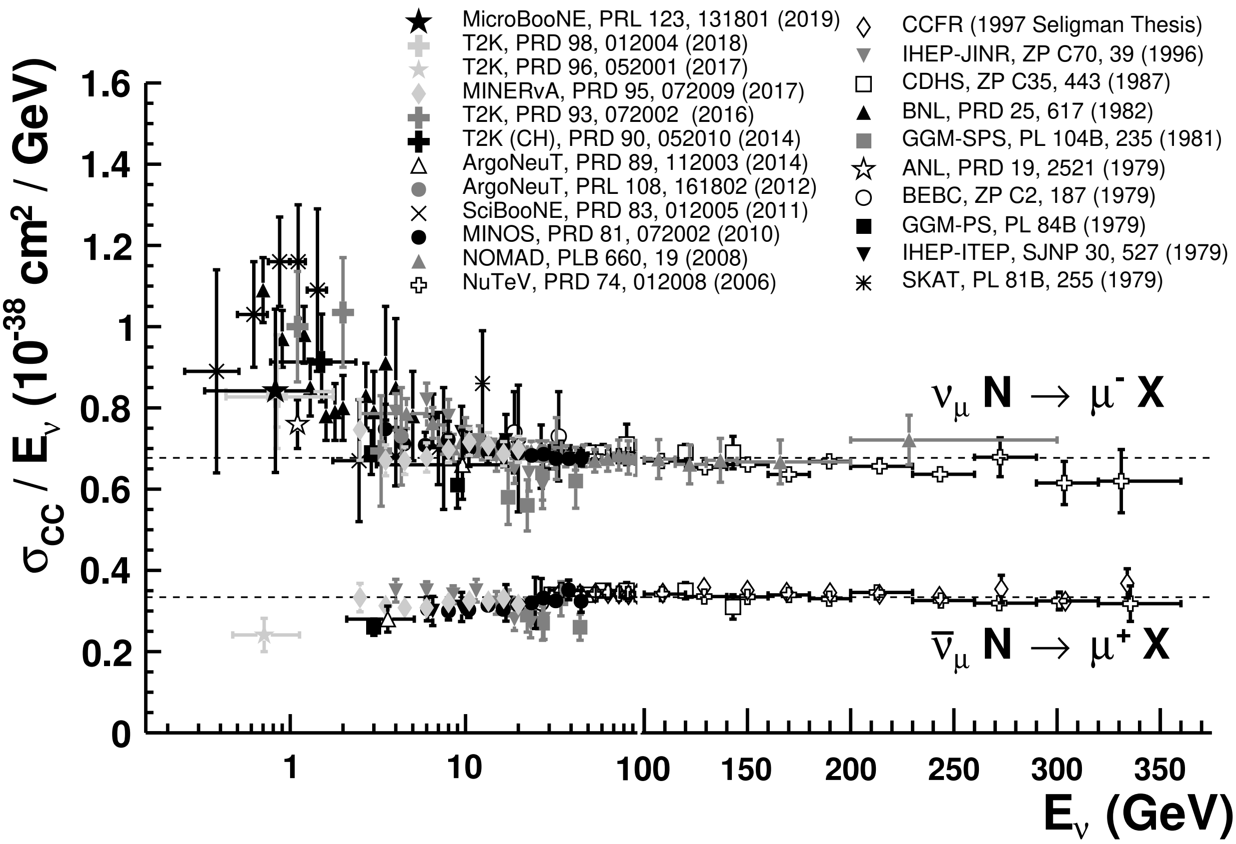

Figure 52.1: Measurements of per nucleon ν_μ and $\overline{\nu}_\mu$ CC inclusive scattering cross sections divided by neutrino energy as a function of neutrino energy. Note the transition between logarithmic and linear scales occurring at 100 GeV. Neutrino cross sections are typically twice as large as their corresponding antineutrino counterparts, although this difference can be larger at lower energies. NC cross sections (not shown) are generally smaller compared to their CC counterpart.

summarized in Table 52.3. Many modern experiments have also recently opted to report nucleon-only cross sections as a function of observed final state particle kinematics [35–48]. Such measurements can be more difficult to directly compare between experiments but have the advantage of being much less model-dependent and provide more stringent tests of the theory than historical cross sections as a function of derived quantities such as neutrino energy (E_ν) or 4-momentum transfer (Q^2). More recent work has been done to develop a means to directly compare experimental measurements produced in these less model-dependent forms [49].

The topic of neutrino QE scattering began drawing considerable attention following the first double differential cross section measurements of this process that revealed a significantly larger cross section than originally anticipated, predominantly in the backwards muon scattering region [40, 41]. Such an enhancement was observed many years prior in transverse electron-nucleus scattering [68] and was attributed to the presence of correlations between nucleons in the target nucleus. As a result, the impact of such nuclear effects on neutrino QE scattering has recently become the subject of intense experimental and theoretical scrutiny with implications on event rates, nucleon emission, neutrino energy reconstruction, and neutrino versus antineutrino cross sections. The reader is referred to reviews of the situation in [4, 69, 70]. To help drive further progress in understanding the underlying nuclear contributions, pionless (e.g., nucleon-only) cross sections have been reported for the first time in the form of double-differential distributions by MiniBooNE [40, 41], MINERvA [35–37, 55], and T2K [42–46]. Such double-differential cross sections in terms of final state particle kinematics reduce the model-dependence of the reported data, provide the most robust measurements available, and allow a more rigorous two-dimensional test of the underlying nuclear theory. MINERvA and T2K have been especially prolific in recent years in probing this interaction process (Table 52.3). Neutrino experiments have also launched dedicated studies of the hadronic side of these interactions, including ArgoNeuT [50, 71], MicroBooNE [47, 48], MINERvA [54], and T2K [67]. MINERvA has been the first modern experiment to measure neutron emission in antineutrino interactions [72]. T2K has probed ratios of oxygen to carbon [45] and asymmetries between neutrino and antineutrino scattering [46] to glean more information on the nature of the underlying nuclear effects. In addition, the exploration of transverse kinematic variables and momentum imbalances in pionless neutrino scattering is allowing better constraints on the various nuclear contributions to the cross section. Such scrutiny includes recent evaluations from MINERvA [35, 36, 38, 39] and T2K [67]. With the MiniBooNE results having first revealed these additional complexities in neutrino-nucleus QE scattering, measurements from multiple neutrino experiments, on multiple targets, and using a variety of kinematic information have been crucial in gaining a better handle on the underlying nuclear physics impacting neutrino-nucleus interactions. What we once thought was "simple" QE scattering is in fact not so simple.

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 [73], MiniBooNE [59, 60], Super-K [63], and T2K [66]. A number of measurements of the Cabibbo-suppressed antineutrino QE hyperon production cross section have additionally been reported [74, 75], although not in recent years.