Measurement of F_2 and $R = \sigma_L/\sigma_T$ on Nuclear-Targets in the Nucleon Resonance Region - E03-110

(First Stage of a Program to Investigate Quark Hadron Duality in Electron and Neutrino Scattering on Nucleons and Nuclei)

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SUMMARY

We propose to measure the longitudinal-transverse (L-T) separated structure functions from nuclear targets in the resonance region. This is the first stage of an overall program to investigate quark-hadron duality in electromagnetic and weak structure of nucleons and nuclei. The targets proposed include Carbon, Quartz, Aluminum, Calcium, Steel and Copper to compliment existing baseline data on Hydrogen and Deuterium. The targets proposed are (or closely resemble) nuclear targets commonly used in neutrino experiments such as the low statistics experiments on Hydrogen, Deuterium, Neon, and Argon and high statistics neutrino experiments on Scintillator, Water and Steel. In addition to performing studies of quark-hadron duality in electron scattering on nuclear targets for the separated structure functions, these data will used as input vector form factors in a future analysis of neutrino data in order to investigate quark hadron-duality in the axial structure function of nucleons and nuclei.

Measurements will be made in the nucleon resonance region ($1 < W^2 < 4$ GeV^2) spanning the four-momentum transfer range $0.5 < Q^2 < 4.0$ (GeV/c)^2 at identical kinematic points to those to be run during JLab Deuterium experiment 02-109. (Therefore, it is most efficient for both experiments to be run at the same time). The decomposition of the inclusive electroproduction cross sections into longitudinal and transverse strengths will accomplished by performing Rosenbluth separations to extract the transverse structure function $F_1(x, Q^2)$, the longitudinal structure function $F_L(x, Q^2)$, and the ratio $R = \sigma_L/\sigma_T$.

The analysis of the separated resonance region proton data from experiment E94-110 [1], which was performed in Hall C, has recently been completed and the excellent precision obtained from that measurement has been presented in JLab hydrogen proposal E94-110 [1]. The extension of the proton measurements to deuterium is approved and will be run by E02-109 [2]. This proposal represents the first global survey of these fundamental separated quantities in the resonance region for nucleons bound in nuclei. Data from all of the previous experiments will be incorporated into the analysis.

Given the experience of these previous experiments, the data taking is straightforward and allows the precision of the proposed measurements to be predicted with great confidence. In addition, the analysis machinery which was developed for E94-110 can be used with only very little modification. The great care and time invested in developing the experimental requirements, systematic uncertainty measurements, and analysis machinery will be of immediate benefit to the proposed experiment. We will also build upon the experience from previous lower statistics studies with (electrons) of the nuclear-dependence of the separated structure functions in the DIS region that were done by SLAC experiment E140 [3], as well as the very low Q^2 high W^2 studies (to test the HERMES effect) that were done by JLab experiment E99-118 [4].

PHYSICS OVERVIEW, MOTIVATION AND GOALS

Due to the small value of the electromagnetic coupling constant, the scattering of electrons from nucleons can be well approximated by the exchange of a single virtual photon, which carries the exchanged 4-momentum squared, q^2. In terms of the incident electron energy, E, the scattered electron energy, $E^{'}$, and the scattering angle, θ, the absolute value of the exchanged 4-momentum squared is given by

$$(-q)^2 = Q^2 = 4EE^{'}\sin^2\frac{\theta}{2}. \tag{1}$$

In the one photon exchange approximation, the spin-independent cross section for inclusive electron-nucleon scattering can be expressed in terms of the photon helicity coupling as

$$\frac{d\sigma}{d\Omega dE'} = \Gamma\left[\sigma_T(x, Q^2) + \epsilon\sigma_L(x, Q^2)\right], \tag{2}$$

where σ_T (σ_L) is the cross section for photo-absorption of purely transverse (longitudinal) polarized photons,

$$\Gamma = \frac{\alpha E^{'}(W^2 - M_p^2)}{2\pi Q^2 M_p E(1-\epsilon)} \tag{3}$$

is the flux of transverse virtual photons, and

$$\epsilon = \left[1 + 2(1 + \frac{\nu^2}{Q^2})\tan^2\frac{\theta}{2}\right]^{-1} \tag{4}$$

is the relative flux of longitudinally polarized virtual photons.

In terms of the structure functions $F_1(x, Q^2)$ and $F_L(x, Q^2)$, the double differential cross section can be written as

$$\frac{d\sigma}{d\Omega dE^{'}} = \Gamma \frac{4\pi^2\alpha}{x(W^2 - M_p^2)}\left[2xF_1(x, Q^2) + \epsilon F_L(x, Q^2)\right]. \tag{5}$$

Comparison of equations 2 and 5 shows that $F_1(x, Q^2)$ is purely transverse, while the combination

$$F_L(x, Q^2) = \frac{1 + 4M_p^2x^2}{Q^2}F_2(x, Q^2) - 2xF_1(x, Q^2) \tag{6}$$

is purely longitudinal. The separation of the unpolarized structure functions into longitudinal and transverse parts from cross section measurements can be accomplished via the Rosenbluth technique [5], by making measurements at two or more values of ϵ for fixed x and Q^2. Fitting the reduced cross section, $d\sigma/\Gamma$, linearly in ϵ, yields σ_T (and therefore $F_1(x, Q^2)$) as the intercept, and the structure function ratio $R(x, Q^2) = \sigma_L/\sigma_T = F_L(x, Q^2)/2xF_1(x, Q^2)$ as the slope.

In neutrino scattering, the separated vector structure functions are related to the separated vector structure functions in electron scattering on protons and neutrons via CVC and Clebsch-Gordan coefficients which depend on the contributions of different isospin amplitudes to the scattering. The relations between the vector structure functions are well determined for elastic (quasi-elastic) scattering on free nucleons for which the isospin of the initial and final states are well determined. Similarly, the relationships between the vector form factors are also well determined for the scattering on free quarks (i.e.the high Q^2 DIS scattering) for which the isospin states of the initial and final state quarks are also well determined. In general, even in these well understood cases, in order to extract the axial structure function in neutrino scattering experiments, the separated vector structure functions from electron scattering, F_{2p}, F_{2n}, R_p, R_n for bound nucleons are needed.

In contrast, in the resonance region which includes contributions from final states with different isospins, the relationships between the vector form factors in neutrino and electron scattering is more complicated. Therefore, a unified investigation of quark-hadron duality for the same nuclear targets with electrons and neutrinos is interesting.

High statistics samples in neutrino experiments on nuclear targets such as iron and hydrocarbons will be measured beginning in 2005 in experiments at the near detector hall at the Fermilab-NUMI beam At present, as described in the next section, the physics emphasis of these experiments is the investigation of neutrino cross sections at low energies as a tool to study neutrino oscillations. Members of this collaboration are proposing to investigate quark-hadron duality in high statistics electron scattering with the same nuclear targets first. This will be followed by a comparison with all existing neutrino data, with the aim of continuing these studies with the higher statistics neutrino experiments in the future. Note that investigation of quark-hadron duality in the axial structure functions of nucleons and nuclei with neutrinos also add a new dimension to these studies.

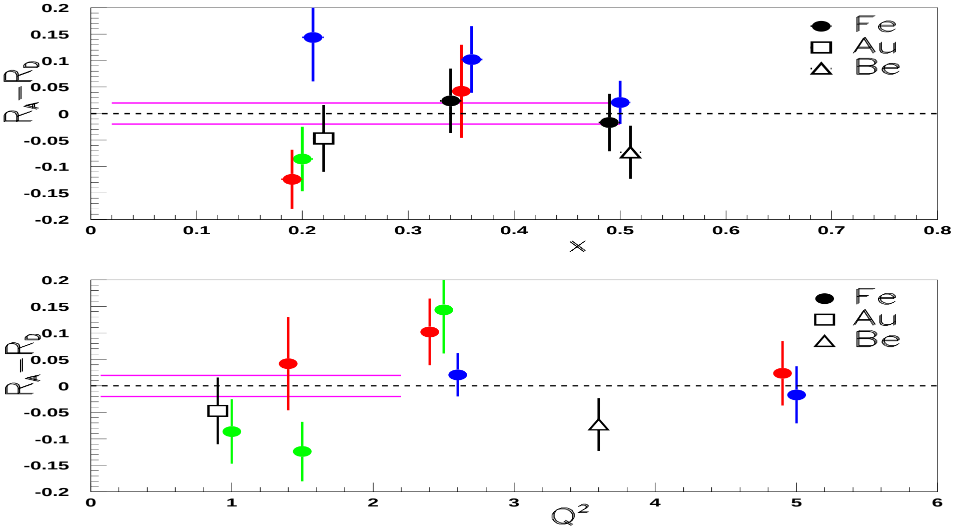

FIG. 1. The SLAC E140 data set of $R_A - R_D$ on deuterium in the Deep Inelastic Region .

The existing world's data measurements of the nuclear dependence of R in the DIS region from SLAC Experiment E140 [3] are shown in Figure 1. As seen in the figure, the errors in the DIS region are very large, and no data exists in the resonance region. Preliminary JLab data on tests of duality in the resonance region at higher Q^2 is shown in Figure 2.

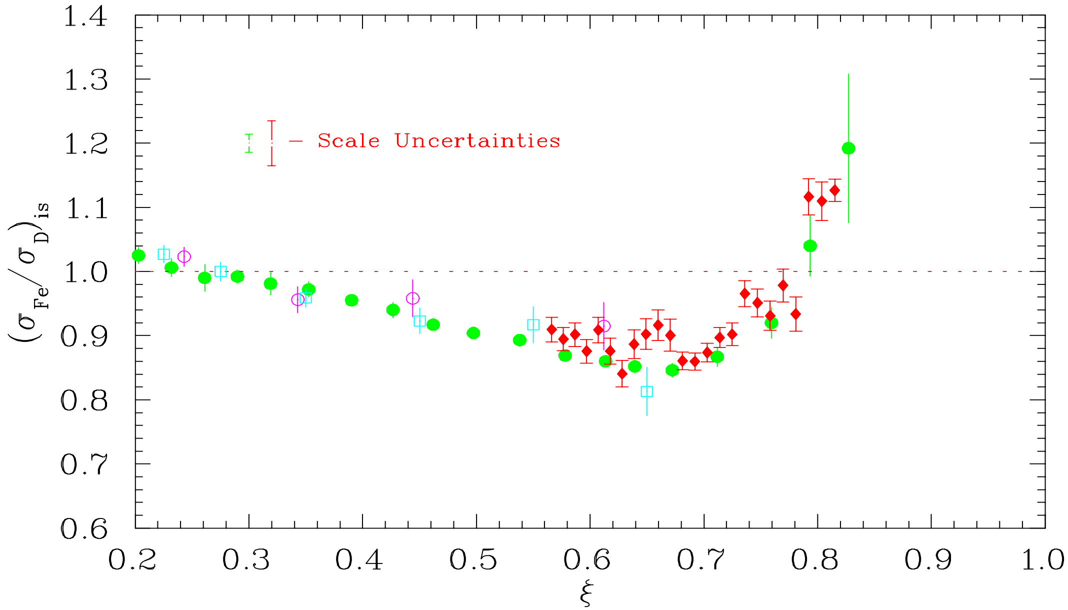

FIG. 2. A comparison of the ratio of cross sections of iron to deuterium in the resonance region versus the ratio measured in the DIS region. These preliminary data from JLab indicate that the nuclear effects in the DIS and resonance region are the same if plotted versus the Nachtman variable as expected from duality.

BROAD IMPACT OF THESE MEASUREMENTS ON NEUTRINO PHYSICS

A detailed study of σ_L/σ_T on nuclear targets in the resonance region is an important ingredient in forming an integrated description of charged lepton and neutrino scattering cross-sections. High rate neutrino beams now under construction or planned at Fermilab and J-PARC will allow the first precision experimental comparisons of electron and neutrino cross-sections and present and future neutrino oscillation experiments will use these results to predict event rates.

The recent discoveries of neutrino oscillations in atmospheric neutrinos [6] and in neutrinos from the sun [7,8] motivate the detailed studies of neutrino oscillations at future high intensity neutrino beams from accelerators. The two disparate mass scales observed in oscillations from these astrophysical sources, $\delta m^2{}_{\rm atm} \approx 2 \times 10^{-3}{\rm eV}^2$ and $\delta m^2{}_{\rm solar} \sim 10^{-4}{\rm eV}^2$, along with the stringent limits on $\overline{\nu}_e$ disappearance at the atmospheric L/E in the CHOOZ and Palo Verde reactor experiments experiments [10,11], have raised the possibility that there may be an observable CP-asymmetry in $\nu_\mu \to \nu_e$ transitions. This rare, sub-leading transition in the neutrino flavor sector is analogous to to searching for first and third generation mixing in the quark sector, which has led to a rich phenomenology of CP-violation, meson mixing and rare decays in the quark sector.

These neutrino oscillation experiments are very challenging, because of the required L/E of 400 km/GeV, and require megawatt proton sources, 1 GeV neutrino beams and multi-kiloton detectors to make the observations. The measurements are further complicated by the low transition probability of $\nu_\mu \to \nu_e$ and the need to compare to $\overline{\nu}_\mu \to \overline{\nu}_e$ at high precision. This requires a detailed knowledge of the neutrino interaction cross-sections both for the dominant signal processes and for background processes, such as $\nu N \to \nu N \pi^0$ where the π^0 is misidentified as an electron in a many kiloton sampling detector.

The phenomenology of neutrino cross-sections in relatively simple when $E\nu \ll 1$ GeV or when $E\nu \gg$ few GeV since these regimes are dominated by (quasi)-elastic and deep inelastic processes, respectively. However in the 1 to few GeV region, there are contributions to the cross-section from both of these processes as well as resonance-dominated hadroproduction. A successful phenomenological approach to modeling the resonance region in electron scattering is the use of quark-hadron duality to relate quark-model cross-sections to the cross-section over the discrete resonances [12] as shown in Fig. 3, Fig. 4 and Fig. 5. Figure 3 shows a fit by Bodek and Yang to inelastic electron and muon scattering data with a modified scaling variable and GRV98 PDFs with additional corrections (based on consideration of the Adler and Gilman sum rules [24]. Figure 4 and Figure 5 compare the predictions of the fit to data in the resonance region (which is not included in the fit, as well as other data such a photoproduction and high energy neutrino data). All predictions assume quark-model relations, and an empirical fit to R (R_{1998}). This approach requires the separation of the F_2, which has a simple representation in the quark model, and R whose description requires a different prescription. We hope to build successful models of neutrino scattering using this same prescription with the addition of a quark-model representation of the axial vector component of the cross-section. As mentioned earlier, since neutrino data are measured in nuclear targets, even in the quark model case, the separated vector structure functions from electron scattering, F_{2p}, F_{2n}, R_p, R_n for bound nucleons are needed in order to understand the axial structure function in neutrino scattering experiments.

The new precise data will also allow us to redo a combined analysis of electron-nucleon and neutrino nucleon data in the resonance region within the Feynman quark-oscillator model as done years ago (with poor precision) by Rein and Seghal [13]. The results of the updated Rein-Seghal type of analysis will be compared to an analysis which is based on duality.

The full program of studies requires first additional precise electron scattering data, in particular σ_L and σ_T (or equivalenty F_2 and R) on nuclear targets (materials suited for future neutrino oscillation detectors – water [14], hydrocarbons [15], liquid argon – and steel, where the most precise high energy neutrino cross-sections have been measured [16]) in the relevant kinematic regime. Later, as the new generation of high rate neutrino beams at Fermilab and J-PARC become available, the approach can be directly validated with comparisons to data from high rate neutrino cross-section experiments on the same targets [17].

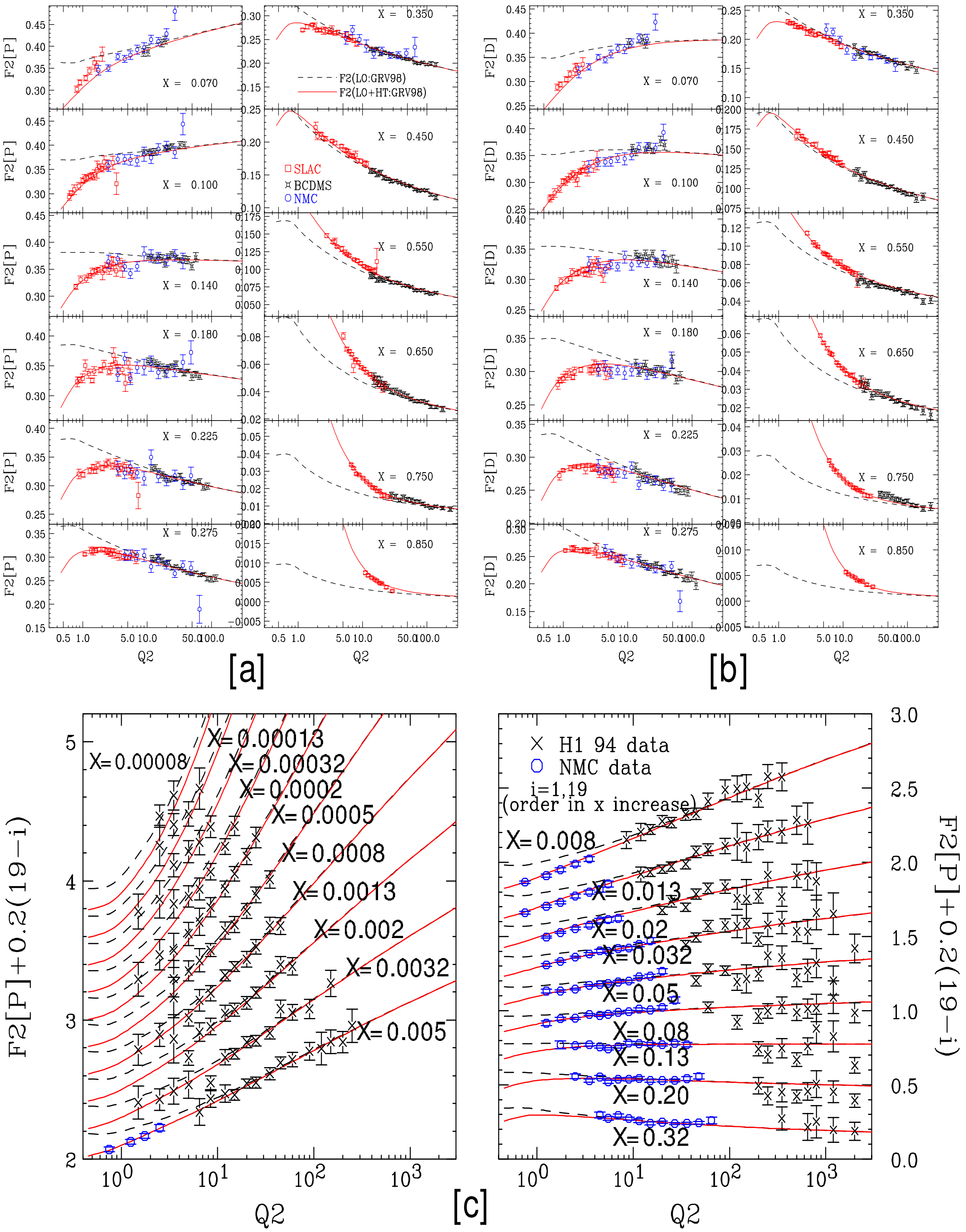

FIG. 3. Electron and muon F_2 data (SLAC, BCDMS, NMC, H1 94) used to obtain the parameters of the Bodek-Yang modified GRV98 ξ_w fit compared to the predictions of the unmodified GRV98 PDFs (LO, dashed line) and the modified GRV98 PDFs fits (LO+HT, solid line); [a] for F_2 proton, [b] for F_2 deuteron, and [c] for the H1 and NMC proton data at low x.

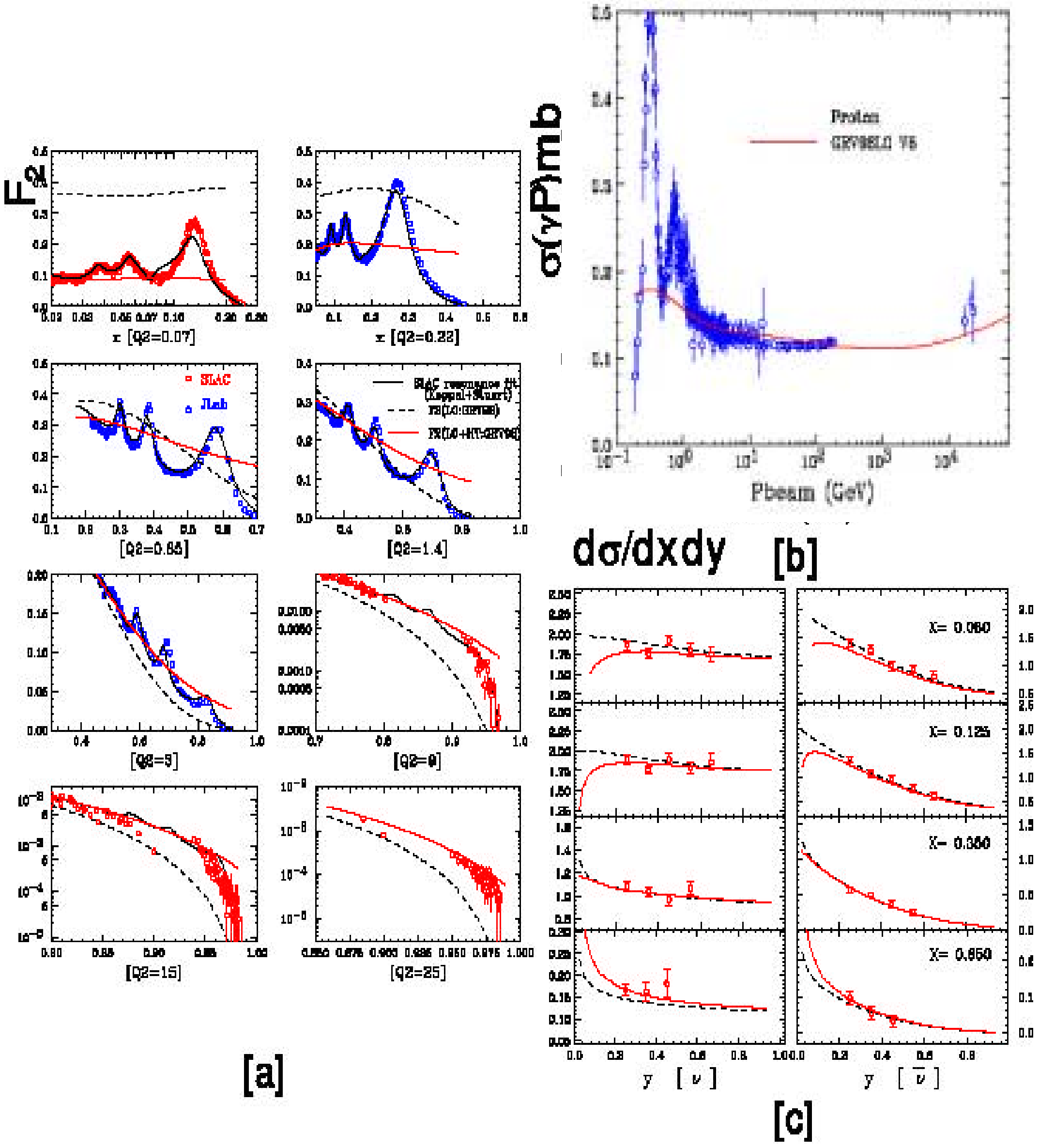

FIG. 4. Comparisons to proton and iron data not included in the Bodek-Yang GRV98 ξ_w fit. (a) Comparison of SLAC and JLab (electron) F_{2p} data in the resonance region (or fits to these data) and the predictions of the GRV98 PDFs with (LO+HT, solid) and without (LO, dashed) the Bodek-Yang modifications. (b) Comparison of photoproduction data on protons to predictions using Bodek-Yang modified GRV98 PDFs. (c) Comparison of representative CCFR ν_μ and $\overline{\nu}_\mu$ charged-current differential cross sections on iron at 55 GeV and the predictions of the GRV98 PDFs with (LO+HT, solid) and without (LO, dashed) Bodek-Yang modifications.

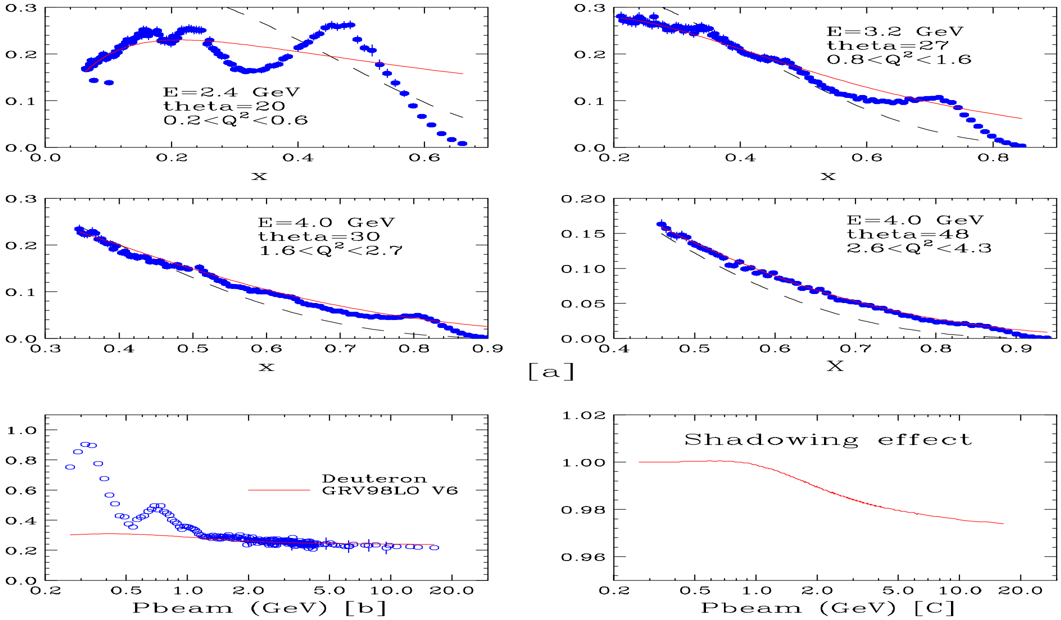

FIG. 5. Comparisons to data on deuterium which were not included in the Bodek-Yang GRV98 ξ_w fit. (a) Comparison of SLAC and JLab (electron) F_{2d} data in the resonance region and the predictions of the GRV98 PDFs with (LO+HT, solid) and without (LO, dashed) our modifications. (b) Comparison of photoproduction data on deuterium to predictions using Bodek-Yang modified GRV98 PDFs (including shadowing corrections). (c) The shadowing corrections that were applied to the PDFs for predicting the photoproduction cross section on deuterium.

$Target$	$(Z,A), Z/A$	$r.l.(g/cm^2)$	$r.l.(cm)$
H	(1, 1.00794), 0.99212	61.28	866
D	(1, 2.01404), 0.49652	122.4	724
C (approx CH2)	(6, 12.011), 0.49954	42.7	18.8
Ne	(10, 20.1797), 0.49555	28.94	14.0
Poly-CH2	0.53768	43.72	43.4
Water-H2O	0.55509	36.08	36.1
Quartz-SiO2	0.49926	27.05	12.3
O2(in Water, Quartz)	(8, 15.999), 0.50002		
Si(in Quartz)	(14, 28.0855), 0.49848	21.82	9.36
Al(Approx Si)	(13, 26.9815), 0.48181	24.01	8.90
Ar	(18, 39.948), 0.45059	19.55	14.0
Ca (approx Ar)	(20, 40.078), 0.49903	16.14	10.42
Fe	(26, 55.805), 0.46556	13.84	1.76
Cu (approx Fe)	(29, 63.506), 0.45636	12.86	1.43

TABLE I. Targets used in low energy low statistics neutrino experiments (H, D, Ne, Ar, Polystyrene Scintillator, Water, Iron), and additional targets that may be used to approximate them (Carbon, Quartz, Silicon, Calcium, Copper). Note that future high statistics experiments are planned with Hydrocarbon, Water and Iron targets.

NUCLEAR TARGETS AND KINEMATICS

Table I shows the kinds of nuclear targets that are of interest to neutrino experiments. Table II shows nuclear targets that we propose to add to the target ladder of experiment E02-109 which already is approved to take data with a Deuterium target and with an Aluminum empty target replica.

The differential cross sections for inclusive electron scattering on Deuterium will be measured in E02-109 according to the following definition:

$$\frac{d^2\sigma}{d\Omega dW^2} = \frac{\Delta N}{\Delta\Omega\Delta W^2}\frac{1}{Qnd}, \tag{7}$$

where ΔN is the counts per W^2 bin, n is the density of deuterium, d the target thickness, and Q is the integrated number of incident electrons on target. Table III gives a breakdown of beam time requirements for E02-109 for the Δ running only. The last column shows additional time that is needed to measure nuclear targets with the same number of events at each point as for Deuterium if this experiment (E03-110) were to run at the same time as E02-109.

$Target - Thickness\ r.l.$	Running Ratio	$Data$	$comment$
$H - 0.005$	2.0	$All\ Q^2$	$E94 - 110$
$D - 0.005$	1.0	$All\ Q^2$	$E02 - 109$
$Al - 0.005$	(5.1$*$)	$All\ Q^2$	$E02 - 109$
$C - 0.06$	0.2	$All\ Q^2$	$nominal$
$Quartz - 0.06$	0.4	$Q^2 < 4$	$nominal$
$Si - 0.06$	0.5	$Q^2 < 4$	$nominal$
$Ca - 0.06$	0.6	$Q^2 < 4$	$nominal$
$Fe - 0.06$	0.7	$Q^2 < 4$	$nominal$
$Cu - 0.06$	0.8	$All\ Q^2$	$nominal$
$C - 0.02$	0.7	$All\ Q^2$	$Rad - Cor$
$C - 0.12$	0.1	$All\ Q^2$	$Rad - Cor$
$Cu - 0.02$	2.4	$All\ Q^2$	$Rad - Cor$
$Cu - 0.12$	0.4	$All\ Q^2$	$Rad - Cor$
$Fe - 0.02$	2.2	$Q^2 < 4$	$Rad - Cor$
$Fe - 0.12$	0.4	$Q^2 < 4$	$Rad - Cor$
$Water - 0.02$	0.8	$Q^2 < 4$	TBI

TABLE II. Targets to be used in this proposal (E03-110). Running Ratio is the ratio of the running time relative to running with a 4 cm (0.005 r.l.) Deuterium target to get the same number of events (at constant current of 80 μA, which is planned for E02-109). Note that data with Hydrogen is already available from JLab experiment E94-110, and Deuterium and Aluminum data need need NOT be taken if this experiment (E03-110) runs at the same time as E02-109 (thus minimizing the error on the ratio of structure functions on nuclear targets to deuterium). All Q^2 identifies targets for which data will be taken at all values of Q^2, and $Q^2 < 4$ identifies targets for which no high Q^2 data will be taken. The nominal targets are identified. Rad-Cor indicates targets to be used for Radiative Corrections Studies, and TBI indicates Option To Be Investigated. $*$ Note that the Al target is only used for empty target, and therefore statistics equal to D2 are not needed.

Details of Event Rate Calculations

A minimum time of one half hour per kinematic setting, a maximum rate of 1000 Hz, and a beam current of 80 μA were used in the calculation of the running time for Deuterium for E02-109. The calculated rates listed are for bins of width $\Delta W^2 = (25\text{MeV})^2$ averaged over a momentum acceptance of ±8% and assuming an effective solid angle of the HMS of 6.5 msr at the Δ resonance. The data for the higher resonances comes in at higher rates and requires $\approx 50\%$ additional beam time. The data acquisition time listed in Table III reflects the total time required for the Δ resonance only. The SOS will be used to collect positron yields (from neutral pion production) for charge symmetric background studies and will be run in a simultaneous single arm mode with the HMS data and, so, this adds little time to the beam time request. The extraction of neutron structure functions from D_2 data for E02-109 requires the subtraction of the proton data taken in E94-110. As a cross check on relative normalizations, E02-109 plans to do measurements of the hydrogen resonance region cross sections for $Q^2 < 3.0$ (GeV/c^2)^2 to compare to E94-110. This takes an additional 8 hrs. A minimum central spectrometer momentum setting of 400 MeV/c was assumed. All proposed measurements with deuterium in E02-109 use the Hall C 4 cm deuterium target. In addition, E02-109 plans to take elastic proton data at all angles and energies for kinematic uncertainty checks.

Q^2_Δ $(GeV/c)^2$	E (GeV)	E'_Δ (GeV)	θ_Δ (deg)	ϵ_Δ	$Rate_\Delta$ (Hz)	D_2-Time (Hours) E02-109	Nucl. Tgts (hours) E03-110
0.5	1.16	0.55	52*	0.54	1 K	0.5	
	1.64	1.0	33	0.78	1 K	0.5	
	4.04	3.4	11	0.97	1 K	0.5	
1.0	1.64	0.77	52*	0.53	1 K	0.5	
	2.28	1.4	33	0.77	1 K	0.5	
	4.52	3.6	14	0.95	1 K	0.5	
2.0	2.28	0.87	60*	0.43	65	0.5	
	3.24	1.8	35	0.73	285	0.5	
	5.64	4.2	17	0.92	1 K	0.5	
3.0	3.24	1.3	52*	0.51	16	2	
	4.04	2.1	35*	0.70	40	1	
	5.64	3.7	22	0.86	172	0.5	
					sub-total	8	24
4.0	3.24	0.77	79*	0.23	1	22	
	4.04	1.6	47*	0.51	3	8	
	5.64	3.2	27	0.77	53	1	
5.0	4.04	1.0	66*	0.29	1	22	
	4.52	1.4	52*	0.42	3	8	
	5.64	2.5	35	0.66	6	4	
					sub-total	65	40
						Total D **73** E02-109	Total-Nucl **64** E03-110

TABLE III. D_2 Running for E02-109 Beam time requirements for all proposed measurements, as in the E02-109 proposal. All kinematics and rates shown are for a single bin in W^2 of 25 (MeV)^2 width at the Δ resonance. Positron data will be taken in the SOS for the angles indicated by an asterisk. The last column is the additional time needed for heavy targets for this proposal: 6 targets at (C, Quartz, Si, Ca, Fe and Cu) $Q^2 < 4$ and 2 targets (C and Cu) at all Q^2. The beam energies in this table differ slightly and inconsequentially from those in this proposal text, as the original E02-109 energies were slightly disparate from the actual common JLab energies. The text energies are the correct ones for both experiments.

Note that the assumption made in the calculation of the rates for E02-109 are conservative. The 80 μA current is assumed to minimize density difference in the deuterium target. For some of the solid targets in the proposed experiment (E03-110) a higher current of 100 μA can be used (especially at high Q^2). Similarly, a data taking rate of 1000 Hz is also conservative and data can be taken with 2000 Hz (and possibly at 3000 Hz with some upgrades).

The chosen beam energies in the table assume a linac energy of 1.12 GeV (1.18, 2.30, 3,42, 4.54, 5.66), with the exception of two beam energies which assume a linac energy of 0.80 GeV (1.64, 4.04). Both base energies are standard CEBAF accelerator tunes. The required beam time was determined such that the statistical accuracy per W^2 bin was ≈ 3 times greater than the systematic point-to-point accuracy expected. The rates were estimated based upon a fit of previous deuterium resonance region cross section data from JLab [18]. Using the parameters in Table II we can scale the running time for Deuterium and obtain the corresponding additional running time for the nuclear targets (shown in the last columns of Table III and Table IV. The total beam time requested for both E02-109 (D_2) and for this experiment E03-110 (last column Nucl. Tgts) are listed in Table IV).

For D_2 running for E02-109 the total data acquisition time listed reflects the total time from Table III, as well as an additional 40 hours to complete the higher resonances, an additional 60 hours for dummy runs which are needed to subtract the yield contributions from the aluminum end caps of the target, an additional 24 hours needed to complete the hydrogen elastic scattering measurements, and an additional 16 hours to obtain hydrogen resonance region data which is needed for cross checks with E94-110. Also, since the positron data comes in at a slower rate, E02-109 requested an additional 22 hours to complete these measurements. The E02-109 proposal assumes one-quarter hour for each angle change required at a given beam energy, and one-quarter hour for each spectrometer central momentum change not possible to be done concurrently with angle changes. Combined with one day for checkout, the total beam time approved for E02-109 is 13 days [21].

This experiment (E03-110) requests an additional 5 days of running to do the measurements with the nuclear targets. With 2.5 days of additional running, data with all six targets can be measured for all of the E02-109 data points with $Q^2 < 4$. The additional 2.5 days are requested for the measurements at the higher Q^2.

	D- Time Required (Hours) E02-109	Nucl. Tgts. (Hours) E03-110
Data acquisition (Deuterium Δ)/+Nucl. Tgts.	73	64
Data acquisition (Deuterium $W^2 > \Delta$)/+Nucl. Tgts.	40	38
Data acquisition (Dummy)	60	
Data acquisition (hydrogen elastics)	24	
Data acquisition (hydrogen resonance region)	16	
Data acquisition (additional positrons)	22	
D Angle changes (12)/+Nucl. Tgt Changes	3	10
Spectrometer momentum changes (60)	15	
Major beam energy changes (1)	8	
Minor beam energy changes (5)	20	
D Checkout /+ Nucl. Rad correction Tests	24	10
Total	**305** E02-109	**120** E03-110

TABLE IV. D_2 Running for E02-109: Breakdown and tabulation of the total time requested. Based on previous experience, we assume one-half hour for angle changes, 15 minutes for momentum changes, eight hours for linac energy changes (major), and four hours for each energy change accomplished by changing the number of cycles (minor). The last column is the additional time required for heavy targets in this proposal (E03-110)

THE COLLABORATION

The collaboration consists primarily of members of the current E02-109 collaboration. These scientists have participated in a substantial amount of Hall C running. The collaboration has implemented and proven successful techniques to reduce systematical uncertainties in Hall C experiments, including detailed studies of spectrometer optics, spectrometer survey studies, raster phase analysis, and additional beam line instrumentation. This collaboration has the on-site experience, knowledge and expertise requisite to perform a precision measurement of the type proposed. These experimenters include spokespersons of the previous JLab experiments on which this proposal is founded (E94-110, E02-109 and E99-118).

In addition, this proposal brings a significant number of new collaborators from the University of Rochester and University of Massachusetts, including the two spokespersons of SLAC experiment E140 and E140X, and the Rochester NuTeV neutrino group. Two potential Rochester Ph.D. students are shown as well as Rochester theorists who have expressed interest in the results.

CONCLUSION

Using the existing Hall C apparatus, JLab experiment E02-109 has been approved to perform a global survey of L-T separated unpolarized structure functions on deuterium throughout the nucleon resonance region with an order of magnitude better precision than has been achieved before. The recent analysis of the proton data from E94-110 clearly show that these goals are both realistic and attainable. Furthermore, the analysis machinery previously developed can be used nearly without modification and should allow the analysis of the data to proceed in an accelerated fashion.

Here we propose another experiment (E03-110) that in only five days of additional running yields a substantial amount of new data with nuclear targets. These data are a key ingredient in a new program linking the nuclear and high-energy physics communities in investigating quark-hadron duality in nuclear targets using both electron and neutrino beams.

APPENDIX A - RADIATIVE CORRECTIONS STUDIES

SLAC-E140 [3] and SLAC-E139 [19] have performed tests with 0.02, 0.06 and 0.12 radiation length targets. Figure 6 illustrates that the radiative corrections can be well understood even for these relatively thick targets using the analysis techniques of E140. In this experiment, we add a variety of target thicknesses to repeat these radiative corrections tests in the JLab kinematic region.

In addition, in order to obtain more statistics with Aluminum in E01-109 (using the the Aluminum Empty Target runs), we plan to go back to using thick empty targets, a technique pioneered at SLAC [20]. The Aluminum Empty Target replica is made thicker to match the radiation length of the 0.005 r.l. Deuterium target. This greatly increases the counting rate for the empty target replica, as well as making sure that the radiative corrections for the empty target are indeed the same as the correction for the full Deuterium target. Therefore, if this target is used instead, then the 60 hours allocated for empty target replica by E02-109 can yield Aluminum data with about 1/6 of the statistics of the running with deiterium,

APPENDIX B - PRACTICAL ISSUES IN CHOICES OF TARGETS

A consideration in the choice of targets is the maximum amount of current that can be delivered without damaging or changing the density of the target. This experiment as proposed can be done in 5 days using standard targets, but we have made some compromises and may wish to consider future alternatives, as outlined below.

At present 0.02, 0.06 and 0.12 r.l. C, Fe and Cu targets already exist in Hall C. The current that the Fe target can withstand depends on the thermal contact with the water cooled frame. Safe current limits will likely be in a range 30–60μA, depending on the our confidence in this thermal contact. In contrast, C and Cu can easily withstand 80 μA, and therefore those targets were chosen for the high Q^2 running.

The best measurement of cross-sections on water would come from use of the Hall A "waterfall" target, which consists of three "free-falling" water curtains, each of 250 mg/cm^2 and can probably withstand 100 μA. Issues to be investigated with this target include density variation with current and whether it is practical to add this target to the Hall C scattering chamber. Therefore, this kind of target is not part of the proposed run plan, but is a subject of investigation.

The existing Hall C Calcium target may have a current limitation of 30 μA. We plan to investigate if a new Calcium sandwich target may be able to handle higher current.

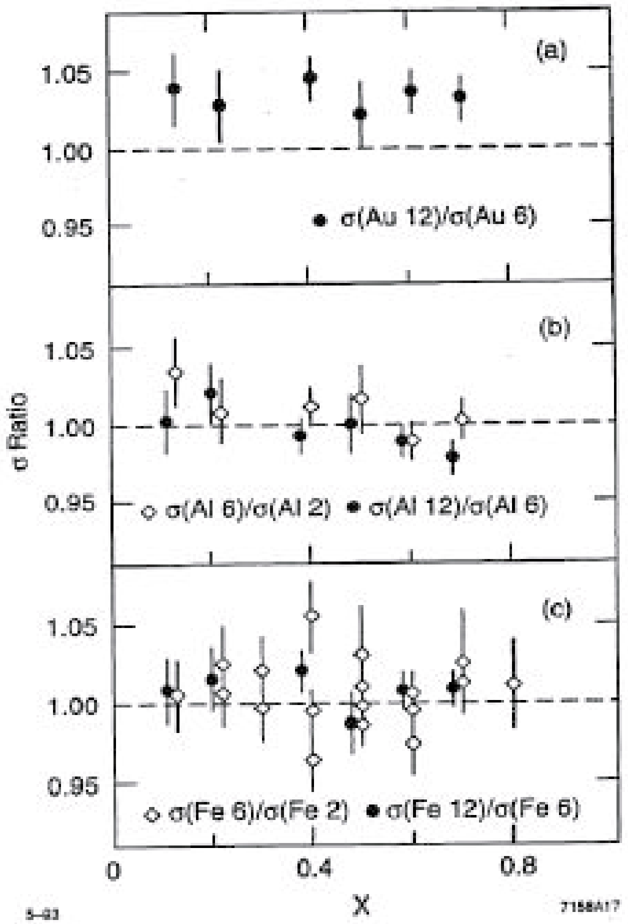

Fig. 26

FIG. 6. Radiative Corrections tests from SLAC E140 and E139.

APPENDIX C -OTHER DATA THAT WILL BE USED IN OUR ANALYSIS

We plan to use previous low Q^2 data in the inelastic region (e.g. Jlab experiment [4] E99-118), and previous data from experiment E02-109 taken in the quasielatic region [23] (for radiative corrections). Other lower precision very high Q^2 data such as SLAC experiment E140 and E140x will also be included in the overall analysis.

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[1] JLab hydrogen experiment 94-110, C.E. Keppel spokesperson

`(http://www.jlab.org/exp_prog/proposals/94/PR94-110.pdf)`

[2] JLab deuterium experiment 02-109, C.E. Keppel, M. E. Christy, spokespersons

`(http://www.jlab.org/exp_prog/proposals/02/PR02-109.ps)`

[3] SLAC Experiment E140, A. Bodek and S. Rock, Spokespersons; S. Dasu et al., Phys. Rev. Lett. 61, 1061 (1988); S. Dasu et al., Phys. Rev. D49, 5641 (1994) ; S. Dasu, Ph.D. Thesis, University of Rochester, 1988 (UR-1059).

[4] JLab experiment 99-118 on the nuclear dependence of R at low Q^2, A. Brull, C.E. Keppel spokespersons

`(http://www.jlab.org/exp_prog/proposals/99/PR99-118.pdf)`

[5] M.N. Rosenbluth, Phys. Rev. 79, 615 (1956)

[6] Y. Fukada *et al.*, Phys.Rev.Lett. 81 (1998) 1562.

[7] SNO Collaboration, `nucl-ex/0204008`, `nucl-ex/0204009`.

[8] K. Eguchi *et al.* [KamLAND Collaboration], Phys. Rev. Lett. **90**, 021802 (2003).

[9] A. Aguilar *et al.* [LSND Collaboration], anti-nu/e appearance in a anti-nu/mu beam," Phys. Rev. D **64**, 112007 (2001).

[10] M. Apollonio *et al.*, Phys.Lett. **B466** (1999) 41.

[11] F. Boehm *et al.*, Nucl.Phys.Proc.Suppl. 91 (2001).

[12] A. Bodek and U. K. Yang, `hep-ex/0203009`, Nucl.Phys.Proc.Suppl.112:70-76,2002.
A. Bodek and U. K. Yang, `hep-ex/0301036`.
A. Bodek, U. K. Yang, `hep-ex/0210024`, J. Phys. G. Nucl. Part. Phys.,**29**, 1 (2003). These were based on previous work by Bodek and Yang including studies in NLO +TM +HT (Phys. Rev. Lett 82, 2467 (1999) ; Phys. Rev. Lett. 84, 3456 (2000)) and studies in NNLO +TM +HT (Eur. Phys. J. C13, 241 (2000))

[13] D. Rein and L. M. Sehgal, Annals Phys. **133** 79 (1981) ;D. Rein, Z. Phys. C. 35, 43 (1987); R. P. Feynman, M. Kislinger and F. Ravndal, Phys. Rev. D**3**, 2706 (1971); and R. Belusevic and D. Rein, Phys. Rev. D **46**, 3747 (1992).

[14] Y. Itow *et al.*, "The JHF-Kamioka Neutrino Project", `hep-ex/0106019`.

[15] `http://www-numi.fnal.gov/fnal_minos/new_initiatives/new_initiatives.html`

[16] U. K. Yang *et al.*(CCFR), Phys. Rev. Lett. **87**, 251802 (2001).

[17] `http://home.fnal.gov/~dharris/xsec_agenda.html`

[18] I. Niculescu. Ph.D. Thesis, Hampton University (1999)

[19] J. G. Gomez, Ph.D. Thesis, American University (1987). The 0.12 radiation length data is unpublished and it has only been used for tests of the external radiative corrections,

[20] A. Bodek, Nucl. Inst. Meth. 103, 603 (1973)

[21] `http://www.jlab.org/exp_prog/generated/hallc.html`

[22] `http://www.jlab.org/exp_prog/PACpage/PAC24/PACinfo.html`

[23] JLab experiments in the quasielastic region (e.g. E02-109), from

`(http://www.jlab.org/exp_prog/generated/nucleon.html)`

[24] S. L. Adler, Phys. Rev.**143**, 1144 (166); F. Gilman, Phys. Rev. **167**, 1365 (1968).