

## 48. Neutrino Cross Section Measurements

Revised October 2013 by G.P. Zeller (Fermilab)

Neutrino interaction cross sections are an essential ingredient in all neutrino experiments. Interest in neutrino scattering has recently increased due to the need for such information in the interpretation of neutrino oscillation data. Historically, neutrino scattering results on both charged current (CC) and neutral current (NC) interaction channels have been collected over many decades using a variety of targets, analysis techniques, and detector technologies. With the advent of intense neutrino sources constructed for neutrino oscillation investigations, experiments are now remeasuring these cross sections with a renewed appreciation for nuclear effects<sup>†</sup> and the importance of improved neutrino flux estimates. This work summarizes accelerator-based neutrino cross section measurements performed in the  $\sim 0.1 - 300$  GeV range with an emphasis on inclusive, quasi-elastic, and single-pion production processes, areas where we have the most experimental input at present (Table 48.1). For a more comprehensive discussion of neutrino cross sections, including neutrino-electron elastic scattering and lower energy measurements, the reader is directed to a recent review of this subject [1]. Here, we survey existing experimental data on neutrino interactions and do not attempt to provide a census of the associated theoretical calculations, of which there are many.

**Table 48.1:** Summary of modern accelerator-based experiments and their published results on neutrino CC inclusive, quasi-elastic (QE) scattering, and pion production cross sections. MINOS, NOvA, and T2K refer to their near detectors.

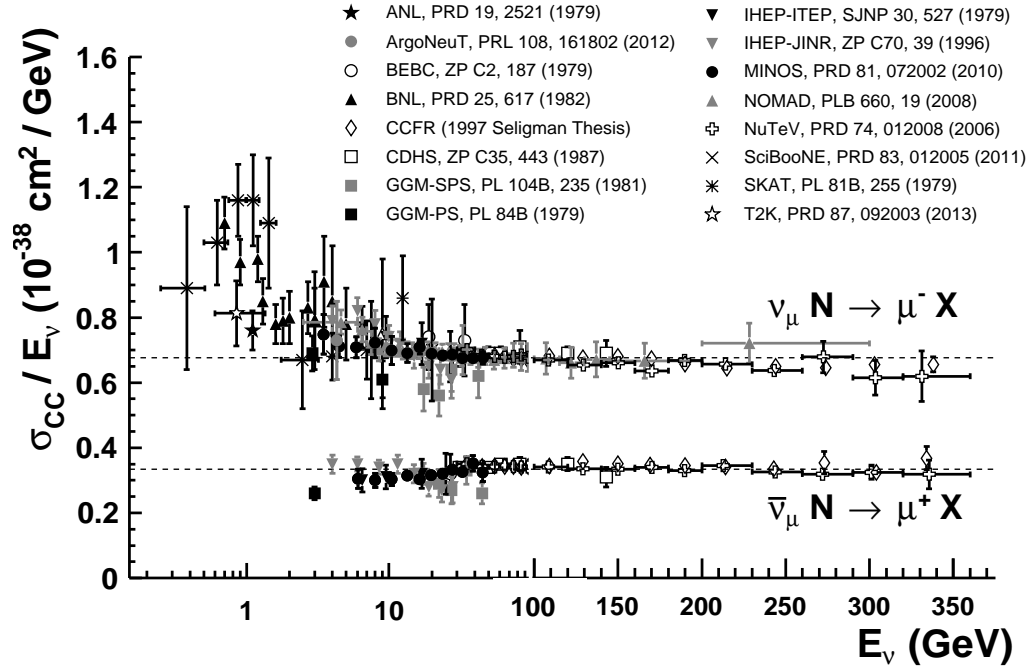
Experiment	beam	$\langle E_\nu \rangle$ GeV	neutrino target(s)	run period	$\sigma_\nu$ publications by topic
ArgoNeuT	$\nu, \bar{\nu}$	3.3	Ar	2009 – 2010	CC [2], QE [3]
ICARUS	$\nu$	20.0	Ar	2010 – present	—
K2K	$\nu$	1.3	CH, H <sub>2</sub> O	2003 – 2004	QE [4], $\pi$ [5,6,7,8]
MicroBooNE	$\nu$	0.8	Ar	scheduled 2014	—
MINER $\nu$ A	$\nu, \bar{\nu}$	3.3, 6.5	C, Fe, Pb, He, H <sub>2</sub> O	2009 – present	CC [9], QE [10,11]
MiniBooNE	$\nu, \bar{\nu}$	0.8	CH <sub>2</sub>	2002 – 2012	QE [12,13,14,15,16], $\pi$ [17,18,19,20,21]
MINOS	$\nu, \bar{\nu}$	3.3, 6.5	Fe	2004 – present	CC [22]
NOMAD	$\nu, \bar{\nu}$	26.0	C	1995 – 1998	CC [23], QE [24], $\pi$ [25]
NOvA	$\nu, \bar{\nu}$	2.0	CH <sub>2</sub>	scheduled 2014	—
SciBooNE	$\nu, \bar{\nu}$	0.8	CH	2007 – 2008	CC [26], $\pi$ [27,28,29]
T2K	$\nu$	0.85	CH, H <sub>2</sub> O	2010 – present	CC [30]

<sup>†</sup> Nuclear effects refer to kinematic and final state effects which impact neutrino scattering off nuclei. Such effects can be significant and are particularly relevant given that modern neutrino experiments make use of nuclear targets to increase their event yields.

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### 48.1. Inclusive Scattering

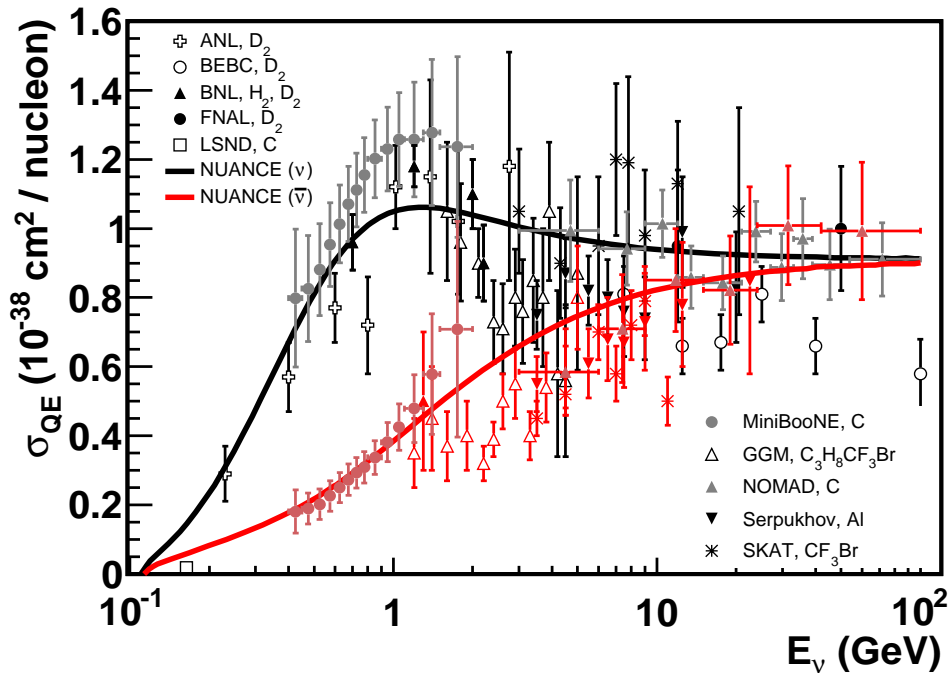
Over the years, many experiments have measured the total inclusive cross section for neutrino ( $\nu_\mu N \rightarrow \mu^- X$ ) and antineutrino ( $\bar{\nu}_\mu N \rightarrow \mu^+ X$ ) scattering off nucleons covering a broad range of neutrino energies. As can be seen in Fig. 48.1, the inclusive cross section approaches a linear dependence on neutrino energy. Such behavior is expected for point-like scattering of neutrinos from quarks, an assumption which breaks down at lower energies. To provide a more complete picture, differential cross sections for such inclusive scattering processes have been reported - these include measurements on iron from NuTeV [31] and, more recently, at lower energies on argon from ArgoNeuT [2] and carbon from T2K [30]. MINERvA has also provided new measurements of the ratios of the CC inclusive scattering cross section on a variety of targets (lead, iron, plastic) [9]. At high energy, the inclusive cross section is dominated by deep inelastic scattering (DIS). Several high energy neutrino experiments have measured the DIS cross sections for specific final states, for example opposite-sign dimuon production. The most recent dimuon cross section measurements include those from CHORUS [32], NOMAD [33], and NuTeV [34]. At lower neutrino energies, the inclusive cross section is an additionally complex combination of quasi-elastic scattering and resonance production processes, two areas we discuss next.



**Figure 48.1:** Measurements of  $\nu_\mu$  and  $\bar{\nu}_\mu$  CC inclusive scattering cross sections divided by neutrino energy as a function of neutrino energy. Note the transition between logarithmic and linear scales occurring at 100 GeV. Neutrino cross sections are typically twice as large as their corresponding antineutrino counterparts, although this difference can be larger at lower energies. NC cross sections (not shown) are generally smaller but non-negligible compared to the CC scattering case.

## 48.2. Quasi-elastic scattering

Quasi-elastic (QE) scattering is the dominant neutrino interaction for neutrino energies less than  $\sim 1$  GeV and represents a large fraction of the signal samples in many neutrino oscillation experiments. Historically, neutrino (antineutrino) quasi-elastic scattering refers to the process,  $\nu_\mu n \rightarrow \mu^- p$  ( $\bar{\nu}_\mu p \rightarrow \mu^+ n$ ), where a charged lepton and single nucleon are ejected in the elastic interaction of a neutrino (or antineutrino) with a nucleon in the target material. This is the final state one would strictly observe, for example, in scattering off of a free nucleon target. Fig. 48.2 displays the current status of existing measurements of  $\nu_\mu$  and  $\bar{\nu}_\mu$  QE scattering cross sections as a function of neutrino energy. In this plot, and all others in this review, the prediction from a representative neutrino event generator (NUANCE) [35] provides a theoretical comparator. Other generators and more sophisticated calculations exist which can give significantly different predictions [36]. Note that modern experiments have recently opted to report QE cross sections as a function of final state muon or proton kinematics, much less model-dependent quantities than neutrino energy [3,14,13].



**Figure 48.2:** Measurements of  $\nu_\mu$  (black) and  $\bar{\nu}_\mu$  (red) QE scattering cross sections (per nucleon) as a function of neutrino energy. Data on a variety of nuclear targets are shown, including measurements from ANL [37], BEBC [38], BNL [39], FNAL [40], Gargamelle [41], LSND [42], MiniBooNE [13,14], NOMAD [24], Serpukhov [43], and SKAT [44]. Shown is the QE free nucleon scattering prediction from NUAGE [35] assuming  $M_A = 1.0$  GeV. This prediction is significantly altered by nuclear effects in the case of neutrino-nucleus scattering. Although plotted together, care should be taken in interpreting measurements performed on targets heavier than  $D_2$  due to possible differences in QE selection criteria and kinematics.

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In many of these initial measurements of the neutrino QE cross section, bubble chamber experiments typically employed light targets ( $H_2$  or  $D_2$ ) and required both the detection of the final state muon and single nucleon<sup>‡</sup>; thus the final state was clear and elastic kinematic conditions could be verified. The situation is more complicated, of course, for heavier nuclear targets. In this case, nuclear effects can impact the size and shape of the cross section as well as the final state kinematics and topology. Due to intranuclear hadron rescattering and the possible effects of correlations between target nucleons, additional nucleons may be ejected in the final state; hence, a QE interaction on a nuclear target does not always imply the ejection of a *single* nucleon. Thus, one needs to take some care in defining what one means by neutrino QE scattering when scattering off targets heavier than  $H_2$  or  $D_2$ . Adding to the complexity, recent MiniBooNE measurements [13,14] of the  $\nu_\mu$  and  $\bar{\nu}_\mu$  QE scattering cross sections on carbon at low energy have revealed a significantly larger cross section than expected, an enhancement also seen in electron-nucleus scattering [45] and now believed to be signaling the existence of sizable nuclear effects also present in neutrino-nucleus scattering. As a result, the impact of such nuclear effects on neutrino QE scattering has recently been the subject of intense experimental and theoretical scrutiny with potential implications on event rates, nucleon ejection, neutrino energy reconstruction, and neutrino/antineutrino ratios. The reader is referred to a recent review of the situation in [46]. Additional measurements are clearly needed before a complete understanding is achieved. To help drive further progress, neutrino-nucleus QE cross sections have been reported for the first time in the form of double-differential distributions in muon kinematics,  $d^2\sigma/dT_\mu d\cos\theta_\mu$ , by MiniBooNE [13,14] thus reducing the model-dependence of the reported data and allowing a more stringent test of the underlying nuclear theory. Experiments such as ArgoNeuT have begun to provide the first detailed measurements of proton multiplicities in neutrino-argon QE scattering [3], a critical ingredient in understanding the hadronic side of these interactions. Most recently, MINERvA has measured the differential cross section,  $d\sigma/dQ_{QE}^2$ , and vertex energy in both  $\nu_\mu$  and  $\bar{\nu}_\mu$  QE interactions in hydrocarbon [10,11]. In the case of neutrino QE scattering, the results indicate an excess of energy deposited near the event vertex consistent with multiple protons in the final state. Both MINOS and NOvA have also started to study QE interactions in their near detectors [47,48]. Additional QE measurements from these and other neutrino experiments are expected in the coming years.

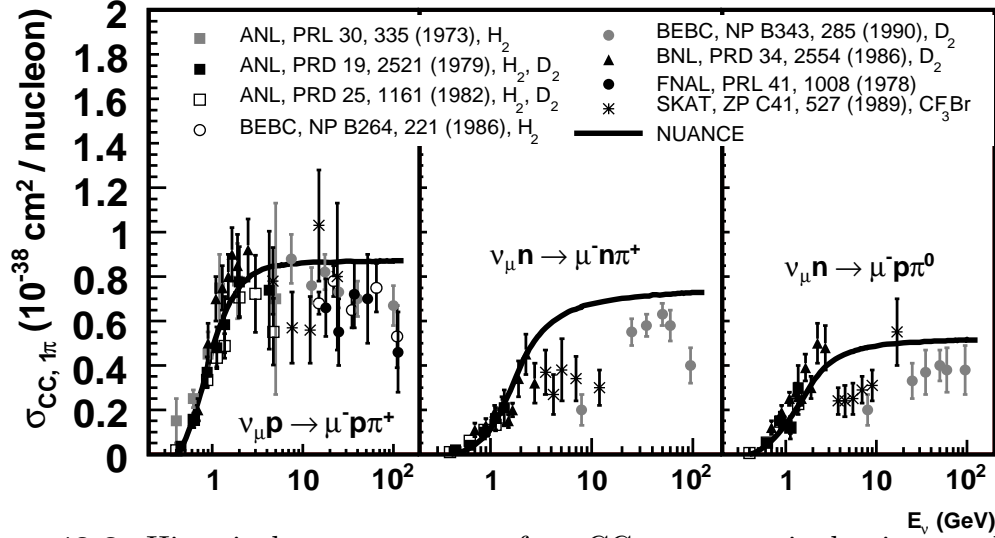
In addition to such charged current investigations, measurements of the neutral current counterpart of this channel have also been performed. The most recent NC elastic scattering cross section measurements include those from BNL E734 [49] and MiniBooNE [12,15]. A number of measurements of the Cabibbo-suppressed antineutrino QE hyperon production cross section have additionally been reported [44,50], although not in recent years.

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<sup>‡</sup> In the case of  $D_2$ , many experiments additionally observed the spectator proton.

## 48.3. Pion Production

In addition to such elastic processes, neutrinos can also inelastically scatter producing a nucleon excited state ( $\Delta$ ,  $N^*$ ). Such baryonic resonances quickly decay, most often to a nucleon and single-pion final state. Fig. 48.3 and Fig. 48.4 show a collection of historical resonance single-pion production cross section data for both CC and NC neutrino scattering. Decades ago, BEBC, FNAL, Gargamelle, and SKAT also performed similar measurements for antineutrinos [51]. Most often, these experiments reported measurements of NC/CC single-pion cross section ratios [52].

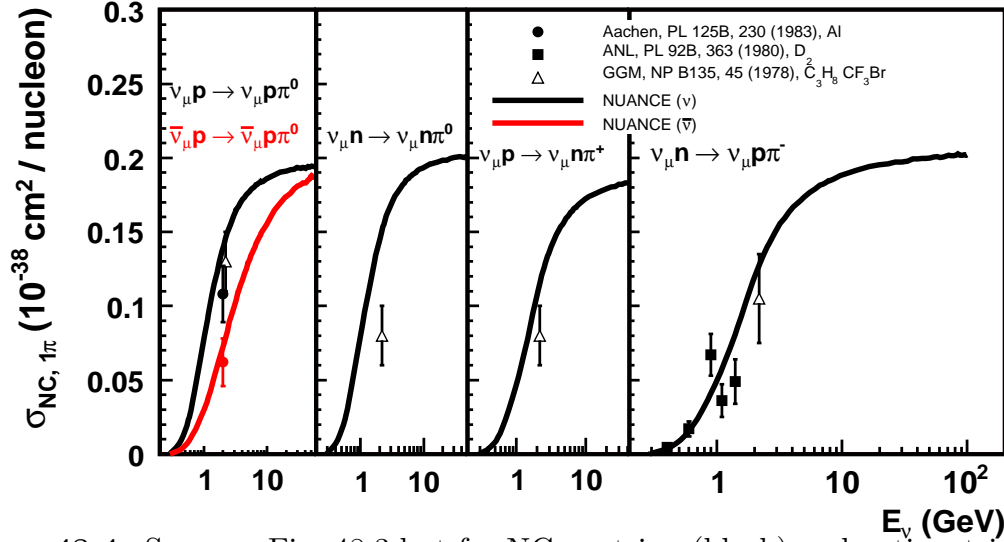


**Figure 48.3:** Historical measurements of  $\nu_\mu$  CC resonant single-pion production. The data appear as reported by the experiments; no additional corrections have been applied to account for differing nuclear targets or invariant mass ranges. The free scattering curve from NUANCE assumes  $M_A = 1.1$  GeV [35]. Note that other absolute measurements have been made by MiniBooNE [17,18] but cannot be directly compared with this historical data - such modern measurements are more inclusive and have quantified the production of pions leaving the target nucleus rather than specific  $\pi + N$  final states as identified at the neutrino interaction vertex.

It should be noted that baryonic resonances can also decay to multi-pion, other mesonic ( $K$ ,  $\eta$ ,  $\rho$ , etc.), and even photon final states. Experimental results for these channels are typically sparse or non-existent [1]; however, photon production processes can be an important background for  $\nu_\mu \rightarrow \nu_e$  appearance searches and thus have become the focus of some recent experimental investigations [53].

In addition to resonance production processes, neutrinos can also coherently scatter off of the entire nucleus and produce a distinctly forward-scattered single-pion final state. Both CC ( $\nu_\mu A \rightarrow \mu^- A \pi^+$ ,  $\bar{\nu}_\mu A \rightarrow \mu^+ A \pi^-$ ) and NC ( $\nu_\mu A \rightarrow \nu_\mu A \pi^0$ ,  $\bar{\nu}_\mu A \rightarrow \bar{\nu}_\mu A \pi^0$ ) processes are possible in this case. The level of coherent pion production is predicted to be small compared to incoherent processes, but observations exist across a broad energy range and on multiple nuclear targets [25,55,56]. Most of these measurements have

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**Figure 48.4:** Same as Fig. 48.3 but for NC neutrino (black) and antineutrino (red) scattering. The Gargamelle (GGM) measurements come from a re-analysis of this data [54]. Note that more recent absolute cross section measurements exist [19] but cannot be directly compared with this data for the same reasons as in Fig. 48.3.

been performed at energies above 2 GeV, but several modern experiments have started to search for coherent pion production at lower neutrino energies, including K2K [8], MiniBooNE [21], and SciBooNE [27,29].

As with QE scattering, a new appreciation for the significance of nuclear effects has surfaced in pion production channels, again due to the use of heavy targets in modern neutrino experiments. Many experiments have been careful to report cross sections for various detected final states, thereby not correcting for large and uncertain nuclear effects (e.g., pion rescattering, charge exchange, and absorption) which can introduce unwanted sources of uncertainty and model dependence. Recent measurements of single-pion cross sections, as published by K2K [5–7], MiniBooNE [20], and SciBooNE [28], take the form of ratios with respect to QE or CC inclusive scattering samples. Providing the most comprehensive survey of neutrino single-pion production to date, MiniBooNE has recently published a total of 16 single- and double-differential cross sections for both the final state muon (in the case of CC scattering) and pion in these interactions; thus, providing the first measurements of these distributions [17–19]. Regardless of the interaction channel, such differential cross section measurements (in terms of observed final state particle kinematics) are now preferred for their reduced model dependence and for the additional kinematic information they provide. Such a new direction has been the focus of modern measurements as opposed to the reporting of more model-dependent cross sections as a function of  $E_\nu$  or  $Q^2$ . Together with similar results for other interaction channels, a better understanding and modeling of nuclear effects will be possible moving forward.

## 48.4. Outlook

Coming soon, additional neutrino and antineutrino cross section measurements in the few-GeV energy range are anticipated from MiniBooNE, MINOS, NOMAD, and SciBooNE. In addition, a few new experiments are now collecting data or will soon be commissioning their detectors. Analysis of a broad energy range of data on a variety of targets in the MINER $\nu$ A experiment will provide the most detailed analysis yet of nuclear effects in neutrino interactions. Data from ArgoNeuT, ICARUS, and MicroBooNE will probe deeper into complex neutrino final states using the superior capabilities of liquid argon time projection chambers, while the T2K and NO $\nu$ A near detectors will collect high statistics samples in intense neutrino beams. Together, these investigations should significantly advance our understanding of neutrino-nucleus scattering in the years to come.

## 48.5. Acknowledgments

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