SLAC–PUB–6347
September 1993
(E)

RESULTS ON STRUCTURE FUNCTIONS FROM FIXED-TARGET EXPERIMENTS

Emlyn Hughes

Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309

ABSTRACT

A review of proton and neutron structure function measurements from fixed-target experiments is presented. Results on unpolarized structure functions have stabilized for $x > 0.1$, and new results on lower x measurements are appearing. Recent results on the measurement of the neutron spin structure function are given and discussed in relation to previous surprising results from the proton spin structure function measurement.

Invited talk presented at the XIII International Conference on Physics in Collision, Heidelberg, Germany, June 16–18, 1993

Work supported by the Department of Energy, contract DE-AC03-76SF00515

Led by the new collider measurements from HERA at DESY, the field of nucleon structure functions is rapidly being directed to new kinematic ranges focussed at high energies and low Bjorken x. As a result of this migration of a community to Hamburg, the old field of unpolarized nucleon structure function studies from fixed-target experiments is ramping down and is now in the clean-up stage. The first half of this report discusses the results from unpolarized structure function measurements emphasizing the recent data at moderately low x ($0.008 < x < 0.1$). These results are useful in bridging the gap to the very low x HERA data.[1] In addition, we discuss a few points relevant to understanding the nucleon sea. The second half of this report covers very recent results on the measurement of polarized structure functions. A somewhat historical approach is taken to describe the spin structure functions, since only a few experiments have been performed, and they extend over a period of twenty years.

Unpolarized Structure Functions

Deep inelastic scattering formalism is well established. Fixed target experiments to study unpolarized structure functions involve scattering high-energy E beams of electrons, muons or neutrinos off proton or neutron targets (Fig. 1). The lepton scattering angle θ, and energy E$'$ are measured and can be written in terms of three *scaling* variables x, y, and Q^2 given below,

$$x = \frac{Q^2}{2M(E-E')} \qquad y = \frac{E-E'}{E} \qquad Q^2 = 4EE'\sin^2(\theta/2) \qquad (1)$$

The three unpolarized structure functions F_1, F_2, and F_3 are each functions of x and Q^2 only. The relationship between the scattering cross-sections and the structure functions is

$$\frac{d^2\sigma}{dxdy} = K[2xF_1(x,Q^2)(y^2/2) + F_2(x,Q^2)(1-y) + xF_3(x,Q^2)(y - y^2/2)] \qquad (2)$$

Here the coupling constant for electron or muon scattering is described by virtual photon exchange ($K = 8\pi\alpha^2 ME/Q^4$) and for neutrino scattering by W exchange

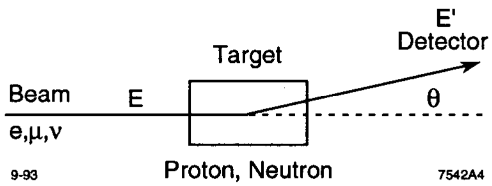

Figure 1. Schematic of a fixed-target experiment. E, E', and θ correspond to the three measured kinematic quantities; electron initial and final energies, and scattering angle, respectively.

($K = G^2ME/\pi$). F_1 and F_2 are both parity conserving and can be extracted either from virtual photon exchange in electron or muon scattering or from charged current interactions via W exchange in neutrino scattering. F_3, on the other hand, is parity violating and can only be extracted from neutrino interactions.

In the Quark Parton Model (QPM), the three structure functions have simple interpretations. F_2 is the sum over the square of the quark charge e_i multiplied by the quark distribution $q_i(x)$, namely $F_2 = \Sigma e_i^2 x q_i(x)$; in the scaling limit ($Q^2$ large) F_1 is related to F_2 via the Callan Gross relationship $F_2 = 2xF_1$; and F_3 characterizes the valence quark contribution via $xF_3 \sim xq_i - x\bar{q}_i$.

Structure Functions at low x

The measurement of structure functions at low x from fixed-target experiments is limited by the maximum beam energy. Table 1 presents a comparison of the kinematic ranges accessible to the three types of lepton beams. Although the ability to attain measurements at low x is clearly limited, the precision of these measurements is impressive and far more accurate than the first existing collider results.[1] The high precision from fixed-target experiments, consequentially, serves as an ideal calibration for the upcoming "low x" collider measurements, in addition to testing QCD via the study of scaling violations.

In the next three sections we describe results from four experiments: two neutrino experiments, CDHS (CERN) and CCFR (Fermilab), and two muon experiments, NMC (CERN) and E665 (Fermilab). All results have been published or presented within the last two years.

Table 1. Kinematics accessible for studying structure functions at low x with various lepton beams.

Low x structure function kinematics			
Beam	Maximum Energy	$Q^2(x < 0.1)$	lowest x
Electron	25 GeV	1 to 3 GeV^2	0.07
Muon	490 GeV	1 to 11 GeV^2	0.008
Neutrino	600 GeV	2 to 12 GeV^2	0.015

The NMC collaboration at CERN has reported on a precise determination of the proton and neutron structure functions.[2] The NMC data was collected in 1986 and 1987 at beam energies of 90 and 280 GeV. The results on F_2 for the proton and deuteron are presented in Fig. 2. For $x > 0.07$, the agreement with earlier structure function measurements of BCDMS and SLAC is excellent. The NMC results, in addition, extend down to x of 0.008. The observation of large scaling violations at low x is evident, and the description of this variation is well described by perturbative QCD (PQCD) fits.

The CCFR experiment at Fermilab recently reported on new structure function measurements from their 1985 and 1988 runs, with neutrino beam energies up to 600 GeV.[4] Figure 3 compares the CCFR results with those of NMC. The agreement over the range of $x > 0.1$ is excellent. However, a discrepancy appears at low x. The CCFR data favors a higher value of the structure function ($\sim 5\%$) significantly outside the statistical uncertainties. Systematic uncertainties are still being evaluated by the CCFR collaboration.

The non-singlet structure function xF_3 can only be extracted from neutrino scattering, since it arises from parity violation in weak interactions. The logarithmic Q^2 dependence of xF_3 can be used to extract the strong coupling constant, α_s, without invoking knowledge of the gluon distributions.[5] The CDHS experiment at CERN was the first to extract xF_3 with high statistical precision[6] (Fig. 4a). The apparent discrepancy between the result and QCD is attributed to

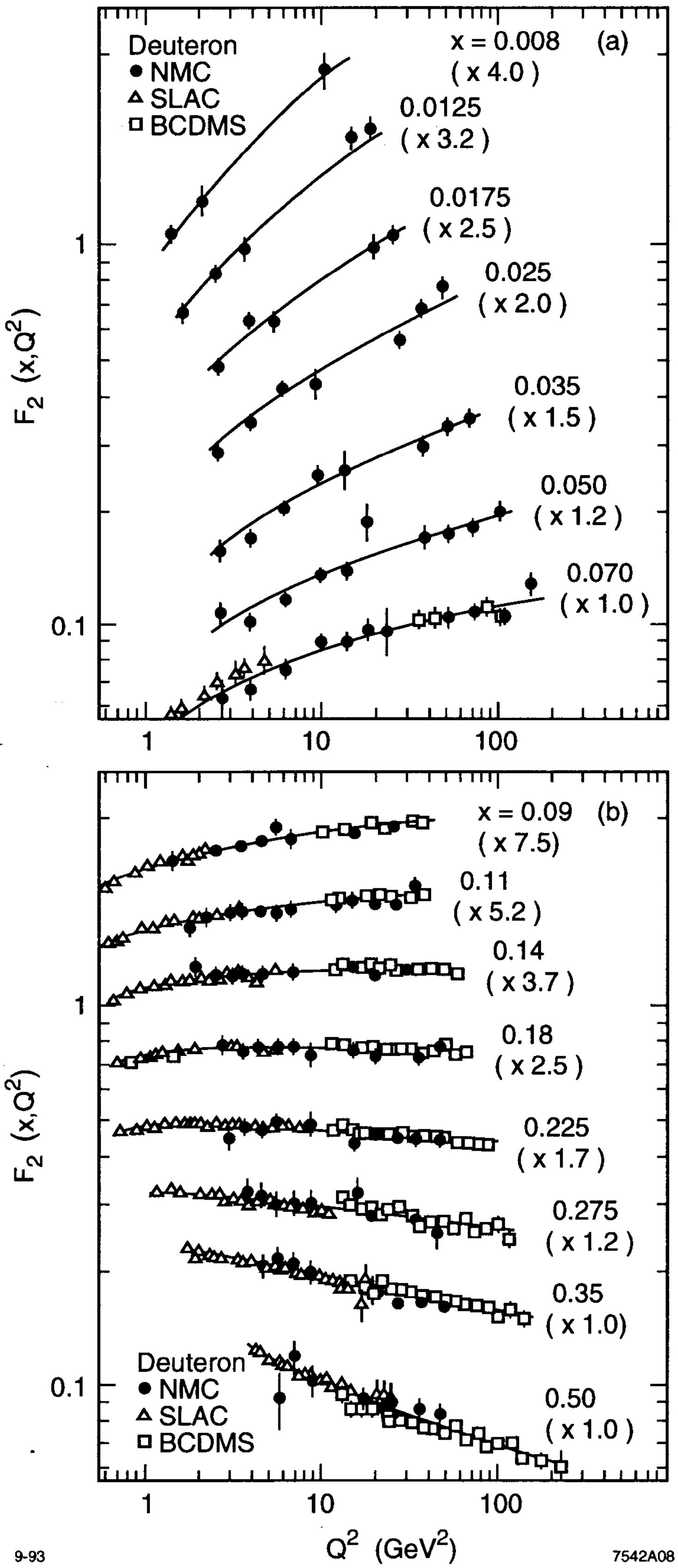

Figure 2. Results from the NMC collaboration on the deuteron structure function F_2. A comparison to BCDMS and SLAC is presented for $x > 0.07$.

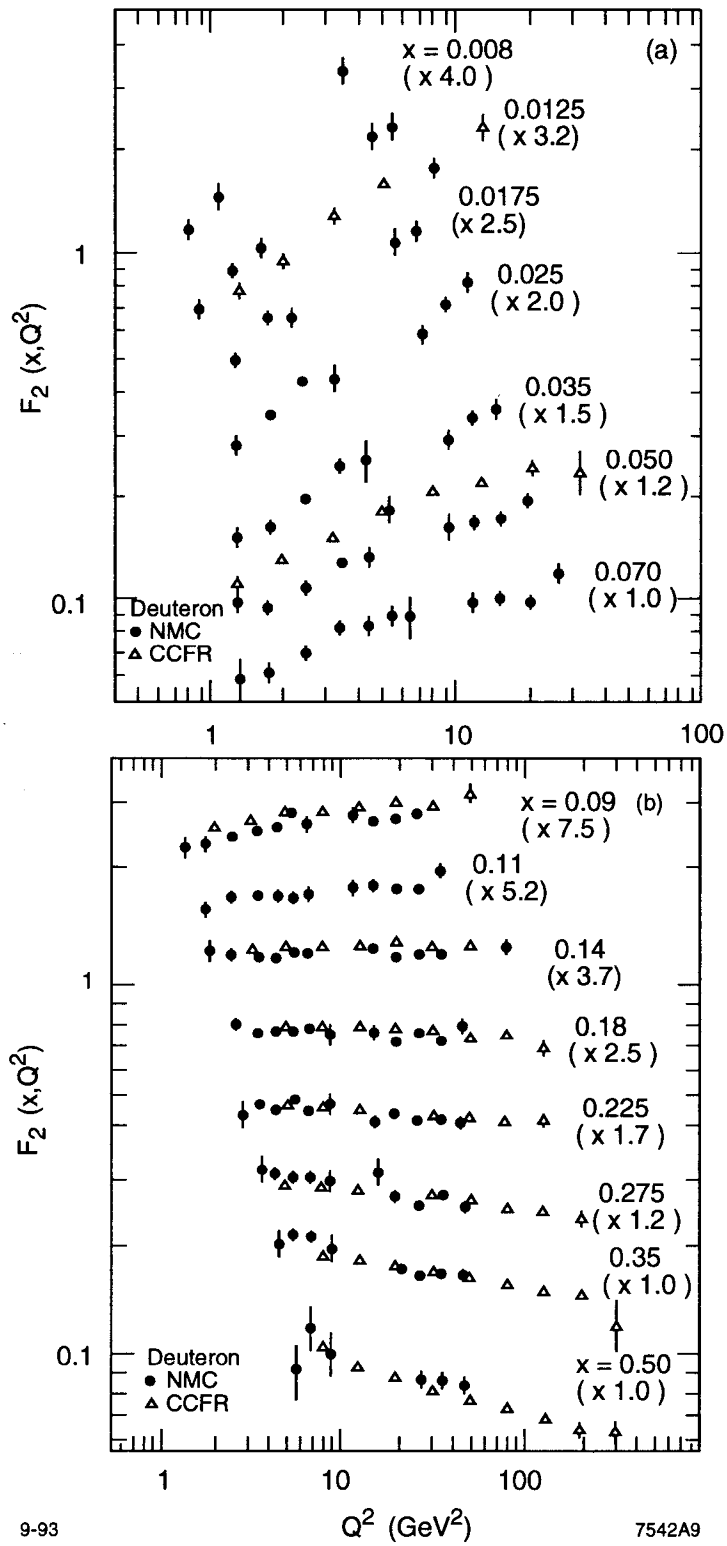

Figure 3. Comparison of recent preliminary CCFR neutrino data on F_2 to the NMC results. Agreement is excellent at high x and marginal at low x.

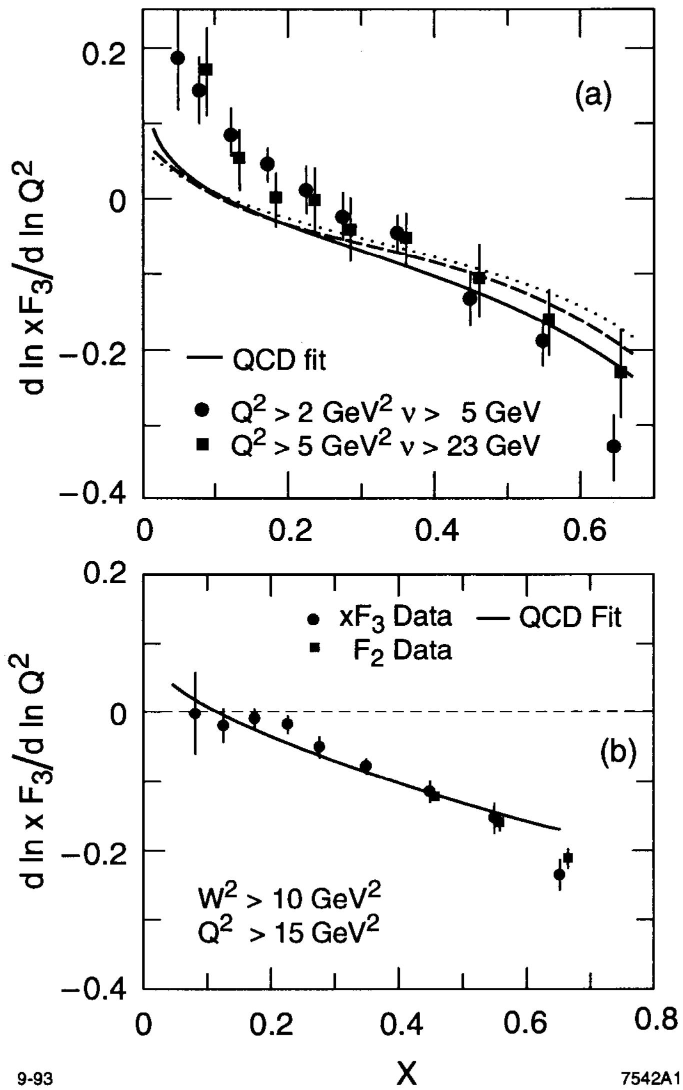

Figure 4. Results on the Q^2 evolution of the non-singlet structure function xF_3 from CDHS (a) and CCFR (b). A comparison to QCD fits is given.

systematic errors in the energy calibration. A preliminary result from the CCFR collaboration at Fermilab shows good agreement with QCD (Fig. 4b). Final results from the CCFR data with a full treatment of systematic errors will hopefully clarify the status of the comparison to QCD and its description of scaling violations.

Up and Down Sea

The nucleon sea resides at low x. Lower x measurements of the structure functions give increasingly more detailed information on the contribution of both the sea and the gluons to nucleon structure. In this section, we do not discuss the status of the determination of quark sea distributions, but rather point out some interesting implications on the total up and down sea content.

Probably the most interesting recent work is the extraction of the difference between the proton and neutron structure function F_2 measured at low x by NMC. The results from this experiment[3] appear to violate the Gottfried sum rule given below (Fig. 5):

$$\text{Gottfried Sum Rule} \qquad \int_0^1 \frac{F_2^{\mu p} - F_2^{\mu n}}{x} dx = \frac{1}{3} \tag{3}$$

$$\text{NMC Result} \qquad \int_0^1 \frac{F_2^{\mu p} - F_2^{\mu n}}{x} dx = 0.240 \pm 0.016(\text{stat.}) \pm 0.021(\text{syst.}) \tag{4}$$

The above violation resulted in two points of view; one supports the sum rule, the other supports the experimental result.

The difficulty in extracting the integral over the full x range is always a shortcoming in testing sum rules. The small x convergence is especially tricky due to the $1/x$ term in the integral. The NMC experimental result requires a theoretical extrapolation to low x for determining the contribution to the integral below x of 0.01. Large contributions to the integral below x of 0.01 have been postulated.[7] Another criticism is that the deuteron does not provide adequate neutron information, since the neutron in the deuteron is not free. However, shadowing in nuclei tends to lower the cross-section per nucleon, and shadowing in the deuteron should imply that the true $F_2^{\mu n}$ is even larger than the $F_2^{\mu n}$ extracted from the deuteron measurement.[8] Such an effect tends to increase the violation of the Gottfried sum rule, not explain it!

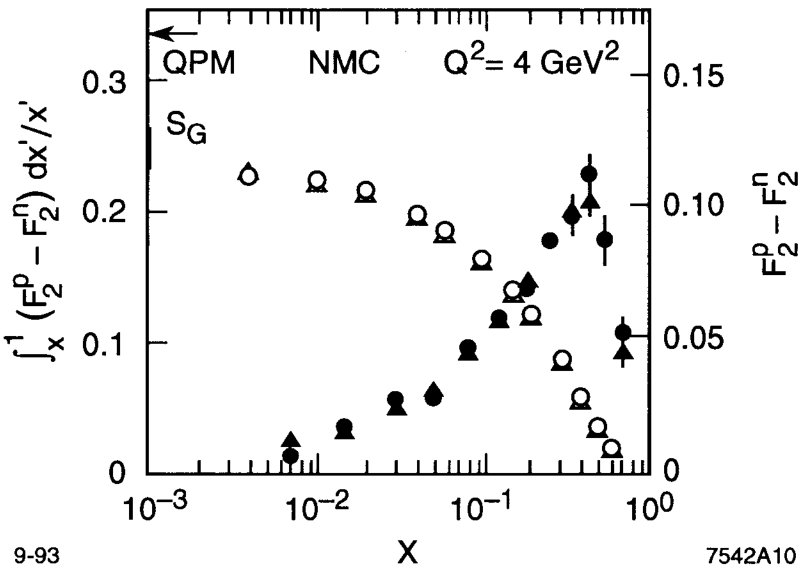

Figure 5. Results on $F_2^P - F_2^N$ vs. x as measured by NMC. The difference between the QPM prediction for $\int(F_2^P - F_2^N)\mathrm{d}x/x$ and the measurement is evident.

The weakest assumption in the derivation of the Gottfried sum rule is that the amount of $\bar{\mathrm{u}}$ and $\bar{\mathrm{d}}$ sea is the same. In fact, leaving the amount of $\bar{\mathrm{u}}$ and $\bar{\mathrm{d}}$ unconstrained, the NMC result implies that $\int [\bar{\mathrm{d}}(\mathrm{x}) - \bar{\mathrm{u}}(\mathrm{x})]\, \mathrm{dx} = 0.135 \pm 0.024$. Since this result does not threaten QCD, such a violation has mostly generated work on models of nucleon structure, rather than controversy. Over the last two years, much theoretical work has been done on the implications of a flavor asymmetric sea. Two particularly interesting ideas are Pauli blocking[9] and the pion cloud model of the nucleon.[10] Pauli blocking argues that since there are more up than down valence quarks in the proton, there will be more down than up sea quarks. The suppression of up quarks in the proton sea arises as a consequence of the Pauli exclusion principle. A second interesting model suggests that the proton consists of a cloud of π^+ ($\mathrm{u}\bar{\mathrm{d}}$). The implication is that significantly more scattering cross-section exists for a $\bar{\mathrm{d}}$ than a $\bar{\mathrm{u}}$ in the proton.

The NMC low-x measurements have brought on valuable discussions of the QPM and the nucleon sea. More measurements of the structure functions at lower x for proton and neutron scattering are needed. E665 (Fermilab) has reported on

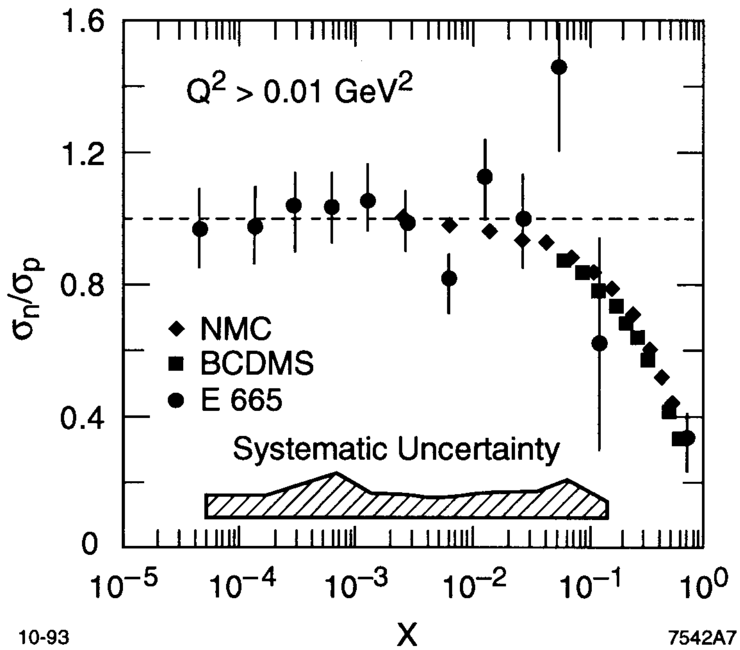

Figure 6. Results on σ_n/σ_p vs. x as measured by the E665 down to very low x.

a measurement of σ_n/σ_p down to x of 10^{-5} (Fig. 6).[11] Since the Q^2 is low and the statistics are limited, the E665 result provides no new information for addressing the Gottfried sum rule violation. Nevertheless, this work represents an important study at low x.

Strange Sea Determination

New results on the strange sea content are reported by the CCFR collaboration at Fermilab. By studying neutrino interactions producing a single μ^+ along with a single μ^- in the final state, one probes the strange quark content in the nucleon (Fig. 7). The CCFR results come from a sample of 5044 neutrino and 1062 anti-neutrino opposite-sign dimuon events. CCFR[12] determines the amount of strange sea and a constraint on the mass of the charm quark up to leading log corrections to be $K = 2\,\bar{s} \,/\, (\bar{u} + \bar{d}) = 0.373 \pm 0.051$ and $m_c = 1.31 \pm 0.25$. A recent next-to-leading-order analysis on the same data sample yields a modification of the results to be $K = 0.435 \pm 0.059$ and $m_c = 1.61 \pm 0.26$ GeV/c^2.[13] These results

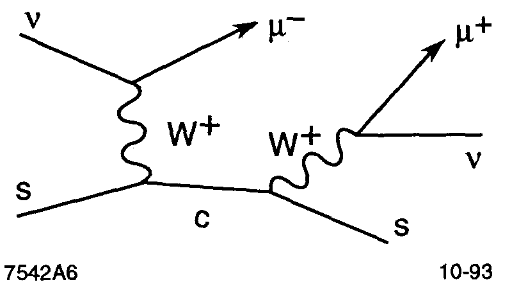

Figure 7. Production of an opposite-sign dimuon event from neutrino scattering. These events allow for a determination of the strange sea content in the nucleon and a constraint on the mass of the charm quark.

are in good agreement with an old CDHS determination that K = 0.52 ± 0.09.[14] The small apparent discrepancy comes from a change in the value of $\bar{u}$ and $\bar{d}$ which dominates the CDHS uncertainty. The CDHS dimuon event sample was actually larger with a total of 11041 neutrino and 3684 anti-neutrino dimuon events.

Summary of Unpolarized Structure Function Studies

A number of interesting results have emerged in the last couple of years. Elegant results on low-x structure function measurements from NMC have been published. An independent check of the results from the CCFR neutrino experiment is important and analysis of systematic effects is ongoing.

The Gottfried sum rule still appears to be violated, implying in the most likely case that there is more $\bar{d}$ than $\bar{u}$ sea in the proton. This result is important in understanding the structure of the nucleon.

New strange sea results from CCFR have confirmed the old CDHS results at higher energies, and the new results include a fit to the mass of the charm quark.

Although a significant data base of unanalyzed data from the muon experiments still exists, in particular, there are no approved experiments to continue studying unpolarized structure functions from fixed-target experiments. A preliminary conclusion from the summer of 1993 is that the running of fixed-target experiments to study specifically the unpolarized proton and neutron structure functions has ended.

Polarized Structure Functions

A growing field in nucleon structure function studies is the measurement of nucleon spin structure. These experiments scatter longitudinally polarized leptons off polarized targets and measure asymmetries in the scattering cross-sections $d\sigma(x, Q^2)$ between beam and target spins parallel ($\uparrow\uparrow$) versus anti-parallel ($\uparrow\downarrow$),

$$A(x, Q^2) = \frac{d\sigma^{\uparrow\downarrow}(x, Q^2) - d\sigma^{\uparrow\uparrow}(x, Q^2)}{d\sigma^{\uparrow\downarrow}(x, Q^2) + d\sigma^{\uparrow\uparrow}(x, Q^2)}. \tag{5}$$

From these measured asymmetries and the unpolarized structure functions, the nucleon spin structure functions are extracted,

$$g_1(x, Q^2) = F_1(x, Q^2)[\frac{A(x, Q^2)}{D}] \tag{6}$$

where D is a kinematic factor characterizing the virtual photon polarization.

Integrating the proton and neutron spin structure functions over x allows for a test of a foundation QCD sum rule derived by Bjorken[15] and a QPM sum rule derived by Ellis and Jaffe.[16] The Bjorken sum rule essentially motivates this field of study. Corrections to the Bjorken sum rule taken at finite Q^2 are described by perturbative QCD (PQCD) and experiments directed at measuring the Bjorken sum rule essentially test the validity of PQCD. The Bjorken sum rule given below relates the difference in the proton and neutron spin structure function integrals to the weak coupling constant extracted from neutron decay g_A/g_V,

$$\int_0^1 g_1^p(x)dx - \int_0^1 g_1^n(x)dx = \frac{1}{6}\frac{g_A}{g_V}(1 - \Delta^{QCD}), \tag{7}$$

where Δ^{QCD} are the PQCD corrections to the sum rule which have been calculated up to third order in α_s.[17] The second sum rule (Ellis & Jaffe) characterizes the quark contribution to the nucleon spin. This sum rule assumes that SU(3) is valid for up, down, and strange quarks and that the strange sea is unpolarized. From these assumptions, Ellis and Jaffe extract separate integrals over the proton and neutron spin structure functions and relate these integrals to the F and D constants that are extracted from hyperon decay measurements,

$$\int_0^1 g_1^p(x)dx = \frac{1}{18}(9F - D) \sim 0.19 \qquad PROTON \tag{8}$$

$$\int_0^1 g_1^n(x)dx = \frac{1}{18}(4F - 6D) \sim 0 \qquad NEUTRON. \tag{9}$$

A violation of this sum rule is no direct threat to QCD, but does have interesting implications on the Quark Parton Model.

The true excitement in this field of physics began in 1988 from the EMC result[18] that claimed a violation of the Ellis-Jaffe sum rule for the proton. The high energy (200 GeV) EMC data provided a measurement of g_1^p down to x of 0.01 and the resulting proton integral came out low (Fig. 8). Notice the similarity to the Gottfried sum rule violation (Fig. 5). Numerically, EMC found that the proton integral was $\int g_1^p(x)dx = 0.126 \pm 0.018$. This result was compared to the Ellis Jaffe sum rule which at the time yielded a proton integral of 0.189 ± 0.002. Since then the F and D constants have been reanalyzed more carefully and present-day more conservative estimates yield a proton integral of 0.175 ± 0.018.[19]

What was astounding about the EMC result was the QPM implications of the violation. The contribution to the nucleon spin from the up, down, and strange seas can be extracted from a single spin structure function measurement and the F and D constants. If the quark spin contribution per flavor is defined as $\Delta q = \int[q^{\uparrow}(x) - q^{\downarrow}(x)]dx$, where $q^{\uparrow}$ ($q^{\downarrow}$) corresponds to the quark helicity

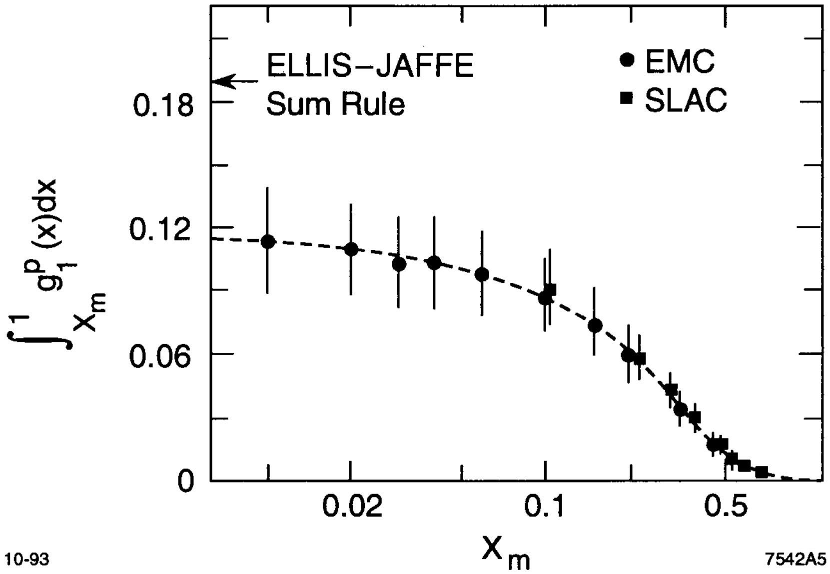

Figure 8. Results on $\int g_1^P(x)dx$ vs. x as measured by the EMC collaboration. The disagreement with the Ellis Jaffe sum rule prediction is evident.

distributions for quark spin parallel (antiparallel) to the nucleon spin, then the EMC proton measurement and the F and D constants of 1988 determined that

$$\Delta u = 0.78 \pm 0.06 \qquad \Delta d = -0.47 \pm 0.06 \qquad \Delta s = -0.19 \pm 0.06 \tag{10}$$

The two surprises are that the strange sea is significantly negatively polarized (non-zero), and that the total quark contribution to the proton spin ($\Delta u + \Delta d + \Delta s$) is small ($\sim 0.12 \pm 0.16$). That the quarks does not account for the proton spin has been dubbed the "Proton Spin Crisis." This crisis has generated hundreds of theoretical papers. With the proton spin in an uproar, the natural question for the experimentalists was, what does the neutron have to say. This year marks the first results on the determination of the neutron spin structure function from both CERN and SLAC.

The SMC experiment at CERN.[20] provided a first measurement of the deuteron spin structure function. In this experiment a longitudinally polarized muon beam (100 GeV) orginating from parity-violating pion decay scattered off a polarized deuterated butanol target, and the scattered muons are detected in an upgraded version of the NMC spectrometer. Measurement of the difference in spin-dependent cross sections was achieved by reversing the spin direction of the polarized target, which itself consists of two halves polarized in opposite directions. Target spins were reversed a few times a day.

The E142 experiment[21] at SLAC provided a fairly direct determination of the neutron spin structure function by scattering polarized electrons off a polarized ^{3}He target. The ^{3}He nucleus consists of a neutron and two protons. To the extent that ^{3}He is in a spatially symmetric S-state ($\sim$ 90 %), the two proton spins align themselves anti-parallel to one another due to the Pauli exclusion principle, and the neutron spin lines up parallel to the nuclear ^{3}He spin direction. Scattering off a polarized ^{3}He is essentially equivalent to scattering off a polarized neutron plus two unpolarized protons. The E142 experiment scattered longitudinally polarized electrons (23 GeV) off a polarized ^{3}He target and detected scattered electrons in two single-arm spectrometers set up at 4.5° and 7°. Reversal of the beam spin direction was performed on a pulse-to-pulse basis, and the target spins were reversed a few times a day.

Table 2 compares some main features of the two experiments. They were technically different and provided complementary information. The higher-energy SMC experiment allows for measurements of the structure functions to lower x values, whereas the high-intensity SLAC electron beam provides a superior statistical measurement over the accessible kinematic range.

A comparison of the structure function g_1 results for the proton (EMC), the neutron (E142), and the deuteron (SMC) is given in Fig. 9. Note that by plotting xg_1 versus $\log x$, the area under the data points represents the integral over g_1. The observation of the convergence of g_1 at low x is also apparent on log scale. Fig. 10 shows a comparison of the neutron asymmetry A/D extracted from E142 and from the SMC deuteron data minus the EMC proton data. The higher precision from SLAC and lower x measurements from CERN are apparent.

Table 2. Comparison of the CERN SMC muon scattering experiment to the SLAC E142 electron scattering experiment.

Comparison of SMC to E142		
	SMC	E142
Beam particle	Muons	Electrons
Beam Energy	100 GeV	19 to 26 GeV
Beam current	0.4 pA	3 μA
Beam polarization	82 %	39 %
Target material	Deuterated Butanol	^{3}He and glass
Target polarization	35 %	35 %
Fraction pol. nucleons	0.19	0.11
Run time	$\approx$ 6 months	$\approx$ 6 weeks
x range	$0.006 < x < 0.6$	$0.03 < x < 0.6$
Q^2 range	$1 < Q^2 < 30\ GeV^2$	$1 < Q^2 < 6\ GeV^2$

The published g_1 integrals from the three experiments are

EMC Proton
$$\int_0^1 \mathrm{g_1^p(x)dx} = 0.126 \pm 0.010 \pm 0.015 \tag{11}$$

E142 Neutron
$$\int_0^1 \mathrm{g_1^n(x)dx} = -0.022 \pm 0.007 \pm 0.009 \tag{12}$$

SMC Deuteron
$$\int_0^1 \mathrm{g_1^d(x)dx} = 0.023 \pm 0.015 \pm 0.020 \tag{13}$$

Any pair of these integrals provide a test of the Bjorken sum rule to the extent that integrals can be combined at different average Q^2. Assuming that the asymmetries are independent of Q^2, Table 3 compares the left- and right-hand sides of the

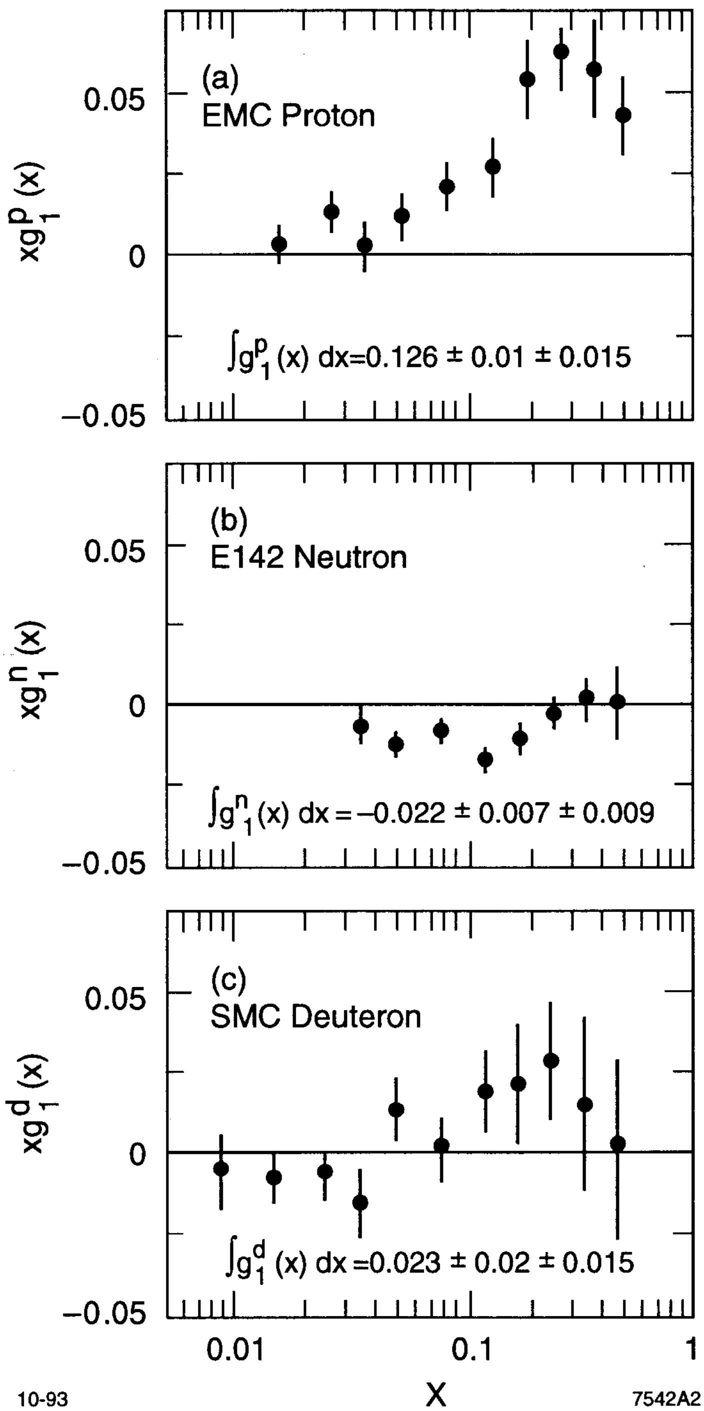

Figure 9. Results on the spin structure function measurements xg_1 vs. x for the proton (CERN EMC), neutron (SLAC E142), and deuteron (CERN SMC).

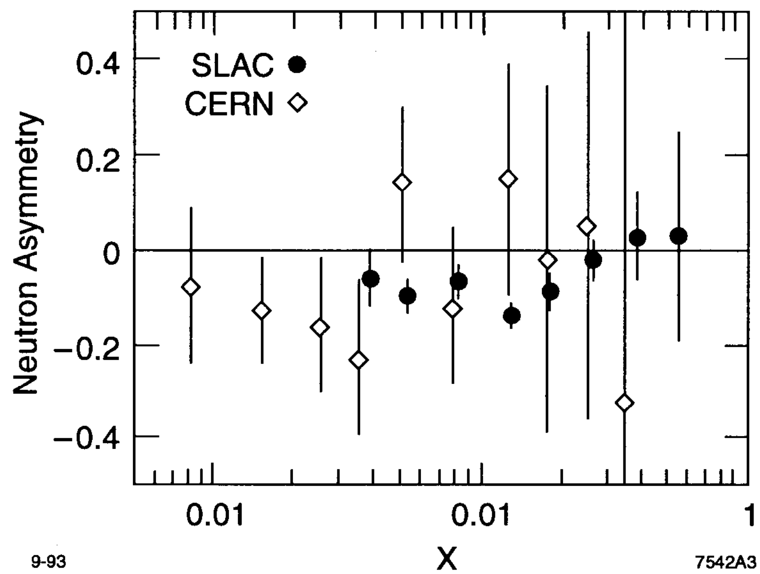

Figure 10. Results on the neutron asymmetries A_1^n versus x from CERN (EMC/SMC) and SLAC (E142).

Table 3. Comparison of the left-hand side (spin structure functions) and right-hand side (coupling constant with PQCD corrections) of the Bjorken sum rule. Calculations for the right-hand side results are given using only first-order PQCD corrections and up to third-order PQCD corrections. No theoretical uncertainties are assigned to the PQCD corrections.

Bjorken Sum Rule				
Experiments	Q^2	LHS	RHS (1st order)	RHS (3rd order)
proton/deuteron	5 GeV^2	0.20 ± 0.064	0.191	0.184
proton/neutron	2 GeV^2	0.148 ± 0.021	0.183	0.168
deuteron/neutron	2 GeV^2	0.090 ± 0.055	0.183	0.168

Bjorken sum rule. For the right-hand side, first-order PQCD and up to third-order PQCD corrections are presented. Within the large theoretical uncertainty from the PQCD corrections, there is clearly no evidence of a violation of the Bjorken sum rule.

For a given set of F and D constants, each of the three experimental results can be used to extract the contribution of the up, down, and strange quarks to the proton spin. Note that the neutron results can be used assuming isospin invariance, namely $\Delta u^{proton} = \Delta d^{neutron}$. Table 4 presents a comparison of the QPM results. In a world with only CERN results, the strange sea appears to have a large negative polarization and the quarks carry little of the nucleon spin; whereas, a "SLAC only" world finds no evidence for a polarized strange sea, and quarks carry half the nucleon spin. An average value of all world data is consistent within one sigma of each of the results. Higher-order perturbative and non-perturbative corrections may also be contributing to the small apparent discrepancy. To the extent that it is still unknown whether or not the quarks carry the nucleon spin, the nucleon spin crisis is alive. A list of possible scenarios that could play out in the future is given below:

- An experiment is wrong or has large fluctuations.
- The Bjorken sum rule is wrong (unlikely!).
- The strange sea is highly polarized and concentrated at low x below where E142 measured (i.e., below x of 0.03).
- QCD theoretical corrections (perturbative and/or non-perturbative) are large.
- ^{3}He and/or deuterium nuclear corrections used to extract the neutron are large.

Numerous experimental programs to study spin structure functions are now active. CERN SMC (200 GeV) and SLAC E143 (30 GeV) will provide results on another round of proton measurements in 1994. SLAC E143 will also make a first measurement of the deuteron in electron scattering. A third program (HERMES) at DESY is quickly coming online and should begin collecting data in 1995. The HERA ring at DESY will provide 30 GeV polarized electrons which will scatter off pure polarized H_2, D_2, and ^{3}He gas targets in the storage ring. HERMES should provide high-precision measurements of the nucleon spin structure function with

Table 4. Comparison of the quark parton model spin distributions extracted from the same F and D constants and each of the three experiments of EMC, SMC, and E142.

QPM Results			
Quark spin distribution	EMC	SMC	E142
Δu	0.78 ± 0.08	0.76 ± 0.11	0.93 ± 0.06
Δd	-0.50 ± 0.08	-0.49 ± 0.11	-0.35 ± 0.06
Δs	-0.16 ± 0.08	-0.21 ± 0.11	-0.01 ± 0.06
Δq	0.13 ± 0.19	0.06 ± 0.25	0.57 ± 0.11

clean targets and investigate spin dependent scattering in exclusive reactions for the first time at these energies.

Today DESY leads the field in studying new kinematic ranges of unpolarized nucleon structure functions. With the upcoming precision HERMES program, DESY may soon become a center for studying nucleon spin structure.

REFERENCES

[1] S. Egli and U. Dosselli, paper presented in these proceedings.

[2] P. Amaudruz *et al.*, Phys. Lett. **B295**, 159 (1992).

[3] P. Amaudruz *et al.*, Phys. Rev. Lett. **66**, 2712 (1991).

[4] W.G. Seligman et al., talk presented at 1993 Rencontre de Moriond: QCD and High-Energy Hadronic Interactions.

[5] G. Altarelli and G. Parisi, Nucl. Phys. **B126**, 298 (1977).

[6] H. Abramowicz *et al.*, Z. Phys., **C49**, 187 (1991).

[7] L.N. Epele *et al.*, La Plata preprint, PRINT-92-249 (1992).

[8] V.R. Zoller, Phys. Lett. **B279**, 145 (1992).

[9] A.I. Signal *et al.*, Phys. Rev. **D40**, 2832 (1989); Phys. Lett. **B221**, 481 (1988).

[10] J. Stern and G. Clement, Phys. Lett. **B264**, 426 (1991).

[11] M.R. Adams *et al.*, Fermilab–Pub–93–065–E, March 1993.

[12] S.A. Rabinowitz *et al.*, Phys. Rev. Lett. **70**, 134 (1993).

[13] A.O. Bazarko *et al.*, Nevis Report 1492, presented at 1993 Rencontre de Moriond: QCD and High-Energy Hadronic Interactions.

[14] H. Abramowicz *et al.*, Z. Phys. **15C**, 19 (1982).

[15] J.D. Bjorken, Phys. Rev. **148**, 1467 (1966); Phys. Rev. **D1**, 1376 (1970)

[16] J. Ellis and R. Jaffe, Phys. Rev **D9**, 1444 (1974).

[17] S.A. Larin and J.A.M. Vermaseren, Phys. Lett. **B259**, 345 (1991).

[18] J. Ashman *et al.*, Phys. Lett. **B206**, 364 (1988); Nucl. Phys. **B328**, 1 (1989).

[19] R.L. Jaffe and A.V. Manohar, Nucl. Phys. **B337**, 509 (1990).

[20] B. Adeva *et al.*, Phys. Lett. **362B**, 553 (1993).

[21] P.L. Anthony *et al.*, Phys. Rev. Lett. **71**, 959 (1993).