# 45. Neutrino Cross Section Measurements

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Neutrino interaction cross sections are an essential ingredient in most neutrino experiments. Interest in neutrino scattering has recently increased due to the need for such information in the interpretation of neutrino oscillation data. Scattering results on both charged current (CC) and neutral current (NC) neutrino channels have been collected over many decades using a variety of targets, analysis techniques, and detector technologies. With the advent of intense neutrino sources for oscillation measurements, experiments are remeasuring these cross sections with a renewed appreciation for nuclear effects† and precise knowledge of their incoming neutrino fluxes. This review summarizes accelerator-based neutrino cross section measurements made 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). For a more comprehensive discussion of neutrino interaction cross sections, including neutrino-electron scattering and lower energy measurements, the reader is directed to a recent review of this subject [1].

## 45.1. Inclusive Scattering

Over the years, many experiments have measured the total cross section for neutrino ($\nu_\mu N \to \mu^- X$) and antineutrino ($\overline{\nu}_\mu N \to \mu^+ X$) scattering off nucleons covering a broad range of energies (Fig. 45.1). As can be seen, 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 also been reported on iron by NuTeV [2] and at lower energies on argon by ArgoNeuT [3]. 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 [4], NOMAD [5], and NuTeV [6]. At lower neutrino energies, the inclusive cross section is largely a combination of quasi-elastic scattering and resonance production processes, two areas we will turn to next.

† Kinematic and final state effects which impact neutrino scattering off nuclei. Note that most modern neutrino experiments use nuclear targets to increase their event yields.

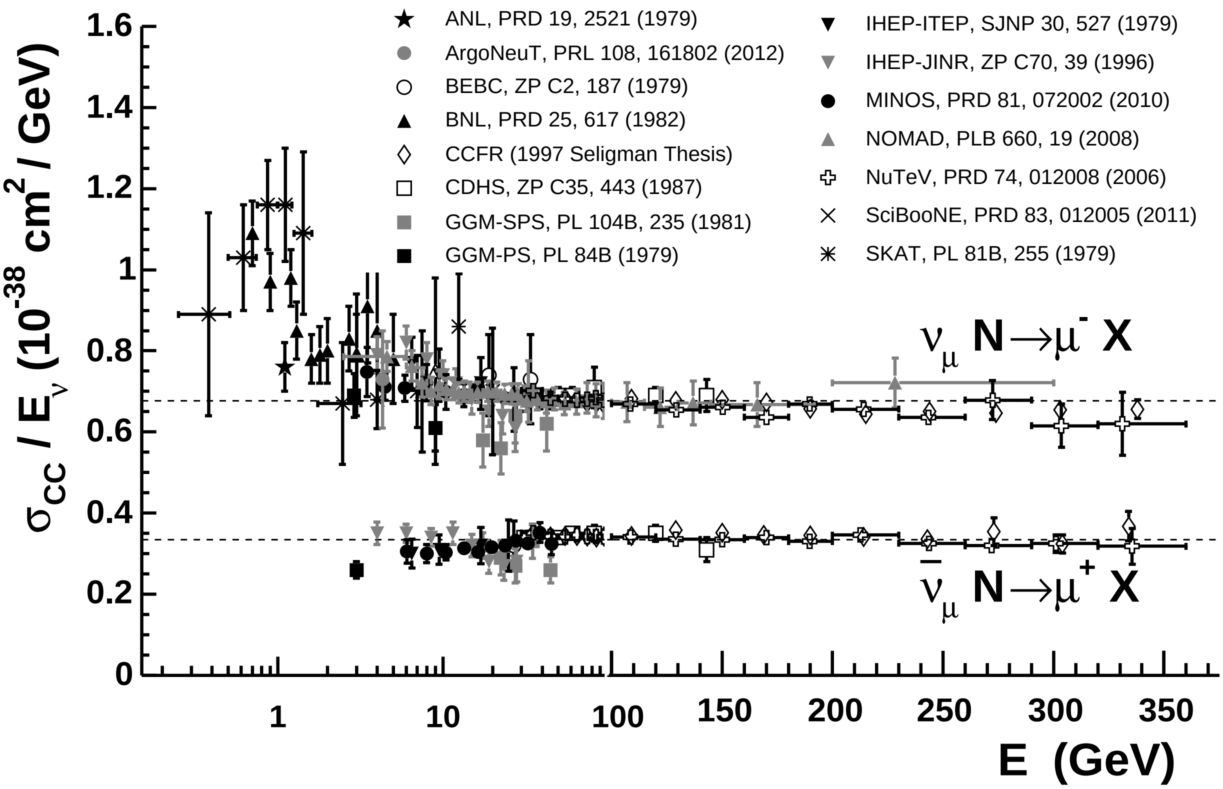


**Figure 45.1:** Measurements of $\nu_\mu$ and $\overline{\nu}_\mu$ CC inclusive scattering cross sections divided by neutrino energy as a function of neutrino energy. Note the transition between logarithmic and linear scales occurring at 100 GeV. Neutrino-nucleon cross sections are typically twice as large as the corresponding antineutrino cross sections, though this difference can be larger at lower energies. NC cross sections (not shown) are generally smaller (but non-negligible) compared to their CC counterparts.

## 45.2. Quasi-elastic scattering

Historically, neutrino (or antineutrino) quasi-elastic scattering refers to the processes, $\nu_\mu n \rightarrow \mu^- p$ and $\overline{\nu}_\mu p \rightarrow \mu^+ n$, 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. QE scattering is important as it is the dominant neutrino interaction at energies less than about 1 GeV and is a large signal sample in many neutrino oscillation experiments.

Fig. 45.2 displays the current status of existing measurements of $\nu_\mu$ and $\overline{\nu}_\mu$ 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) [7] provides a theoretical comparator. Other generators and more sophisticated calculations exist which can give different predictions [8].

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

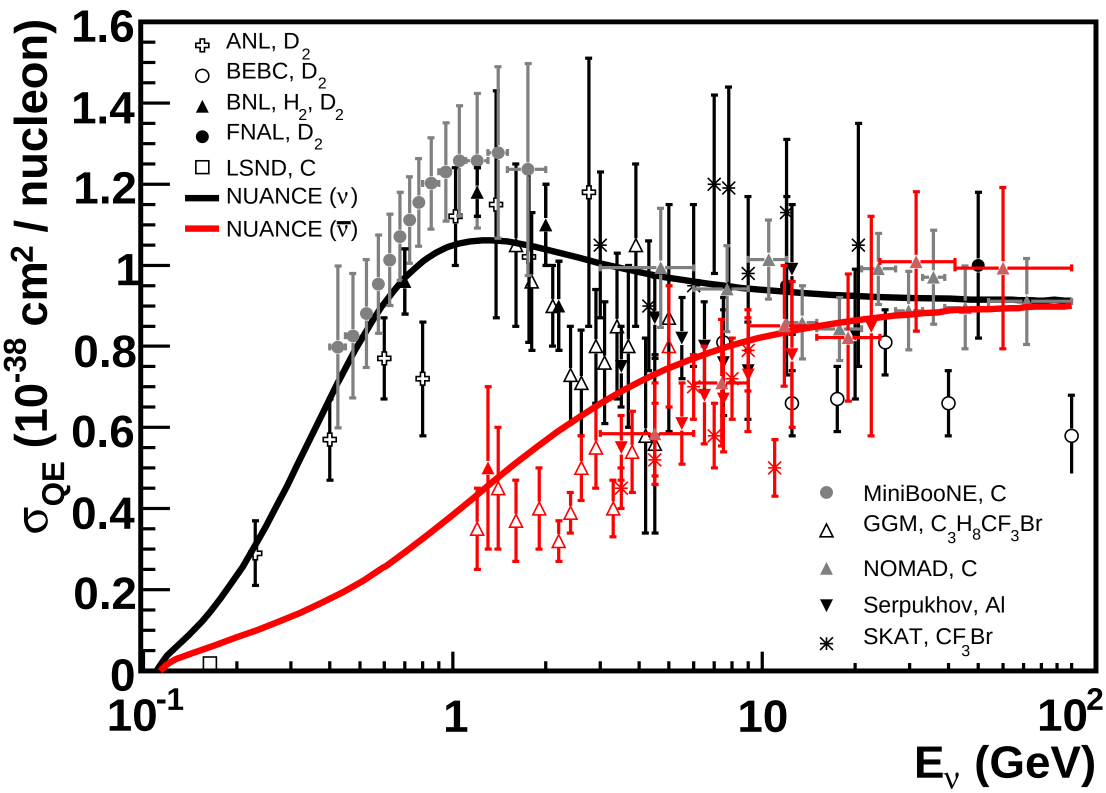


**Figure 45.2:** Measurements of $\nu_\mu$ (black) and $\overline{\nu}_\mu$ (red) quasi-elastic scattering cross sections (per nucleon) as a function of neutrino energy. Data on a variety of nuclear targets are shown, including measurements from ANL [10], BEBC [11], BNL [12], FNAL [13], Gargamelle [14], LSND [15], MiniBooNE [9], NOMAD [16], Serpukhov [17], and SKAT [18]. Also shown is the QE free nucleon scattering prediction [7] assuming $M_A = 1.0$ GeV. This prediction is significantly altered by nuclear corrections in the case of neutrino-nucleus scattering. Care should be taken in interpreting measurements on targets heavier than deuterium.

detection of the final state muon and single nucleon‡; 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 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 measurements [9] of the $\nu_\mu$ QE scattering cross section on carbon at low energy have observed a significantly larger than expected cross section, an enhancement believed to be signaling the presence of sizable nuclear effects. Such cross sections have also been reported for the first time in

‡ In the case of $D_2$, many experiments additionally observed the spectator proton.

the form of double-differential distributions [9], thus reducing the model-dependence of the data and allowing a much more stringent test of the underlying nuclear theory. The impact of nuclear effects on neutrino QE scattering has been the subject of intense theoretical scrutiny over the past year [19] with potential implications on nucleon ejection [20], neutrino energy reconstruction [21], and the neutrino/antineutrino cross section ratio [22]. The reader is referred to a recent review of the situation in [23]. Additional measurements are clearly needed before a complete understanding is achieved. In addition to such CC investigations, measurements of the NC counterpart of this channel have also been performed. The most recent NC elastic scattering cross section measurements include those from BNL E734 [24] and MiniBooNE [25]. A number of measurements of the Cabibbo-suppressed antineutrino QE hyperon production cross section have additionally been reported [18,26], although none in recent years.

## 45.3. 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. 45.3 and Fig. 45.4 show a collection of 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 [27]. Most often these experiments reported measurements of NC/CC single pion cross section ratios [28].

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 $\nu_\mu \to \nu_e$ appearance searches and thus have become the focus of some recent experimental investigations [29].

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 ($\nu_\mu\, A \to \mu^-\, A\, \pi^+$, $\overline{\nu}_\mu\, A \to \mu^+\, A\, \pi^-$ ) and NC ($\nu_\mu A \to \nu_\mu A \pi^0$, $\overline{\nu}_\mu A \to \overline{\nu} \mu A \pi^0$) processes are possible in this case. The level of coherent pion production is predicted to be small compared to incoherent processes [33], but observations exist across a broad energy range and on multiple nuclear targets [34–36]. Most of these measurements have 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 [37], MiniBooNE [38], and SciBooNE [39].

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 [40], MiniBooNE [41], and SciBooNE [42], take the form of ratios with respect to QE or CC inclusive scattering samples. Providing the most

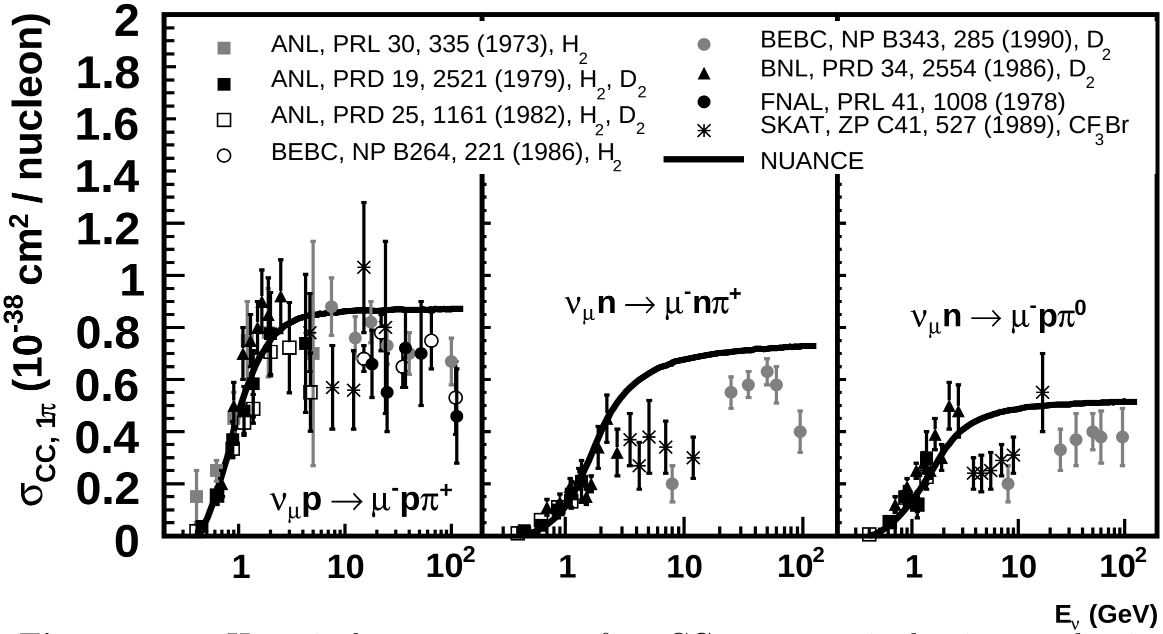


**Figure 45.3:** Historical measurements of $\nu_\mu$ CC resonant single pion production. The data appear as reported by the experiments; no additional corrections have been applied to account for differing nuclear targets or invariant mass ranges. The free scattering prediction is from [7] with $M_A = 1.1$ GeV. Note that other absolute measurements have been made by MiniBooNE [30] but cannot be directly compared with this historical data - the 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.

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 [30,32]. 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 (model-dependent) cross sections as a function of neutrino energy. Together with similar results for other interaction channels, a better understanding and modeling of nuclear effects will be possible moving forward.

## 45.4. Outlook

Coming soon, additional neutrino and antineutrino cross section measurements in the few-GeV energy range are anticipated from ArgoNeuT, 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 ICARUS and MicroBooNE will probe deeper

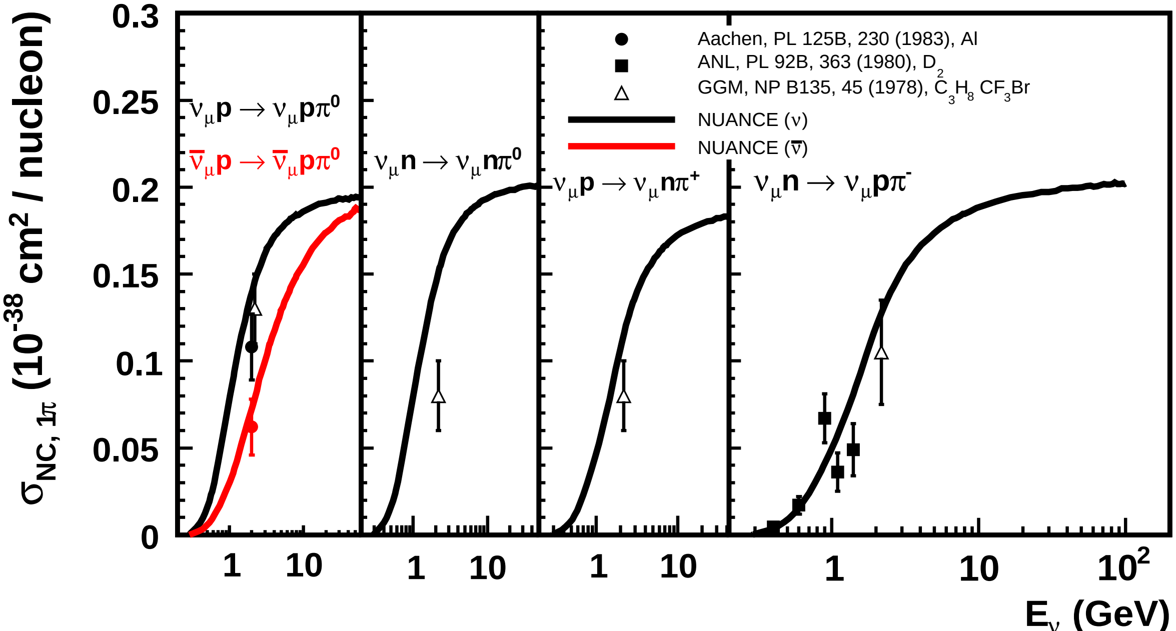


**Figure 45.4:** Same as Fig. 45.3 but for NC neutrino (black) and antineutrino (red) scattering. The Gargamelle measurements come from a re-analysis of this data [31]. Note that more recent absolute measurements exist [32] but cannot be directly compared with this data for the same reasons as in Fig. 45.3.

into complex neutrino final states using the superior capabilities of liquid argon time projection chambers, while the T2K and NOvA 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.

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