Neutrino-Nucleus Quasi-Elastic Scattering in a Relativistic Model

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Abstract. A relativistic distorted-wave impulse-approximation model is applied to neutral-current and charged-current quasi-elastic neutrino-nucleus scattering. The effects of final state interactions are investigated and the sensitivity of the results to the strange nucleon form factors is discussed in view of their possible experimental determination.

1 Introduction

Neutrino-nucleus scattering has gained in recent years a wide interest that goes beyond the study of the intrinsic properties of neutrinos and extends to different fields, such as astrophysics, cosmology, particle and nuclear physics. The observation of neutrino oscillations and the proposal and realization of new experiments, aimed at determining neutrino properties with high accuracy, renewed interest in neutrino scattering on complex nuclei. In fact, neutrino detectors contain nuclei and a detailed knowledge of the ν-nucleus interaction is necessary for a proper interpretation of the experimental data. Neutrino-nucleus scattering, however, is not only an useful tool to detect neutrinos, but plays an important role also in understanding various astrophysical processes. The influence of neutrinos extends to cosmological questions. Moreover, neutrinos provide a suitable tool to test the limits of the standard model, the properties of the weak interaction and for investigating nuclear structure. In hadronic and nuclear physics neutrinos can give information on the structure of the hadronic weak current and on the strange quark contribution to the spin structure of the nucleon.

Thus, neutrino physics is of great interest and involves many different phenomena. The problem is that neutrinos are elusive particles. They are chargeless, almost massless, and only weakly interacting. Their presence can only be inferred detecting the particles they create when colliding or interacting with matter. Nuclei are often used as neutrino detectors providing relatively large cross sections. Therefore, the interpretation of data requires reliable calculations where nuclear effects are properly taken into account.

General review papers about neutrino-nucleus interactions can be found in [1–4]. Both weak neutral-current (NC) and charged-current (CC) scattering have stimulated detailed analyses in the intermediate-energy region [5–16] using a variety of methods, including Fermi Gas (FG), Random-Phase-Approximation (RPA) and Shell-Model (SM) calculations. The effects of Final State Interactions (FSI) were investigated within the Relativistic FG (RFG) model [17], the RPA [18] and in the continuum RPA (CRPA) theory [19]. Nuclear structure effects on the determination of the strange quark contribution in NC scattering were studied in [11, 20], and in [21] in the framework of a Relativistic Plane Wave Impulse Approximation (RPWIA). The effects of FSI on the ratio of proton-to-neutron cross sections in NC scattering were discussed in [11, 22–24].

We study CC and NC ν- and $\bar{\nu}$-nucleus scattering in the QE region. In this region the dominant contribution is given by one-nucleon knockout processes, where the interaction occurs on a nucleon, that is bound in the nucleus but is assumed to be a quasi-free nucleon in the process, this nucleon is emitted and the remaining nucleons are spectators. In the QE region we have applied the same Relativistic Distorted Wave Impulse Approximation (RDWIA) model that was successfully tested in comparison with data for the exclusive (e,e′p) knockout reaction [25,26]. The analysis of NC ν-nucleus reactions, however, introduces additional complications, as the final neutrino cannot be measured in practice and a final hadron has to be detected: the corresponding cross sections are therefore semi-inclusive in the hadronic sector and inclusive in the leptonic one. The same approach is here applied to the CC scattering where only the outgoing nucleon is detected. The case of the inclusive CC scattering where only the outgoing charged lepton is detected was studied in [27] through a relativistic Green's function approach, that was firstly applied to the inclusive QE electron scattering [28] and where FSI are accounted for by means of a complex optical potential but without loss of flux.

The formalism is outlined in Section 2. Nuclear effects, in particular the effects of FSI, are discussed in Section 3. The effects of the strange nucleon form factors and their possible determination are investigated Section 4. Some conclusions are drawn in Section 5.

2 Formalism of Quasi-Elastic Neutrino-Nucleus Scattering

The $\nu(\bar{\nu})$-nucleus cross section for the process where one nucleon is emitted is given, in the one-boson exchange approximation, by the contraction between the lepton and the hadron tensor, i.e.,

$$\mathrm{d}\sigma = \frac{G_{\mathrm{F}}^2}{2}\, 2\pi\, L^{\mu\nu}\, W_{\mu\nu}\, \frac{\mathrm{d}^3 k}{(2\pi)^3}\, \frac{\mathrm{d}^3 p_{\mathrm{N}}}{(2\pi)^3}\,, \tag{1}$$

where $G_{\mathrm{F}} \simeq 1.16639 \times 10^{-11}$ MeV^{-2} is the Fermi constant, $k_i^{\mu} = (\varepsilon_i, \boldsymbol{k}_i)$, $k^{\mu} = (\varepsilon, \boldsymbol{k})$ are the four-momentum of the incident and final leptons, respectively, and $\boldsymbol{p}_{\mathrm{N}}$ is the momentum of the emitted nucleon. For CC processes G_{F}^2 has to be multiplied by $\cos^2 \vartheta_{\mathrm{C}} \simeq 0.9749$, where ϑ_{C} is the Cabibbo angle.

The lepton tensor $L^{\mu\nu}$ has a similar structure as in electron scattering and separates into a symmetrical and an antisymmetrical part [25, 27, 29]. The components of the lepton tensor are kinematical factors which depend only on the lepton kinematics. The components of the hadron tensor are given by bilinear products of the transition matrix elements of the nuclear weak-current operator J^μ between the initial state $|\Psi_0\rangle$ of the nucleus, of energy E_0, and the final states, of energy E_f, that are given by the product of a discrete (or continuum) state $|n\rangle$ of the residual nucleus and a scattering state $\chi^{(-)}_{\boldsymbol{p}_\mathrm{N}}$ of the emitted nucleon, with momentum $\boldsymbol{p}_\mathrm{N}$ and energy E_N:

$$\begin{aligned} W^{\mu\nu}(\omega,q) = &\sum_n \langle n;\chi^{(-)}_{\boldsymbol{p}_\mathrm{N}} \mid J^\mu(\boldsymbol{q}) \mid \Psi_0\rangle\langle\Psi_0 \mid J^{\nu\dagger}(\boldsymbol{q}) \mid n;\chi^{(-)}_{\boldsymbol{p}_\mathrm{N}}\rangle \\ &\times \delta(E_0+\omega-E_\mathrm{f}) \ , \end{aligned} \tag{2}$$

where the sum runs over all the states of the residual nucleus. In the first order perturbation theory and using the impulse approximation, the transition amplitude is assumed to be adequately described as the sum of terms similar to those appearing in the exclusive (e,e′p) knockout reaction [25,26]

$$\langle n;\chi^{(-)}_{\boldsymbol{p}_\mathrm{N}} \mid J^\mu(\boldsymbol{q}) \mid \Psi_0\rangle = \langle\chi^{(-)}_{\boldsymbol{p}_\mathrm{N}} \mid j^\mu(\boldsymbol{q}) \mid \varphi_n\rangle \ . \tag{3}$$

The transition amplitudes are thus obtained in a one-body representation and contain three ingredients: the one-body nuclear weak current j^μ, the one-nucleon overlap function $\varphi_n = \langle n|\Psi_0\rangle$, that is a single-particle (s.p.) bound state wave function, and the s.p. scattering wave function $\chi^{(-)}$ for the outgoing nucleon.

Bound and scattering states are consistently derived in the model as eigenfunctions of an optical potential. In practice, calculations are performed with the same phenomenological ingredients already used in the RDWIA calculations for the (e,e′p) reaction. The s.p. overlap functions φ_n are Dirac-Hartree solutions of a relativistic Lagrangian, containing scalar and vector potentials. They are obtained in the framework of the relativistic mean field theory and reproduce the s.p. properties of several nuclei [30,31]. The relativistic scattering wave function is written in terms of its upper component, following the direct Pauli reduction scheme and solving a Schrödinger-like equation containing equivalent central and spin-orbit potentials, written in terms of the relativistic scalar and vector potentials [33,34]. Calculations have been performed with the energy-dependent and A-dependent EDAD1 optical potential of [32].

The s.p. operator related to the weak current is

$$\begin{aligned} j^\mu &= F_1^\mathrm{V}(Q^2)\gamma^\mu + i\frac{\kappa}{2M}F_2^\mathrm{V}(Q^2)\sigma^{\mu\nu}q_\nu - G_\mathrm{A}(Q^2)\gamma^\mu\gamma^5 \ \ (\mathrm{NC}) \ , \\ j^\mu &= \Big[F_1^\mathrm{V}(Q^2)\gamma^\mu + i\frac{\kappa}{2M}F_2^\mathrm{V}(Q^2)\sigma^{\mu\nu}q_\nu \\ &\quad - G_\mathrm{A}(Q^2)\gamma^\mu\gamma^5 + F_\mathrm{P}(Q^2)q^\mu\gamma^5\Big]\tau^\pm \ \ (\mathrm{CC}) \ , \end{aligned} \tag{4}$$

where $\tau^\pm$ are the isospin operators, κ is the anomalous part of the magnetic moment, $q^\mu = (\omega,\boldsymbol{q})$, with $Q^2 = |\boldsymbol{q}|^2 - \omega^2$, is the four-momentum transfer, and $\sigma^{\mu\nu} = (i/2)\,[\gamma^\mu,\gamma^\nu]$. G_A is the axial form factor and F_P is the induced pseudoscalar form factor. The weak isovector Dirac and Pauli form factors, F_1^V and F_2^V, are related to the corresponding electromagnetic form factors by the conservation of the vector current (CVC) hypothesis [1] plus, for NC reactions, a possible isoscalar strange-quark contribution F_i^{s}, i.e.,

$$\begin{aligned} F_i^{\mathrm{V,p(n)}} &= \left(\frac{1}{2} - 2\sin^2\theta_{\mathrm{W}}\right) F_i^{\mathrm{p(n)}} - \frac{1}{2}F_i^{\mathrm{n(p)}} - \frac{1}{2}F_i^{\mathrm{s}} \quad (\mathrm{NC}) , \\ F_i^{\mathrm{V}} &= F_i^{\mathrm{p}} - F_i^{\mathrm{n}} \quad (\mathrm{CC}) , \end{aligned} \tag{5}$$

where θ_{W} is the Weinberg angle $(\sin^2\theta_{\mathrm{W}} \simeq 0.23143)$. The electromagnetic form factors are taken from [35] and the strange form factors as [3]

$$F_1^{\mathrm{s}}(Q^2) = \frac{(\rho^{\mathrm{s}} + \mu^{\mathrm{s}})\tau}{(1+\tau)(1+Q^2/M_{\mathrm{V}}^2)^2} , \; F_2^{\mathrm{s}}(Q^2) = \frac{(\mu^{\mathrm{s}} - \tau\rho^{\mathrm{s}})}{(1+\tau)(1+Q^2/M_{\mathrm{V}}^2)^2} , \tag{6}$$

where $\tau = Q^2/(4M^2)$ and M_{V} = 0.843 GeV. The constants ρ^{s} and μ^{s} describe the strange quark contribution to the electric and magnetic form factors, respectively. The axial form factor is expressed as [36]

$$\begin{aligned} G_{\mathrm{A}} &= \frac{1}{2}\left(\tau_3 g_{\mathrm{A}} - g_{\mathrm{A}}^{\mathrm{s}}\right) G \quad (\mathrm{NC}) , \\ G_{\mathrm{A}} &= g_{\mathrm{A}} G \quad (\mathrm{CC}) , \end{aligned} \tag{7}$$

where $g_{\mathrm{A}} \simeq 1.26$, $g_{\mathrm{A}}^{\mathrm{s}}$ describes possible strange-quark contributions, $G = (1 + Q^2/M_{\mathrm{A}}^2)^{-2}$, and $\tau_3 = +1(-1)$ for proton (neutron) knockout. The axial mass has been taken as M_{A} = (1.026±0.021) GeV [37].

The single differential cross section with respect to the outgoing nucleon kinetic energy T_{N} is obtained after integrating over the energy and angle of the final lepton and over the solid angle of the final nucleon.

In the calculations a pure SM description is assumed for nuclear structure. The state n is assumed to be a one-hole state in the SM and φ_n are s.p. SM states with a unitary spectral strength. The sum over in Eq. (2) runs over all the occupied states in the SM. In this way we include the contributions of all the nucleons in the nucleus but neglect the effects of correlations that, anyhow, are expected to be small in the situations considered in the present investigation.

The cross section for the $\nu(\bar{\nu})$-nucleus scattering where only one-nucleon is detected is obtained from the sum of all the integrated exclusive one-nucleon knockout channels. FSI are described by means of a complex optical potential whose imaginary part gives an absorption that reduces the calculated cross section. It accounts for the flux lost in a particular channel and that goes towards other channels. This approach is conceptually correct for an exclusive reaction, where only one channel contributes, but it would be conceptually wrong for an inclusive reaction, where all the channels contribute and the total flux must be conserved. In fact, for the inclusive electron scattering [28] and for the CC scattering where only the outgoing lepton is detected [27] we adopt a different treatment of FSI, which makes use of a complex optical potential and where the total flux is conserved. Here, we consider semi-inclusive situations where an emitted nucleon is always detected and some of the reaction channels which are responsible for the imaginary part of the optical potential, like fragmentation of the nucleus, re-absorption, etc., are not included in the experimental cross section. From this point of view, it is correct to include the absorptive imaginary part of the optical potential. There are, however, contributions that are not included in our model and that can be included in the experimental cross section, for instance, contributions due to multi-step processes, where the outgoing nucleon is re-emitted after re-scattering in a detected channel simulating the kinematics of a QE reaction. The relevance of these contributions depends on kinematics and should not be too large in the situations considered in this paper. Anyhow, even if the use of an optical potential with an absorptive imaginary part can introduce some uncertainties in the comparison with data, we deem it a more correct and clearer way to evaluate the effects of FSI.

3 Nuclear Effects and Final State Interactions

Calculations have been performed for NC and CC ν_μ ($\bar{\nu}_\mu$) scattering from ^{12}C in an energy range between 500 and 1000 MeV, where one-nucleon knockout is expected to be the most important contribution. In this Section nuclear effects are investigated in calculations where the strange form factors are neglected. The effects of the strange nucleon form factors are discussed in the next Section.

Nuclear effects are included in the phenomenological ingredients for the bound and scattering states. Calculations performed with different bound state wave functions and with different optical potentials are not very sensitive to the choice and to the details of the phenomenological ingredients. Large effects are, however, produced by FSI. An example is shown in Figure 1, where the cross sections of the ^{12}C$(\nu_\mu, \mu^- p)$ and ^{12}C$(\bar{\nu}_\mu, \mu^+ n)$ CC reactions and of the ^{12}C$(\nu_\mu, \nu_\mu p)$ and ^{12}C$(\bar{\nu}_\mu, \bar{\nu}_\mu p)$ NC reactions are compared in RPWIA and RDWIA at $E_{\nu(\bar{\nu})} = 500$ and 1000 MeV. FSI reduce the cross sections of $\simeq 50\%$. This reduction is due to the imaginary part of the optical potential and is in agreement with the reduction found in the (e,e′p) calculations. We note that the cross sections for an incident neutrino are larger than for an incident antineutrino.

4 Strange Nucleon Form Factors

It is well known that the net strangeness of the nucleon is zero. It is also known, however, that according to the quantum field theory in the cloud of a physical nucleon there must be pairs of strange particles. From the viewpoint of QCD the nucleon consists of u and d quarks and of a sea of $q\bar{q}$ pairs produced by virtual gluons. Then, the question is: how do the sea quarks, in particular strange quarks, contribute to the observed properties of the nucleon? The first evidence that the constant $g_{\mathrm{A}}^{\mathrm{s}} = G_{\mathrm{A}}^{\mathrm{s}}(Q^2 = 0)$, that characterizes the matrix element of the axial strange current, is different from zero and large was found by the EMC experiment at CERN [38], in a measurement of deep inelastic scattering of polarized muons on polarized protons. This result triggered new experiments and a lot of theoretical work. It is very important that different and alternative methods are used to determine the matrix elements of the strange current. NC ν scattering is one of these methods and a suitable tool to investigate $g_{\mathrm{A}}^{\mathrm{s}}$.

Different nucleon form factors contribute to the s.p. weak current operator of the NC scattering of Eq. (4). A combination of different measurements is required for a complete information. The electromagnetic form factors, F_1 and F_2 in Eq. (5), can be investigated in electron scattering. The value of the Weinberg angle θ_{W} can be obtained from measurements of NC processes. Quasi-elastic CC scattering can give information on the axial form factor G_{A}, whose determination is very important in general and in particular if we want to determine $g_{\mathrm{A}}^{\mathrm{s}}$, that is highly correlated to G_{A} and thus to the axial mass M_{A}. The strange form factors, F_1^{s}, F_1^{s}, and $G_{\mathrm{A}}^{\mathrm{s}}$, can be investigated in NC ν scattering and in Parity-Violating Electron Scattering (PVES). PVES is essentially sensitive to F_1^{s} and F_1^{s} or, equivalently, to the strange electric and magnetic Sachs form factors $G_{\mathrm{E}}^{\mathrm{s}}$ and $G_{\mathrm{M}}^{\mathrm{s}}$. A determination of $G_{\mathrm{A}}^{\mathrm{s}}$ in PVES is hindered by radiative corrections. In contrast, NC ν scattering is primarily sensitive

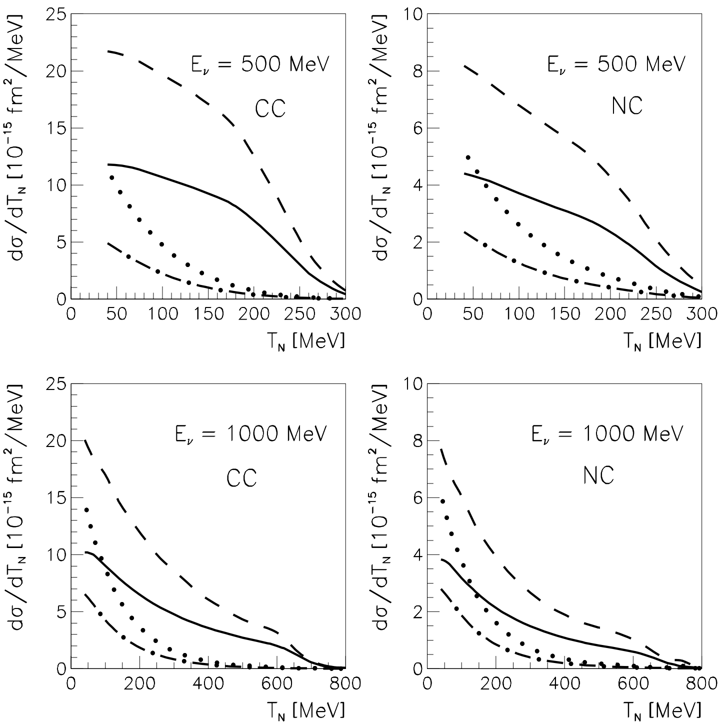

Figure **1.** Differential cross sections of the CC and NC ν_μ ($\bar{\nu}_\mu$) QE scattering on ^{12}C as a function of $\mathrm{T_N}$. Solid and dashed lines are the results in RDWIA and RPWIA, respectively, for an incident neutrino. Dot-dashed and dotted lines are the results in RDWIA and RPWIA, respectively, for an incident antineutrino. The strangeness contribution in the NC scattering is neglected.

to $G_{\mathrm{A}}^{\mathrm{s}}$. The interference with the strange vector form factors can be resolved by complementary experiments of PVES.

A determination of the form factors is beyond the scope of the present investigation. Our main aim here is to study the sensitivity of NC ν-nucleus scattering to the strange quark contribution. In Figure 2 the cross sections calculated, both for proton and neutron emission, with a particular choice for the values of the parameters, $g_{\mathrm{A}}^{\mathrm{s}} = -0.10$, $\mu^{\mathrm{s}} = -0.50$, and $\rho^{\mathrm{s}} = +2$, are compared with the results obtained without strange form factors. The cross sections with $g_{\mathrm{A}}^{\mathrm{s}} = -0.10$ are enhanced in the case of proton knockout and reduced in the case of neutron knockout by $\simeq 10\%$ with respect to those with $g_{\mathrm{A}}^{\mathrm{s}} = 0$. The effect of μ^{s} is comparable to that of $g_{\mathrm{A}}^{\mathrm{s}}$, whereas the contribution of ρ^{s} is very small for neutron knockout and practically negligible for proton knockout.

An absolute cross section measurement is a very hard experimental task due to difficulties in the determination of the neutrino flux. Thus, ratios of cross sections were proposed as an alternative way to extract $g_{\mathrm{A}}^{\mathrm{s}}$. Difficulties due to the determination of the absolute neutrino flux are reduced in the ratios. Moreover, also nuclear

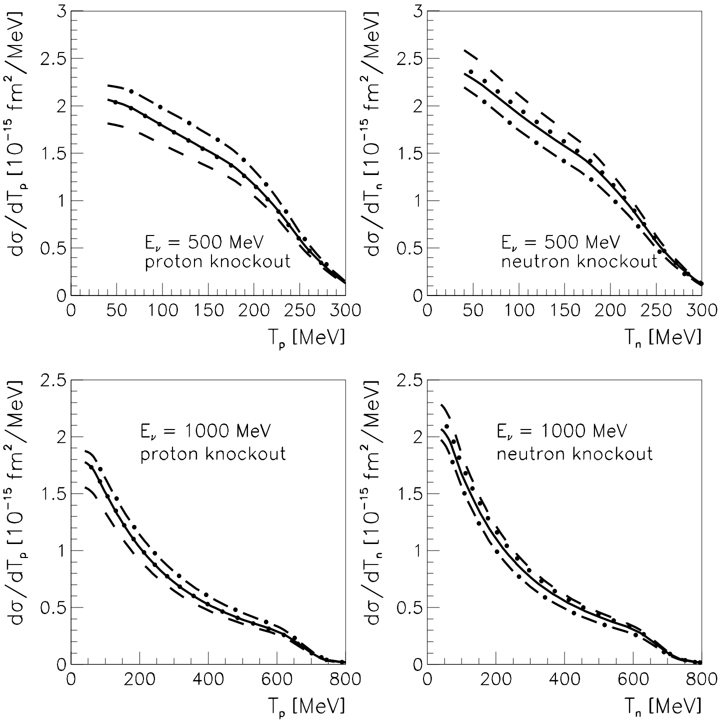

Figure **2.** Differential cross sections of the NC ν_μ QE scattering on ^{12}C as a function of T_{N}. Dashed lines are the results with no strangeness contribution, solid lines with $g_{\mathrm{A}}^{\mathrm{s}} = -0.10$, dot-dashed lines with $g_{\mathrm{A}}^{\mathrm{s}} = -0.10$ and $\mu^{\mathrm{s}} = -0.50$, dotted lines with $g_{\mathrm{A}}^{\mathrm{s}} = -0.10$ and $\rho^{\mathrm{s}} = +2$.

effects can be strongly reduced in the ratios. The effects of FSI are large on the cross sections and almost negligible in the ratios, where they give a similar contribution to the numerator and to the denominator [39]. In contrast, strangeness effects can be emphasized in the ratios, where form factors may contribute in a different way, for instance with a different sign, in the numerator and in the denominator.

Two different ratios are presented in Figure 3. The ratio of proton-to-neutron (p/n) NC cross sections is sensitive to the strange-quark contribution as the interference between g_A^s and g_A contributes with an opposite sign in the numerator and in the denominator [see Eq. (7)]. A precise measurement of this ratio appears, however, problematic due to the difficulties associated with neutron detection. A measurement of the ratio of the NC-to-CC (NC/CC) cross sections appears more feasible and will be measured at FINeSSE [40]. Although sensitive to strangeness only in the numerator, the NC/CC ratio is simply related to the number of events with an outgoing proton and a missing mass with respect to the events with an outgoing proton in coincidence with a muon. The ratios in Figure 3 are sensitive to g_A^s and μ^s, while the effects of ρ^s are very small. The results show similar features at different energies of the incident neutrino.

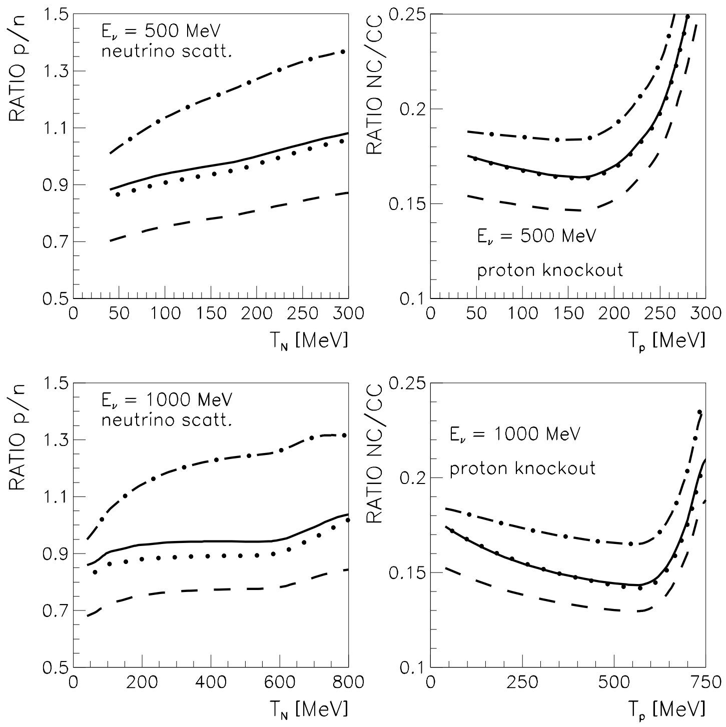

Figure **3.** Ratio of proton-to-neutron NC cross sections (left panel) and of NC-to-CC cross sections (right panel) of the ν QE scattering on ^{12}C. Line convention as in Figure 2.

5 Conclusions

We have presented RDWIA calculations for CC and NC $\nu(\bar{\nu})$-nucleus QE scattering. The effects of FSI are large on the cross section and almost negligible in the (p/n) and (NC/CC) ratios. The results obtained with the strange form factors are sensitive to $g_{\mathrm{A}}^{\mathrm{s}}$ and μ^{s} and practically insensitive to ρ^{s}. Measurements of the (p/n) and (NC/CC) ratios would be interesting to determine the constant $g_{\mathrm{A}}^{\mathrm{s}}$ that characterizes the matrix element of the axial strange current. The interference with the strange vector form factors can be resolved with complementary experiments of PVES.

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