Can two-boson radiative Correction Explain the NuTeV Anomaly? - Internal Note

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ABSTRACT

I discuss the possibility that two-boson radiative effects are the reason for the fact that the rate of neutral-current divided by the rate of charged-current (NC/CC) events in the NuTeV experiment is one percent lower that the standard model prediction.

Although two-boson effects in the charged-current process are included in the Bardin radiative corrections (used by NuTeV) at the quark-parton level, interactions with spectator quarks and and spectator nucleons are not included.

In the case when the second exchanged photon in a two-boson process is soft, its wavelenth is long and effects of interaction with the other spectator-quarks in the nucleon, or the spectator nucleons in the iron target can be important.

A one precent change in the NC/CC ratio can caused by an additional two-boson contribution at a level which is about half of the level which is currently needed to explain recent results in elastic electron-proton scattering.

This note is written in order to motivate more theoretical effort in the calculation of these two-boson spectator effects, and does not claim that this effect is the explanation the NuTeV anomaly. However, in the absense of reliable detailed calculations, this explanation cannot be rulled out at this time.

TWO PHOTON EFFECTS IN ELECTRON AND MUON SCATTERING

Recently, it has been suggested that the electric form factor of the proton as measured in electron scattering using the standard Rosenbluth separation technique [1], is sensitive to two-photon [2] radiative corrections. This has been proposed to explain a difference between the Rosenbluth results and the results using the newer polarization transfer technique [3]. The polarization measurements do not directly measure the form factors, but measure the ratio G_E/G_M, as as shown in Figure 1. There are currently several experiments proposed at Jefferson laboratory to study the magnitude of the two-photon contributions, as well as several theoretical efforts in calculating this effect in more detail. A simple way to parametrize these two-photon effects is in the form of an effective additional longitudinal contribution to the elastic cross section, thus resulting in a larger electric form factor as measured via a Rosenbluth technique.

For elastic scattering the ratio R is related to the ratio of elastic form factors by the following expression $R_{elastic} = (4M^2/Q^2)(G_E/G_M)^2$, or $R^p_{elastic} = (0.481/Q^2)(\mu_p G^p_E/G^p_M)^2$. For example for Q^2 of 2.5 Gev^2 the data in figure 1 (from Bodek, Budd and Arrington [4], show that $R^p_{elastic}$= $(0.19)(0.88)^2$=0.14$\pm$0.04 from the fit to the Rosenbluth separation data and $R^p_e lastic$= $(0.192)(0.72)^2$=0.10$\pm$0.02 from the fit to the polarization transfer data. If this difference is to be attributed to two-photon effects, then it implies a 4% epsilon dependence in the radiative corrections and an uncertainty in R of 0.04 $\pm$ 0.02. A fixed longitudinal contribution of this order becomes much more important at larger values of Q^2 as shown in the figure. As the electric form factor (or $R_{elastic}$) becomes smaller, the two-photon contribution becomes larger than the electric form factor of the proton.

The uncertainty in the longitudinal contribtution from two-photon effects in the inelastic radiative corrections is actually lower than the above estimate because modern radiative corrections programs for inelastic electron and neutrino scattering (e.g. Bardin) already include two photon effects at the parton level.

At present, simple calculations of two-photon effects in the elastic channel cannot fully explain the above experimental difference between the two techniques. In order to explain this difference, the calculations need to include other intermediate states (e.g. delta resonances) in addition to a single proton unexcited proton.

On one hand, the situation in the case of inelastic scattering (within the parton model) is simpler since there can be no intermediate excited quark states. However, the second photon can be be rather soft and in the case of inelastic scattering from a nucleon target, the second photon can interacts not only with the initial parton, but also with the spectator-quarks in the nucleon. For the scattering from a nuclear target, such as iron, the second soft photon can also interact with other spectator-nucleons, or with nuclear-fragments.

In this note, we assume that the the two-photon terms can be estimated by an effective change of R of 0.04 as extracted from the elastic electron-scattering data.

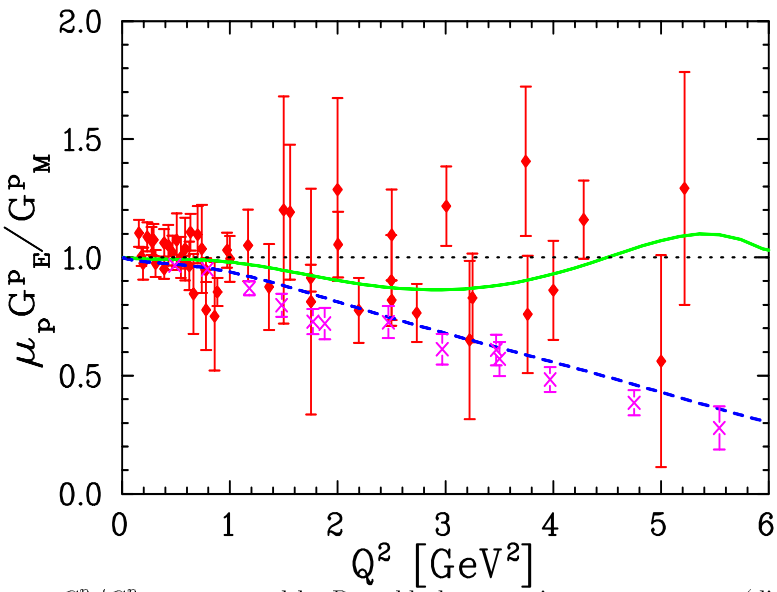


FIG. 1. Ratio $\mu_p\ G^p_E/G^p_M$ as extracted by Rosenbluth separation measurements (diamonds) and as obtained by polarization measurements(X's).

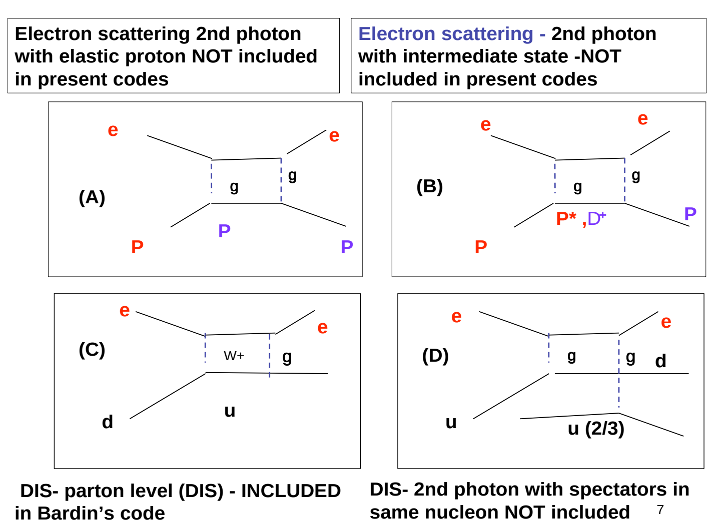


FIG. 2. Two-photon contribution: Diagram 1

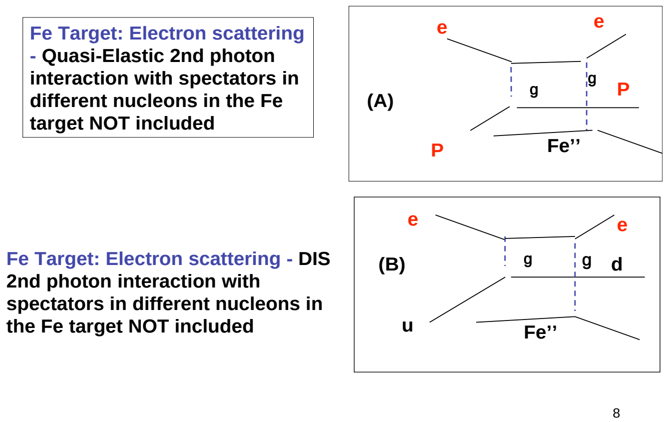


FIG. 3. Two-photon contribution: Diagram 2

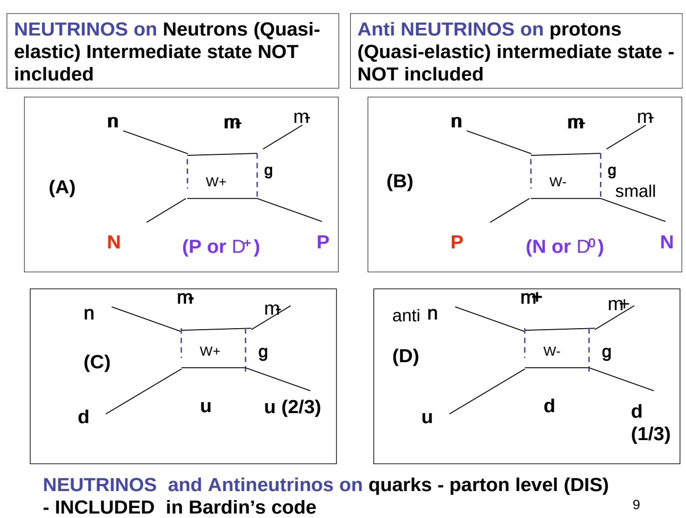


FIG. 4. Two-photon contribution: Diagram 3

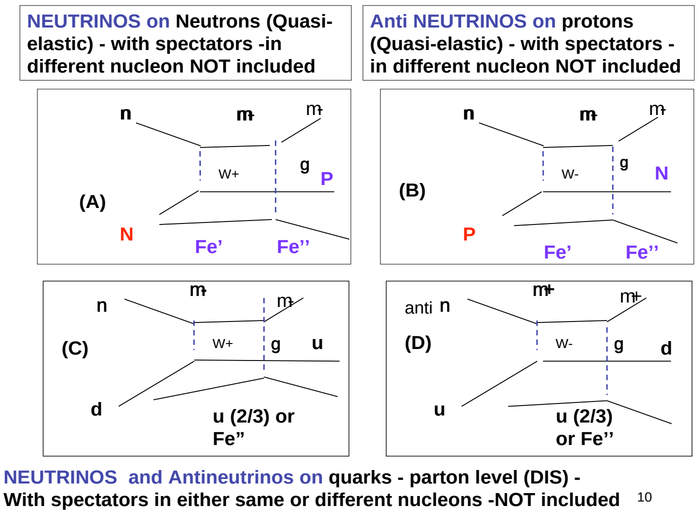
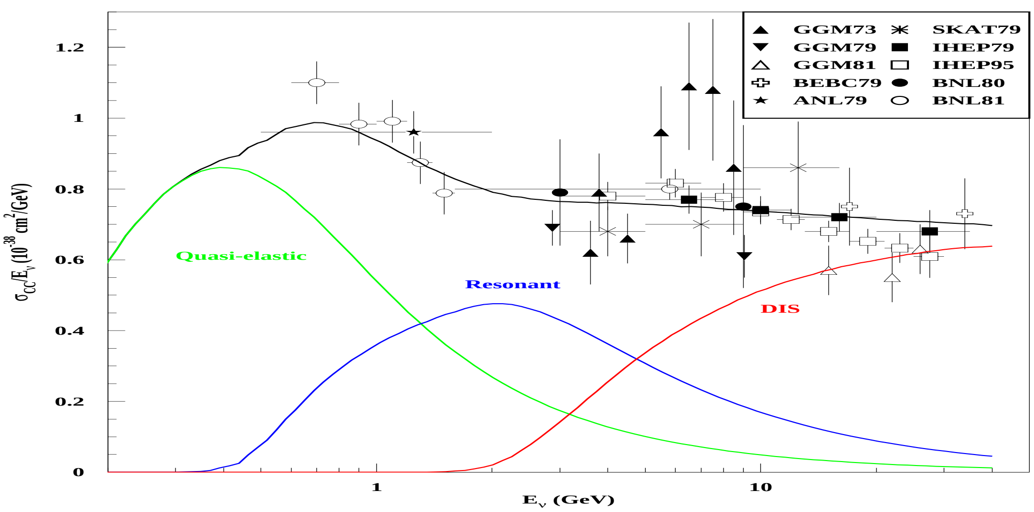


FIG. 5. Two-photon contribution: Diagram 10



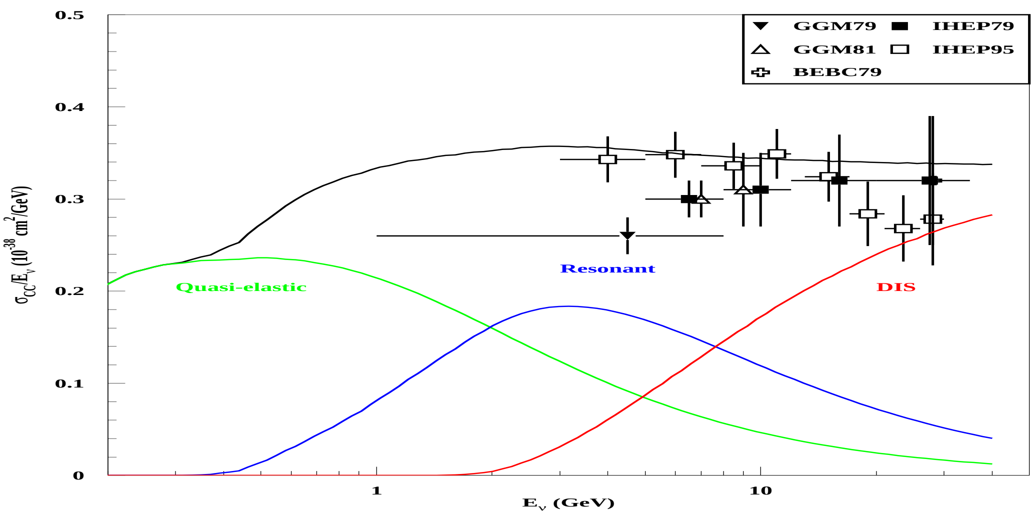


FIG. 6. Total neutrino and anti-neutrino cross-sections (*divided by energy*) versus energy compared to the sum of quasi-elastic, resonant, and inelastic contributions from the NUANCE model.

I. TWO-BOSON EFFECTS IN NEUTRINO SCATTERING

Two-boson effects which include a both a W and a photon are only present in charged current scattering. The primary diagram is the exchange of a W boson with a single quark leading to a final state muon. The two-boson diagram at the parton-level is for the case in which a additional photon is exchanged between the final state muon and the final state quark. That diagrem is divergent. However, the divergence is cancelled by diagrams in which an additional real photon is emitted by either the final state muon, or the final state quark.

This two-boson diagram which involves an extra photon exchange between the final state lepton and final state quark is not present for the case of neutral current scattering (since here the final state lepton is a neutrino). As mentioned earlier, the effect of the extra-photon in charged current scattering (which leades to a change of the NC/CC ratio) is included in the Bardin radiative corrections at the parton level.

Here, we assume that the effect of the extra photon can be estimated by an effective R which 0.04 larger in charged current then in neutral current scattering.

II. SENSITIVITY OF THE NEUTRINO CROSS SECTIONS TO R

The expressions used in this section are from the Appendix.

Within the quark-parton model, the total neutrino and antineutrino cross sections on a nucleon target are given by integrating the differential cross sections over x and y:

$$\sigma^{\nu N} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left[Q^{\nu N} + (1/3)\overline{Q}^{\nu N} + K^{\nu N}\right] \qquad (1)$$

$$\sigma^{\overline{\nu} N} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left[\overline{Q}^{\overline{\nu} N} + (1/3)Q^{\overline{\nu} N} + K^{\overline{\nu} N}\right] \qquad (2)$$

Here Q is the fractional momentum carried by all quarks in the nucleon, $\overline{Q}$ is the fractional momentum carried by all antiquarks in the nucleon and $R = 2\mathrm{K}/(Q+\overline{Q})$ is the average ratio of longitudinal to transverse contribution. For low energies, the antiquark contribution is small.

Therefore, the fractional error in the predicted neutrino and antineutrino total cross sections from an uncertainty in R is $0.5\Delta R$ for neutrinos and $1.5\Delta R$ for antineutrinos, respectively.

A back of an envelope calculation of the sensitivity of the ratio of antineutrino to neutrino total cross section ratio to a change in the average value of R with neutrino energy or from nuclear effects (e.g. $R = 0.3 \pm 0.2$) is illustrative. At low energy, with $\overline{Q}$=0 we obtain the following. If $R = 0$, the ratio is 0.33. If $R = 0.5$, the ratio is $(0.33 + 0.25)/(1.0 + 0.25)$=0.46.

Figure 6 shows the current data for total neutrino and antineutrino cross-sections *divided by energy* (per nucleon for an isoscalar target) versus energy (at low energies) compared to a model of the sum of quasi-elastic, resonant, and inelastic contributions.

At high energies, e.g. NuTeV, the antineutrino to neutrino charged current total cross section ratio is about 0.5. Therefore, the additional contribution from antiquarks needs to be taken into account.

The charged current data is well reproduced by assuming that on average, $R' = 2\mathrm{K}/(Q)$ is 0.26 and f = 0.025/1.196=0.021/Q is about 0.2. For this assumption we get that the ratio of antineutrino to neutrino cross sections is equal to (0.333+0.2+0.13)/(1.0+0.066+0.13) = 0.633/1.196 = 0.529.

Figure 7 (right) shows all available data on R and the nuclear dependence of R in the DIS region. Figures 9 and 8 show preliminary results of analysis of very precise data from Jlab experiment E94-110 [6] on hydrogen in the resonance region. Data with deuterium is expected to be taken in experiment E02-109, and data with nuclear targets is proposed to be taken by Jlab proposal P04-001 (previously P03-110). Note that a difference in R of 0.04 between the predictions of the theory of QCD (including target mass corrections and NNLO higher terms) and the data cannot be measured because experimental errors and uncertainties in the theoretical predictions are larger than that. Even with the new precise data of Jlab E94-110, there still remain the theoretical uncertainties in the predictions which are larger than 0.04. Therefore a difference of 0.04 in R between charged current and neutral current (if originating from two-boson terms) cannot be rulled out by the data on R in charged lepton scattering.

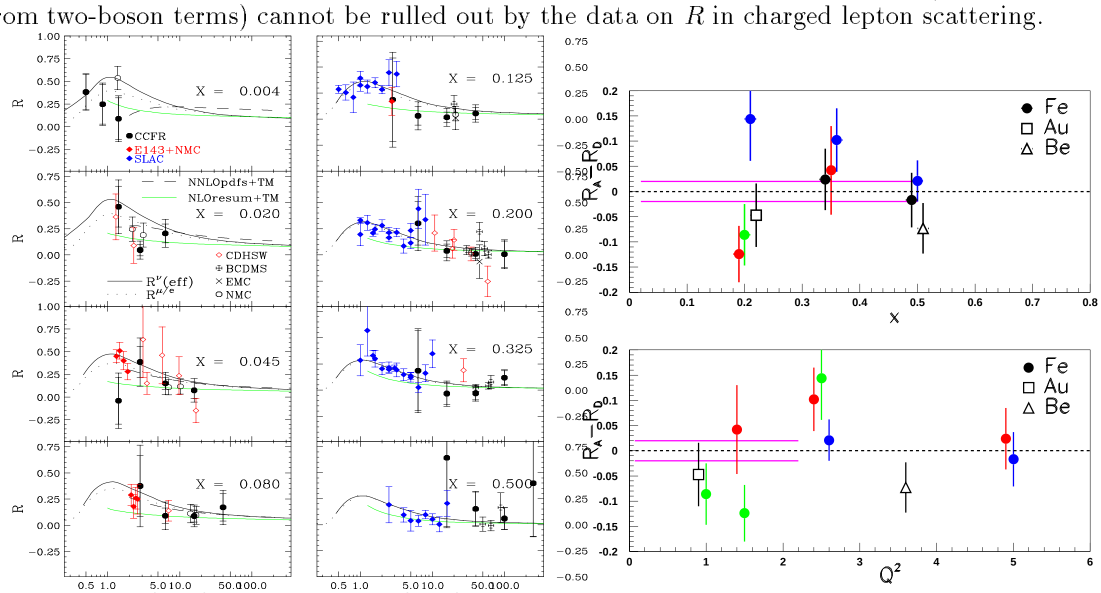


FIG. 7. Left: A compilation of the world's published data on R at high Q^2 on in the DIS region for both nucleons and nuclei. Right: The SLAC E140 data on the nuclear dependence of R in the DIS region presented in the form $R_A - R_D$ (e.g. difference between iron and deuterium. The lines in rhw figure on the right represent the small projected uncertainties of the new measurements proposed by here P04-001 (previously P03-110).

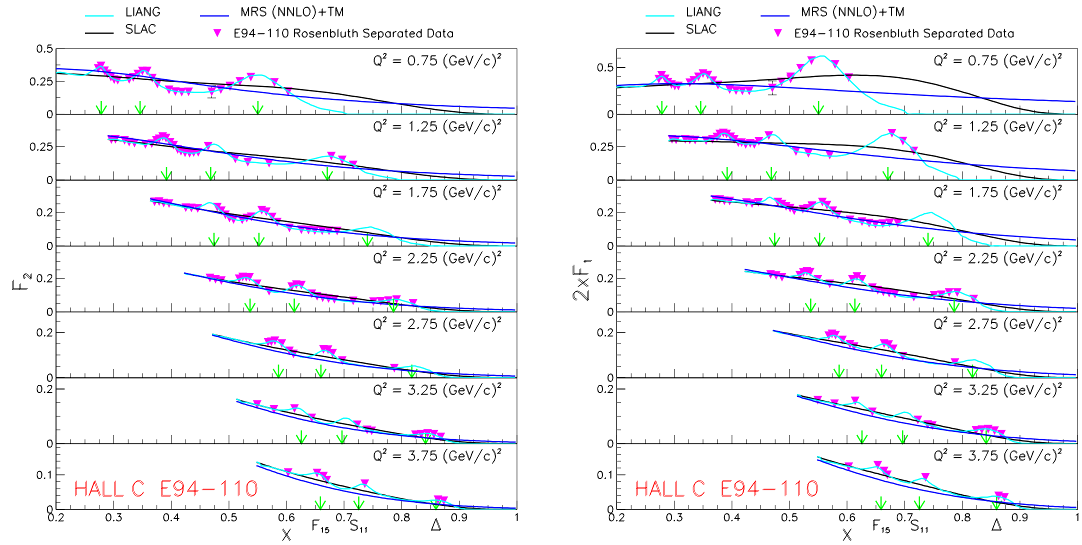


FIG. 8. Recent data from Jlab experiment E94-110 (on Hydrogen) for $2xF_1$ (left) and F_2 (right) in the resonance region. Data with deuterium is expected to be taken in experiment E02-109, and data with nuclear target is proposed to be taken by P04-001 (previoully P03-110).

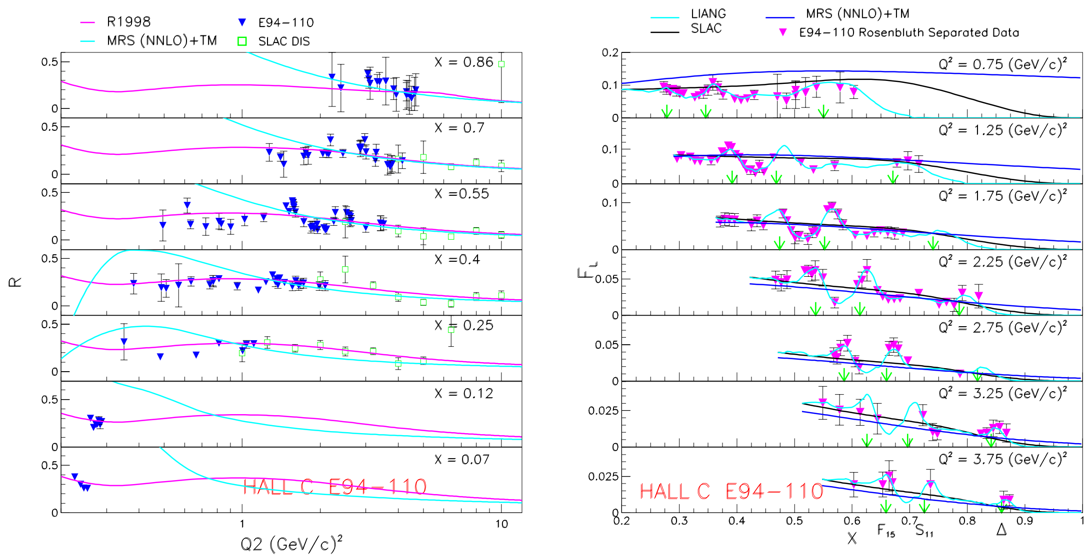


FIG. 9. Recent data from Jlab experiment E94-110 (on hydrogen) for R (left) and F_L (right) in the resonance region. Data with deuterium is expected to be taken in experiment E02-109, and data with nuclear target is proposed to be taken by P04-001 (previoully P03-110).

If we model the two-boson effect as change ΔR of 0.04, for an antiquark contribution of 0.2 it corresponds to a change $\Delta R'$ of 0.05. (In the electron scattering for which the charge of the final state proton is 1.)

In neutrino charged current scattering, a $W+$ boson is echanged and d quarks are transformed to u quarks (in the valence and sea region); and $\overline{u}$ to $\overline{d}$ (in the sea region). Therefore, the charge of the final state quark is typically (2/3)

In anti-neutrino charged current scattering, a $W-$ boson is echanged and u quarks are transformed to d quarks (in the valence and sea region); and $\overline{d}$ to $\overline{d}$ (in the sea region). Therefore, the charge of the final state quark is typically (1/3).

If the the effect of the extra-photon is due to interference between the two-boson and single boson diagram, then $\Delta R'$ from this effect will be twice as large in neutrinos than in antineutrinos, because the charged of the final state quark is larger. However, since the total cross section for antineutrinos is about half of that from neutrinos, the net effect is that the fractional change in the charged current cross section from two-boson effects is about the same for neutrinos and antineutrinos.

A $\Delta R'$ of 0.05 would result in the NC/CC ratio for neutrino scattering of $0.5\Delta R'/1.196$=0.021. The NuTeV anomaly of 0.01 could come from and extra contribution of two boson effects originating from interactions with the spectator quarks or spectator nucleons. A change in the NC/CC ratio of 0.1 requires that these term are about 50% in the mangitude of the entire two-photon contribution needed to explain the elastic electron-proton results. This is consistent with present calculation of two photon effects in elastic scattering which indicate that the mangnitude needed to explain the electric form factor measurements is about twice the value calculated with only a single proton in the intermediate state. In the elastic channel, the additional contribution is attributed to diagrams which include excited intermediate states (such as the delta).

Here a comparison of the relative size of the two-boson contributions in the present Bardin radiaive corrections codes (at the parton level) for inelastic electron, neutrino and an antineutrino scattering would be of great interest.

APPENDIX: CHARGED-CURRENT NEUTRINO AND ANTINEUTRINO CROSS SECTIONS

Quark-Parton Model

Here we use the quark-parton model to illustrate some of physics concepts behind the proposed measurements. Note that at low energies, there are large corrections to this model which need to be taken into account.

In neutrino (ν_μ) nucleon scattering experiments, the three independently measured variables in a charged-current event are the outgoing muon momentum (p_μ), the outgoing muon angle (θ_μ), and the observed energy of the final state hadrons (E_{had}). From these measured variables the neutrino energy is equal to $E_\nu = E_{had} + E_\mu$ as required by energy conservation.

The derivation of the formulae for inclusive charged-current neutrino scattering is very similar to the case of $e - \mu$ scattering. Both do not require any knowledge of the dynamics inside the nucleon. The unknown couplings of the lepton-current to the nucleon are absorbed in the definition of the structure function F_i. In the case of elastic (muon,electron) or quasi-elastic (neutrino) scattering, these can be interpreted as the Fourier transforms of the spacial charge distribution in the nucleon.

The general form of the differential cross section for neutrino-nucleon scattering, mediated by the W boson (in the case of charged-current scattering) is given in terms of three structure functions:

$$\frac{d^2\sigma}{dxdy}^{\nu(\overline{\nu})} = \frac{G^2ME}{\pi}\left[(1-y-\frac{Mxy}{2E})F_2 + \frac{y^2}{2}2xF_1 \pm (1-\frac{y}{2})xF_3\right] \tag{3}$$

where the $+(-)$ terms correspond to neutrino (antineutrino) scattering. Here G_F is the Fermi weak coupling constant. The structure function, F_i are process dependent, and are functions of the kinematics variable, x and Q^2. If the cross section is re-written in terms of the absorption cross-sections by left-handed, right-handed, and longitudinally polarized W bosons, then the structure function F_1 corresponds to the contribution from the sum of left-handed and right-handed bosons, F_2 corresponds to the contribution from all boson polarizations, whereas F_3 corresponds to the contribution from the difference of right-handed and left-handed polarized bosons. The structure function F_3 is non-zero only in weak interactions (for which parity is violated).

The relationship between the experimentally extracted structure functions and the parton distributions in the nucleon (and their dependence on kinematic variables) is determined within the framework of the quark-parton model. If we denote $q(x)$ as the probability to find a parton with momentum fraction x in a frame of a fast moving nucleon, the differential cross section for the scattering from a parton is given by

$$\frac{d\sigma^2}{dx\,dy} \propto \frac{G_F^2 ME}{\pi(1+Q^2/M_W^2)^2}\, xq(x). \tag{4}$$

Therefore, the cross sections for neutrino (and antineutrino) nucleon scattering are the sums of all parton contributions in the nucleon, with the proper angular dependence factors, as follows:

$$\frac{d^2\sigma^{\nu N}}{dxdy} = \frac{G_F^2 ME_\nu x}{\pi(1+Q^2/M_W^2)^2}\left[q^{\nu N}(x) + (1-y)^2\overline{q}^{\nu N}(x) + 2(1-y)k^{\nu N}(x)\right] \tag{5}$$

$$\frac{d^2\sigma^{\overline{\nu} N}}{dxdy} = \frac{G_F^2 ME_\nu x}{\pi(1+Q^2/M_W^2)^2}\left[\overline{q}^{\overline{\nu} N}(x) + (1-y)^2 q^{\overline{\nu} N}(x) + 2(1-y)k^{\overline{\nu} N}(x)\right] \tag{6}$$

The contribution (k) of the longitudinal contribution e.g. from possible spin-0 constituents or quark transverse momenta is also shown. The angular dependence factor for this contribution, $(1-y)$, is the same as for the terms which originate from the small intrinsic transverse (p_t) of spin 1/2 partons.

Total neutrino and antineutrino cross sections

Integrating the above expression over x and y (from 0 to 1) yields:

$$\sigma^{\nu N} = \frac{G_F^2 ME_\nu}{\pi(1+Q^2/M_W^2)^2}\left[Q^{\nu N} + (1/3)\overline{Q}^{\nu N} + K^{\nu N}\right] \tag{7}$$

$$\sigma^{\overline{\nu} N} = \frac{G_F^2 ME_\nu}{\pi(1+Q^2/M_W^2)^2}\left[\overline{Q}^{\overline{\nu} N} + (1/3)Q^{\overline{\nu} N} + K^{\overline{\nu} N}\right] \tag{8}$$

Here Q is the fractional momentum carried by all quarks in the nucleon, $\overline{Q}$ is the fractional momentum carried by all antiquarks in the nucleon and $R = 2\mathrm{K}/(Q+\overline{Q})$ is the average ratio of longitudinal to transverse contribution. For low energies, the antiquark contribution is small. Therefore, the fractional error in the predicted neutrino and antineutrino total cross sections from an uncertainty in R is $0.5\Delta R$ for neutrinos and $1.5\Delta R$ for antineutrinos, respectively.

In the region of the first resonance, R is predicted to be zero in the bound quark oscillator model. In fact, the first results from Jlab experiment E94-110 on hydrogen show a value of R of about 0.3 at low W and low Q^2. This implies that the effects of the nucleon pion cloud are very important in this region. The nuclear dependence of R in the region is totally unknown, and current measurements of the nuclear dependence of R have an error of ΔR of 0.2. It is expected that the nuclear effects on the nucleon pion cloud are very significant at low energies. Therefore, even if we use the preliminary precise measurement of R on hydrogen from experiment E94-110, we are still left with the problem that none of the data have been taken on Carbon or iron. An error ΔR of 0.2 implies a 10% error in the predicted neutrino cross section in this region and an error 30% in the predicted antineutrino cross setion.

A back of an envelope calculation of the sensitivity of the ratio of antineutrino to neutrino total cross section ratio to a change in the average value of R with neutrino energy or from nuclear effects (e.g. $R = 0.3 \pm 0.2$) is illustrative. At low energy, with $\overline{Q}$=0 we obtain the following. If $R = 0$, the ratio is 0.33. If $R = 0.5$, the ratio is $(0.33 + 0.25)/(1.0 + 0.25)$=0.46.

Structure Functions

A comparison of the above parton-level cross sections with Equation 3 yields the following relations between the structure functions and parton distributions:

$$2xF_1^{\nu(\overline{\nu})N} = 2\left[xq^{\nu(\overline{\nu})N}(x) + x\overline{q}^{\nu(\overline{\nu})N}(x)\right]$$

$$F_2^{\nu(\overline{\nu})N} = 2\left[xq^{\nu(\overline{\nu})N}(x) + x\overline{q}^{\nu(\overline{\nu})N}(x) + 2xk^{\nu(\overline{\nu})N}(x)\right] \tag{9}$$

$$xF_3^{\nu(\overline{\nu})N} = 2\left[xq^{\nu(\overline{\nu})N}(x) - x\overline{q}^{\nu(\overline{\nu})N}(x)\right] \tag{10}$$

where terms proportional to Q^2/ν^2 have been neglected. Thus, in the parton model, nucleon structure functions are related to the momentum distributions carried by the partons in the nucleon.

If the scattering takes place exclusively from free spin-$\frac{1}{2}$ constituents, the Callan-Gross relation

$$2xF_1 = F_2 \tag{11}$$

is satisfied. However, the partons also have non-negligible transverse momenta, which at present energies yields an apparent spin-0 type behavior, in the infinite momentum frame. This transverse momentum leads to a difference between F_2 and $2xF_1$ that diminishes as the momentum transfer Q^2 increases. The exact relation between $2xF_1$ and F_2 is obtained by using R, the ratio of the longitudinal structure function (F_L) and transverse structure function ($2xF_1$).

$$R = \frac{F_L}{2xF_1} = \frac{F_2}{2xF_1}(1 + Q^2/\nu^2) - 1 = (1 + \frac{2k}{q + \overline{q}})(1 + Q^2/\nu^2) - 1. \tag{12}$$

Relation to Electromagnetic Structure Functions

The analogous expressions for charged-lepton scattering via virtual photon exchange follow from the pure vector nature of the electromagnetic current. Thus, electromagnetic scattering probes the charge of the partons, whereas neutrino scattering probes the flavor composition of the nucleon constituents.

$$2xF_1^{\ell N} = \sum_i e_i^2\left[xq_i^{\ell N}(x) + x\overline{q}_i^{\ell N}(x)\right] \tag{13}$$

$$F_2^{\ell N} = \sum_i e_i^2\left[xq_i^{\ell T}(x) + x\overline{q}_i^{\ell N} + 2k_i^{\ell N}(x)\right] \tag{14}$$

where e_i is electric charge of parton i. Comparison of neutrino and charged-lepton scattering data provides the measurement of the mean-square charge of the nucleon's interacting constituents.

Neutrino scattering has the ability to resolve the flavor of the nucleon constituents. Because of charge conservation at the quark vertex, charged current neutrino scattering happens only with d, s, $\overline{u}$ and $\overline{c}$ quarks. Similarly, antineutrinos can scatter only from $\overline{d}$, $\overline{s}$, u and c quarks. For a proton target, the parton densities that contribute to the structure functions are:

$$q^{\nu p}(x) = d^p(x) + s^p(x); \overline{q}^{\nu p}(x) = \overline{u}^p(x) + \overline{c}^p(x) \tag{15}$$

$$q^{\overline{\nu}p}(x) = u^p(x) + c^p(x); \overline{q}^{\overline{\nu}p}(x) = \overline{d}^p(x) + \overline{s}^p(x) \tag{16}$$

Isospin invariance (also called charge symmetry) requires symmetry between the light quark densities in the proton and neutron:

$$d^p(x) = u^n(x), \quad u^p(x) = d^n(x), \quad \overline{d}^p(x) = \overline{u}^n(x), \quad \overline{u}^p(x) = \overline{d}^n(x). \tag{17}$$

Using these symmetries, the quark distributions in the neutron are described in terms the quark distributions in the proton. All of the parton distributions are defined with respect to the proton.

$$q^{\nu n}(x) = u(x) + s(x); \overline{q}^{\nu n}(x) = \overline{d}(x) + \overline{c}(x) \tag{18}$$

$$q^{\overline{\nu}n}(x) = d(x) + c(x); \overline{q}^{\overline{\nu}n}(x) = \overline{u}(x) + \overline{s}(x) \tag{19}$$

Finally, the parton densities for an isoscalar nucleon, $\frac{1}{2}$(proton + neutron), are given by:

$$q^{\nu N}(x) = \frac{1}{2}\left[u(x) + d(x) + 2s(x)\right]; \overline{q}^{\nu N}(x) = \frac{1}{2}\left[\overline{u}(x) + \overline{d}(x) + 2\overline{c}(x)\right] \tag{20}$$

$$q^{\overline{\nu} N}(x) = \frac{1}{2}\left[u(x) + d(x) + 2c(x)\right]; \overline{q}^{\overline{\nu} N}(x) = \frac{1}{2}\left[\overline{u}(x) + \overline{d}(x) + 2\overline{s}(x)\right] \tag{21}$$

The quark content of the isoscalar structure function $2xF_1$ for neutrino scattering is obtained by substituting these densities into Equations 9:

$$\begin{aligned} 2xF_1^{\nu N}(x) &= xu(x) + x\overline{u}(x) + xd(x) + x\overline{d}(x) \\ &\quad + xs(x) + x\overline{s}(x) + xc(x) + x\overline{c}(x) \\ &= 2xF_1^{\overline{\nu} N}(x). \end{aligned} \tag{22}$$

In the following discussion (for simplicity) we assume $xs(x) = x\overline{s}(x)$. The charm quark distributions, which are small when compared to the strange quark distributions, are also neglected.

The electromagnetic structure functions $2xF_1^{\ell p}$ and $2xF_1^{\ell n}$ are constructed from Equation 14 using the same parton densities as above, and including the quark charges:

$$\begin{aligned} 2xF_1^{\ell p} &= \left(\frac{1}{3}\right)^2 \left[xd(x) + x\overline{d}x + xs(x) + x\overline{s}(x)\right] \\ &\quad + \left(\frac{2}{3}\right)^2 \left[xu(x) + x\overline{u}(x) + xc(x) + x\overline{c}(x)\right] \end{aligned} \tag{23}$$

$$\begin{aligned} 2xF_1^{\ell n} &= \left(\frac{1}{3}\right)^2 \left[xu(x) + x\overline{u}x + xs(x) + x\overline{s}(x)\right] \\ &\quad + \left(\frac{2}{3}\right)^2 \left[xd(x) + x\overline{d}(x) + xc(x) + x\overline{c}(x)\right]. \end{aligned} \tag{24}$$

$$\tag{25}$$

The $2xF_1^{\ell N}$ for an isoscalar nucleon is found by averaging:

$$\begin{aligned} 2xF_1^{\ell N} &= \frac{1}{2}\left(2xF_1^{\ell p} + 2xF_1^{\ell n}\right) \\ &= \frac{5}{18}\left(xu + x\overline{u} + xd + x\overline{d}\right) \\ &\quad + \frac{1}{9}\left(xs + x\overline{s}\right) + \frac{4}{9}\left(xc + x\overline{c}\right). \end{aligned} \tag{26}$$

Under the assumption that the value of R is the same for electromagnetic neutral-current and weak charged-current structure functions, the ratio of electromagnetic and neutrino structure functions for $2xF_1$ is equal to the ratio for F_2:

$$\frac{F_2^{\ell N}}{F_2^{\nu N}} = \frac{5}{18}\left(1 - \frac{3}{5}\frac{xs + x\overline{s} - xc - x\overline{c}}{xq + x\overline{q}}\right) \tag{27}$$

where $xq + x\overline{q} = 2xF_1^{\nu N}$. This relationship is known as the $5/18ths$ rule. The observation that charged-lepton scattering and neutrino-scattering structure functions are approximately related by a factor of $\sim 5/18$, was a significant triumph for the QPM.

The structure function xF_3 (which is only present in parity violating weak interactions) represents the momentum density of valence quarks. Substitution of the isoscalar parton densities into Equation 10 yields:

$$xF_3^{\nu N}(x) = xu_V(x) + xd_V(x) + 2xs(x) - 2xc(x) \tag{28}$$

$$xF_3^{\overline{\nu} N}(x) = xu_V(x) + xd_V(x) - 2x\overline{s}(x) + 2x\overline{c}(x) \tag{29}$$

where $u_V \equiv u - \overline{u}$ and $d_V \equiv d - \overline{d}$ are the valence densities in the proton. The average value of $xF_3^{\nu N}$ and $xF_3^{\overline{\nu}N}$ yields the total valence quarks distribution. The difference of $xF_3^{\nu N}$ and $xF_3^{\overline{\nu}N}$ is very sensitive to both the strange sea and charm sea in the nucleon as shown below:

$$xF_3(x) = \left[xF_3^{\nu N}(x) + xF_3^{\overline{\nu}N}(x)\right]/2 = xu_v(x) + xd_d(x) \tag{30}$$

$$\Delta xF_3(x) = \left[xF_3^{\nu N}(x) - xF_3^{\overline{\nu}N}(x)\right] = 2(s(x) + \overline{s}(x) - c(x) - \overline{c}(x)) \tag{31}$$

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