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Prospects for Precision Neutrino Cross Section Measurements*

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Abstract

The need for precision cross section measurements is more urgent now than ever before, given the central role neutrino oscillation measurements play in the field of particle physics. The definition of precision is something worth considering, however. In order to build the best model for an oscillation experiment, cross section measurements should span a broad range of energies, neutrino interaction channels, and target nuclei. Precision might better be defined not in the final uncertainty associated with any one measurement but rather with the breadth of measurements that are available to constrain models. Current experience shows that models are better constrained by 10 measurements across different processes and energies with 10% uncertainties than by one measurement of one process on one nucleus with a 1% uncertainty. This article describes the current status of and future prospects for the field of precision cross section measurements considering the metric of how many processes, energies, and nuclei have been studied.

INTRODUCTION

The need for precision cross section measurements is more urgent now than ever before given the requirements of current and future oscillation experiments. These experiments need to measure precisely the oscillation probabilities for neutrinos ranging from 600 MeV to several GeV, using targets ranging from carbon and oxygen to argon and steel. The neutrino energy that is available for any detector technology to measure depends not only on the specific process that the neutrino underwent on a particular nucleon, but also the effect of the nuclear environment on that process.

The nuclear environment can change the cross section from that of a bare nucleon process in several ways. For example, nucleons are not simply in a non-interacting relativistic Fermi Gas when they interact with the exchange boson, they are often interacting with each other. In addition, the final state particles that exit the bare nucleon process can lose energy on the way out of the nucleus, or even undergo charge exchange and leave the nucleus at a different energy and a different charge than the one produced in the bare nucleon process.

Oscillation experiments try to address this challenge using a battery of measurements: first, hadron production measurements and a detailed beamline simulation are needed to provide an accurate prediction of the initial flux of the neutrinos as a function of energy. Second, most oscillation experiments will use a (suite of) near detector(s) to try to measure the neutrino event rate as a function of energy before oscillations have taken place. There is usually an emphasis on having at least part of the near detector include the same nuclei that make up the far detector to reduce uncertainties due to these nuclear effects. However, the amount of energy lost in that nucleus affects the overall neutrino energy scale and will not cancel between the near and far detectors in a measurement of the neutrino mass squared splittings.

External cross section measurements are another important component of an oscillation experiment's strategy for making far detector predictions. For example, T2K uses external cross section measurements from MiniBooNE and MINERvA at higher energies in its fit for oscillation parameters [1]. Until we as a field can produce neutrino interaction models (and associated generators) which can faithfully reproduce cross section measurements, experiments will use what they have on hand and try to determine uncertainties accordingly. The more ways we can test and improve models by providing precision cross section measurements, the better those models will eventually be, and the better the oscillation parameters will be measured.

CURRENT STATUS

Given the needs of oscillation experiments it is worth examining the breadth of measurements have been made so far as well as what measurements are potentially available given the data that has been taken. The important issues for each energy and interaction channel are not only the flux, detector mass, and acceptance that are available, but what uncertainties are achievable on those quantities. Given the few-GeV neutrino energies that are in use by current oscillation experiments, it is most important to measure (and ultimately model) the charged-current quasi-elastic process (CCQE), charged and neutral pion production, coherent pion production, and to a lesser extent deep inelastic scattering (DIS). Since it is sometimes difficult to separate those different processes in any one detector technology, a total charged-current cross-section measurement (refered to as CCINCL in Tab. I) can also be useful to help constrain models. Although the nuclear effects were first seen in DIS in charged leptons [2], there is no guarantee that even if we completely understood all of those effects for charged leptons, that we could then predict how the nucleus would affect these other processes, or even DIS for neutrino scattering.

The energies available range from the 600 MeV narrow band beam at T2K's near detector complex, to the 1 GeV Booster Neutrino Beam, through the NuMI Beamline's broad band energies peaked at 3 GeV and 6 GeV. By using hadron production measurements from HARP, the Booster Neutrino Beam absolute ν_μ ($\bar{\nu}_\mu$) flux uncertainties were dominated by a 14.7% (17.5%) flux uncertainty in π^+ (π^-) production [3, 4]. The T2K neutrino flux uncertainties are approximately 12% at the peak off axis neutrino energy, and are also dominated by hadronic interactions [1]. The MIPP experiment [5] has produced measurements of charged pion and kaon production off the NuMI target which should result in significantly lower total flux uncertainties for both NOvA [6] and MINERvA, and MINERvA's flux uncertainties at the time of NuFact'15 were approximately 12% [7], again dominated by the uncertainties in pion production [8].

The neutrino target nuclei available today range from carbon (in scintillator oil or solid scintillator), to oxygen (in Water Cerenkov), to argon (liquid argon time projection chambers) and finally iron (scintillator-steel tracking calorimetry). These detectors have all been placed in neutrino beams, and some have also been placed in test beams of charged hadrons and electrons, in order to better measure detector response. Most recently, MINERvA has released results on its scintillator detector responses to pions and protons ranging from 0.4 to 2 GeV [9] and the LArIAT test beam program [10] has been collecting data on a Liquid Argon TPC in that same beamline. The typical precision on the absolute energy scale that MINERvA achieved was between 3-4% from this program.

The current coverage of neutrino experiments in terms of energy ranges and target nuclei can be shown in Tab. I.

UPCOMING RESULTS

Although there have been several new results on cross sections since the 2014 NuFact conference, the current data still have many potential channels and kinematics to explore. In addition, the MicroBooNE experiment started operations in a 1 GeV broad band neutrino beam just after the 2015 NuFact conference took place, and will be able to shed more light on the puzzles that exist on pion production because of its improved resolution of pion kinematics using a Liquid Argon Time Projection Chamber, compared to MiniBooNE's resolution using an oil Cerenkov detector.

TABLE I: This table shows the channels that have been measured as a function of target nucleus and process. The entries that are names of experiments correspond to data sets that are being taken now, or if in italics, data sets that are projected to be available in the future.

	Peak Neutrino Energy				
Target	700MeV	1GeV	2 GeV	3 GeV	6 GeV
CH_2		CCQE [11, 12] $\pi^{\pm}, \pi^0$ prod. [13, 14]	NOvA		
CH	CCQE [15] Coherent [19]	CCQE [16]		CCQE [17, 18], Coherent [8] $\pi^{\pm}, \pi^0$ prod. [20, 21]	MINERvA
H_2O	T2K			MINERvA	MINERvA
Ar		MicroBooNE *SBND*		CCINC [22], Coherent [23], CC-noπ [24]	*CAPTAIN* *MINERvA*
Fe		CCINCL ratio [25]		CCQE [26], π prod., coherent, CCINCL [27] CCINCL Ratios [28] DIS Ratios [29]	MINERvA
Pb				CCINCL and DIS ratios [28, 29]	MINERvA

T2K

The T2K near detector suite allows for both on-axis measurements using a broad band beam at 3 GeV, as well as off axis measurements using a narrow band beam at about 700 MeV. The on-axis detector, in particular the central module which allows for proton and some pion identification, will be able to do exclusive-channel cross sections, including a measurement of charged current coherent pion production and 0 pion prodution on Carbon. The off-axis detector suite affords a much broader range of final state channels and target nuclei. For example, T2K expects to have results out shortly on both neutral and charged pion production, as well as electron neutrino measurements. The variety of near detector components means that T2K is also planning to measure oxygen and lead to carbon cross-section ratios.

MINERvA

There are several new measurements from MINERvA that are presented elsewhere in these proceedings. Reference [30] includes a first measurement of the electron neutrino quasi-elastic cross section, which shows that at least to the level of the statistical precision of the data, the electron neutrino cross section is consistent with that of muon neutrinos as a function of momentum transferred to the nucleus. In addition, a first measurement of the ratios of neutrino DIS cross sections between C, Fe, and Pb and CH is given in Ref. [31]. Other expected results that will come from MINERvA's Low Energy (3 GeV) data set is a charged current quasielastic double differential cross section, and pion production cross sections for neutrinos and antineutrinos both, as described in Ref. [32, 33] respectively.

In the future, MINERvA expects to provide measurements using its Medium Energy (6 GeV) data set, which is in progress. The increased flux, cross section, and accumulated protons on target in this beam will mean that the channels that have already been measured on CH (plastic scintillator) can be measured on the solid nuclear targets (C, Fe, Pb) at interesting ($\sim 10\%$ or better) precision.

NOvA

NOvA has already accumulated an impressive near detector data set comprising more than 2 million charged current neutrino interactions [34]. These statistics will allow NOvA to map out both the quasi-elastic and total charged current cross sections at 2 GeV on CH_2 in great detail. Given the muon neutrino statistics, the electron neutrino charged current statistics in NOvA will also be at the tens of thousands of events, and in fact the measurements there will be limited by the uncertainty in the flux, and the detector energy scale. Both of these are expected to improve over time and with the incorporation of hadron production measurements.

FUTURE PROSPECTS

Given the suite of measurements expected from the current operating program, the path foward is clear. Given the DUNE far detector technology of Liquid Argon Time Projection Chambers, and the broad band of energies expected at DUNE, high statistics data on argon nuclei between 0.5 through 6 GeV is clearly needed, for both neutrino and antineutrino interactions.

In order to best constrain models of neutrino interactions on argon, however, comparisons between argon and other nuclei are also in demand, again in both neutrino and antineutrino beams. Although at the time of this writing the MINERvA experiment has a large sample of neutrino events across nuclei ranging from helium to lead, antineutrino statistics have yet to be accumulated. Two of the future experiments described below (SBND and CAPTAIN MINERvA) will aim to make measurements on argon in broad band beams that can be compared to measurements on carbon made in the same neutrino beam. The two experiments, by spanning both the below and above few-GeV neutrino energies, will be able to study nuclear effects across a range of channels and a range of energies.

Finally, the cross section measurements on electron neutrinos are particularly sparse: to date there are a few total cross section measurements [35, 36], and at the time of this writing only one charged current quasi-elastic measurement [30].

1 GeV Liquid Argon Measurements

The Booster Beamline at Fermilab is home to a suite of new Liquid Argon TPC experiments [37]: MicroBooNE, located at 470 m from the booster beamline target and at 61 ton fiducial mass, will provide the first measurements at these energies on an argon target. The Short Baseline Near Detector (SBND) at only 110m from the target and at 110 ton fiducial mass, will collect an estimated 5.2 million muon neutrino charged current events over the expected exposure of 6.2×10^{20} protons on target (POT). In addition SBND will also be able to collect some 38 thousand charged current electron neutrino interactions to study. These measurements will help expand the fields understanding of the nuclear effects that are critical at 1 GeV, a picture that was first painted by MiniBooNE's broad range of interaction measurements on carbon in the same beamline. Because of the energies of this beamline, both the quasi-elastic and single pion production channels can be accessed. Comparisons to MiniBooNE's measurements on CH_2 can provide some handles, although the reconstruction capabilities of the two detector technologies are very different.

3-6 GeV Liquid Argon Measurements

Just as the MicroBooNE and SBND measurements will greatly expand the reach of the MiniBooNE measurements on carbon by enabling cross section ratios to be measured at high precision at 1 GeV, the CAPTAIN MINERvA experiment will do the same thing at the higher energies of 3-6 GeV where the DUNE experiment expects most of its far detector events. This experiment will put a 6 ton Liquid Argon TPC (CAPTAIN) in front of the MINERvA detector to collect on the order of a million charged current interactions on Argon in an exposure of 6.2×10^{20} POT [38]. These can be directly compared to the statistics collected on MINERvA's scintillator target, which is of comparable fiducial mass and reconstruction capabilities. Because of the higher energy of the NuMI beamline where CAPTAIN MINERvA sits, the experiment will have access to not only the quasi-elastic and single pion production, but also to multi-pion final states and Deep Inelastic Scattering.

Narrow Band Measurements on Water

The NuPRISM experiment is a completely different strategy compared to the previous two experiments. Rather than comparing cross sections across different nuclei in a broad-band neutrino beam, NUPRISM aims to map out cross sections in several different monochromatic neutrino beams [39]. These beams are "created" by comparing interaction rates at different angles with respect to the T2K beamline. Those angles are available by building a large cylinder of water that can be instrumented to collect cerenkov light from neutrino interactions at very well-defined angles. This experiment takes advantage of 2-body kinematics and the existence of the T2K beamline to create whatever neutrino energy spectrum would be of interest, simply by adding or subtracting data taken at slightly different angles. This proposal has been presented to the J-PARC Physics Advisory Committee.

CONCLUSIONS

There has been impressive progress on precision cross sections in the past year, where progress has been made not only by collecting substantial data sets on very fine grained detectors in intense beams, but also with significantly better understanding of neutrino fluxes and detector responses through auxiliary measurements. Harvesting the data that has been taken will mean a wealth of cross section measurements that have uncertainties at the 10% level or better, assuming systematics can be kept under control. The clear places where the field is missing precision measurements is in electron neutrino cross sections, antineutrino measurements, and comparisons between argon and other nuclei at several different energies. There are several new efforts underway to help address these shortcomings, and while the field may never get to the one or two per cent precision level for any aboslute cross section, having a broad range of energies, processes, and nuclei will be key to creating a precise model of neutrino interactions.

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