνA, MininBooNE, T2K) measuring neutrino cross sections are listed in Table 1. All three experiments employ a low Z target that is ~ 2 interaction lengths long, and at least one magnetic horn to focus the charged mesons that are produced.

A number of methods are applied to predict or measure the neutrino flux spectrum for cross section measurements. They include:

- The detection of charged current neutrino scattering on the electron, $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$. The threshold of this process is $E_\nu > 12$ GeV, and the initial neutrino energy cannot be fully reconstructed since there is a neutrino in the final state.
- The detection of neutral current neutrino scattering on the electron, $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$. As with the charged current scattering on the electron, the presence of the neutrino in the final state precludes the reconstruction of the neutrino energy.
- The “low-ν” method employs charged current interactions on the nucleons, $\nu_\mu + n \rightarrow \mu^- + X$, where X is the hadronic system in the final state. If the energy carried by the hadronic final state is sufficiently small, the cross section is flat with energy. By identifying interactions with small energy in the hadronic system, the shape of the neutrino spectrum can be extracted. This method requires the ability to measure the energy of hadronic final states. Since the method only constrains the shape of the flux spectrum, an alternative method must provide the absolute normalization of the cross section for scattering on nucleons.

TABLE 1. The configurations of beam lines for current experiments measuring neutrino interaction cross sections.

	MINERνA (NuMI)	**MiniBooNE (Booster)**	**T2K (J-PARC)**
Proton Beam Energy (GeV)	120	8	30
Peak Neutrino Energy (GeV)	3-8	0.8	0.6
Detector Configuration	on-axis	on-axis	off-axis
Target Material	Graphite	Beryllium	Graphite
Hadron Production Data	NA49, NA61	HARP	NA61

- Muon detectors can measure the muons produced in the same two-body decays that produce most of the neutrinos, $\pi^+ \rightarrow \mu^+ + \nu_\mu$. To extract a neutrino spectrum directly from these measurements requires muon detectors that can separate muons from background, measure the muon energy spectrum and are calibrated to extract the absolute rate of muons produced.
- A "bottom-up" approach to predicting the flux relies on ex-situ measurements of the hadron interactions in the target material and in-situ measurements of the proton beam properties and magnetic horn fields to produce a data-driven simulation of the neutrino flux. This approach predicts the spectrum shape and normalization, but does not rely on in-situ measurements of the particles produced in the neutrino beam line.

This article includes descriptions of how the "low-ν" approach, muon detectors and the "bottom-up" approaches are applied in recent and current experiments.

THE "LOW-ν" METHOD

The "low-ν" method developed by the CCFR/NUTEV collaboration [1, 2] takes advantage of the fact that the charged current differential cross section only depends on the structure function $\mathscr{F}_2$, which does not depend on the neutrino energy, as the energy carried by the hadronic system in the final state goes to zero. Detectors that can measure the hadronic energy can separate "low-ν" events and infer the shape of the neutrino spectrum from the energy dependence of "low-ν" events. This procedure has been applied for neutrino energies as low as 3.5 GeV by the MINOS experiment [3].

Recently Bodek *et. al.* [4, 5] have proposed applying the "low-ν" method at energies relevant for MINERνA, MiniBooNE and T2K. In the low energy region, the model dependence of the "low-ν" assumption becomes more significant, however, Bodek *et. al.* have shown that for $E_\nu = 500$ MeV and hadronic energy less than 100 MeV, the model dependent uncertainties on the "low-ν" cross section are $\sim 5\%$. The method has not yet been applied by these experiments.

MUON DETECTORS

Both the NuMI and T2K beam lines employ muon detectors to detect the muons from the two-body $\pi^+ \rightarrow \mu^+ + \nu_\mu$ ($\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$) decays. The NuMI beam line includes four ionization chamber muon monitors downstream of the beam dump located behind varying thicknesses of rock [6]. Since each array of ionization chambers is behind a different thickness of rock, there is a different energy threshold for muons that penetrate to each monitor. This allows the muon monitor measurements to be used to directly constrain the spectra of charged mesons produced in the beam line [7]. The dominant uncertainties in this type of constraint arise from the absolute normalization of the muon signal and the background from δ rays produced in nearby materials.

T2K employs ionization chamber and silicon PIN photodiode array muon monitors at a single location after the beam dump [8, 9]. Only pions with momentum greater than 5 GeV/c decay to muons that penetrate to the T2K muon monitor. Since most of the T2K neutrino flux originates from the decay of pions with momentum less than 5 GeV/c, the T2K muon monitor cannot directly constrain the region of the pion spectrum of interest for the neutrino flux prediction. Instead the T2K muon monitor is used to tune and constrain the beam direction, which is especially important for the T2K off-axis beam.

DATA-DRIVEN FLUX SIMULATION

MINERνA, MiniBooNE [10] and T2K [11] predict their neutrino fluxes with data-driven simulations of the neutrino beam line. The uncertainties on these flux predictions are driven by the uncertainty on the hadron interaction models used to model the interactions of beam protons in the target and secondary hadrons in the target and surrounding materials. The hadron interaction models are tuned to hadron production data from experiments such as NA61/SHINE [12, 13], HARP [14] and NA49 [15]. Measurements of the proton beam intensity and profile before it collides with the target, and the horn fields are also important inputs to the simulation.

T2K uses pion [12] and kaon [13] production data from a 0.04 interaction length "thin" graphite target collected by the NA61/SHINE. As shown in Fig. 1, these data cover much of the phase space relevant for the T2K flux prediction.

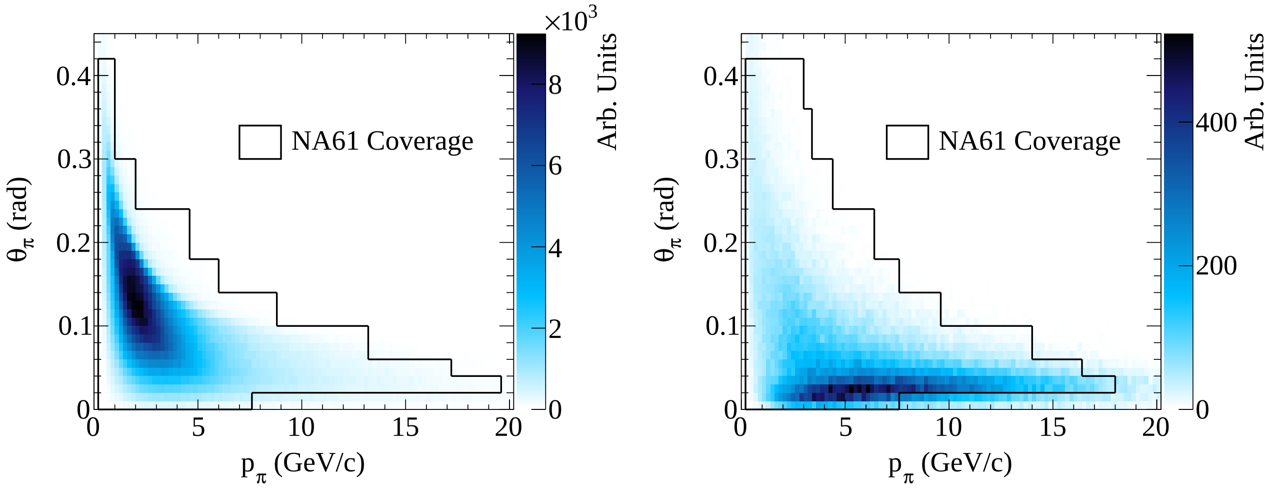

FIGURE 1. The coverage of NA61/SHINE π^+ (left) and π^- (right) production measurements compared to the pion phase space that contributes to the T2K flux.

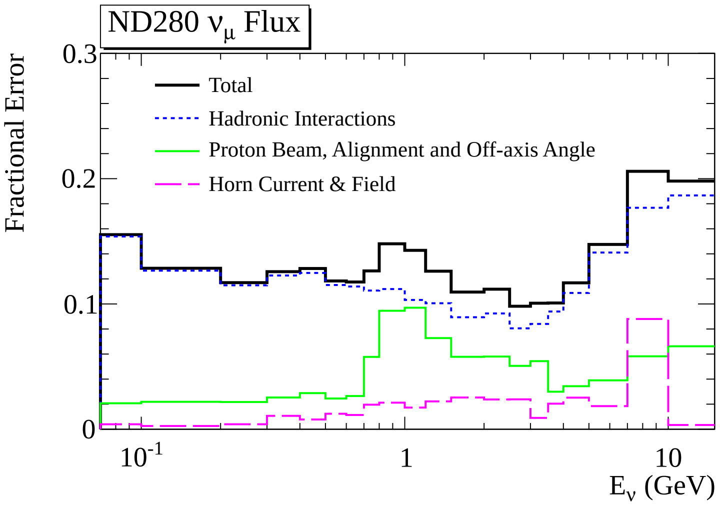

FIGURE 2. The fractional error on the T2K ν_μ flux prediction as a function of the neutrino energy.

Pion production modeling outside of the covered phase is studied by extrapolating the NA61/SHINE data using the BMPT parametrization [16]. T2K tunes the hadron production model with the NA61/SHINE data, and the energy dependent uncertainties on the flux prediction are dominated by the uncertainties on hadron interactions, as shown in Fig. 2. These uncertainties arise from the propagation of systematic errors from the hadron production data, and comparisons of data and models where the model is not tuned to the data.

The uncertainty on the hadron interaction modeling can be reduced by measuring hadron production on targets that are replicas of those used in the neutrino experiments. The NA61/SHINE experiment has collected particle production data using a replica T2K target. A preliminary analysis [17] to tune the T2K flux prediction using the replica target data has shown results that are consistent with the tuning with the thin target data. The analysis and application of a larger replica target data set should provide a significant reduction of the hadron interaction modeling uncertainty for the T2K flux prediction.

CONCLUSION

Experiments measuring the interaction cross sections of muon neutrinos with energy $\mathscr{O}(1) - \mathscr{O}(10)$ GeV employ accelerator based muon neutrino beams. The neutrino flux spectrum of these beams can be measured by detecting neutrinos or muons or by data-driven simulations of the beam lines. Current experiments such as MINERνA, MiniBooNE and T2K rely primarily on the data-driven simulations of their beam lines based on measurements by hadron production experiments. T2K will push the limits of the achievable precision with the data-driven approach by incorporating hadron production data collected on a T2K replica target by the NA61/SHINE experiment.

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