SYMPOSIUM ON FUTURE POLARIZATION PHYSICS AT FERMILAB

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MEASUREMENTS OF NUCLEON SPIN-DEPENDENT STRUCTURE FUNCTIONS - PAST AND FUTURE

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ABSTRACT

A brief review of our present knowledge of the proton spin dependent structure function $g_1^p(x)$ is given based on SLAC and CERN experiments, and the theoretical implications are mentioned. Possible future experiments to measure both the neutron and proton spin-dependent structure functions $g_1^n(x)$ and $g_1^p(x)$ in polarized μ-p and μ-d deep inelastic scattering experiments at CERN and FNAL are discussed. These new experiments would test the fundamental Bjorken polarization sum rule at the 10% level.

1. BRIEF REVIEW OF CURRENT KNOWLEDGE

The spin-dependent structure functions of the nucleon provide the basic information about the spin composition of the proton and neutron and make possible important tests of QCD and of our models of the nucleon. These spin-dependent structure functions are quite independent of the exhaustively studied spin-independent structure functions, and are determined from measurements of spin-dependent asymmetries in the deep inelastic scattering of polarized electrons and muons by polarized nucleons.[1]

Two major experiments have determined the spin-dependent structure function $g_1^p(x)$ of the proton. The first was an experiment with polarized electrons at SLAC by a Yale-SLAC group[2] in the kinematic range x = 0.1 to x = 0.7, and the second was a recent experiment with with polarized muons at CERN by the EMC group[3] in the broader kinematic range x = 0.01 to x = 0.7. The quantity measured in these experiments is $A_1(x) \equiv \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$, in which $\sigma_{1/2}(\sigma_{3/2})$, is the absorption cross section for polarized virtual photons by polarized protons when the total component of angular momentum along the collision axis is 1/2 (3/2). The results of the two experiments are shown in Figure 1. The agreement is excellent in the region of overlap from x = 0.1 to x = 0.7, and the CERN results extend down to x = 0.01.

A fundamental sum rule, originally derived by Bjorken[4] from current algebra but now recognized to be based on QCD in the scaling limit, (a modification calculated with perturbative QCD can also be included[5]) relates the spin-dependent structure functions of the nucleon to the weak interaction coupling constants for neutron beta decay. It reads

$$\int_0^1 dx\,\left(g_1^p(x) - g_1^n(x)\right) = \frac{1}{6}\left|\frac{g_A}{g_V}\right|\left(1 - \frac{\alpha_s(Q^2)}{\pi}\right) = 0.191 \pm 0.002 \qquad (1)$$

Here $g_1^{p(n)}(x) = \dfrac{1}{2x}\ \dfrac{A_1^{p(n)}(x)\ \ F_2^{p(n)}(x)}{1 + R^{p(n)}(x)}$, (2)

in which $F_2(x)$ and $R(x)$ have their usual meanings.

In the quark-parton model

$$g_1(x) = \frac{1}{2}\sum_i e_i^{\,2}\left[f_i^{\uparrow}(x) - f_i^{\downarrow}(x)\right] \qquad (3)$$

where i = quark type with charge e_i and $f_i^{\uparrow(\downarrow)}(x)$ = probability that quark of type i has the fractional momentum x of the nucleon and has its spin parallel (antiparallel) to the nucleon spin.

Auxiliary sum rules for the proton and neutron separately, which involve nucleon model-dependent assumptions - principally that the strange quark sea is unpolarized - have been given by Ellis and Jaffe[6] and by Belyaev et al.,[7]

$$\int_0^1 dx\ g_1^p(x) = \frac{0.99}{6}\left|\frac{g_A}{g_V}\right|\left(1 - \frac{\alpha_s}{\pi}\right) = 0.189 \pm 0.005 \qquad (4)$$

$$\int_0^1 dx\ g_1^n(x) = \frac{-0.01}{6}\left|\frac{g_A}{g_V}\right|\left(1 - \frac{\alpha_s}{\pi}\right) = -0.002 \pm 0.005 \qquad (5)$$

Thus far experimental data are available only for the proton so that the Bjorken sum rule cannot be tested, but the Ellis-Jaffe sum rule for the proton given in eqn. (4) can be tested. From the CERN data alone we find

$$\int_0^1 dx\ g_1^p(x) = 0.114 \pm 0.012(\text{stat.}) \pm (0.026)(\text{syst.}) \qquad (6)$$

in substantial disagreement with the theoretical prediction of eqn. (4). Combination of the CERN and SLAC data[8] gives

$$\int_0^1 dx\ g_1^p(x) = 0.116 \pm 0.009 \pm 0.019 \qquad (7)$$

Figure 2 shows the CERN and SLAC data on the first moment of g_1^p as a function of the lower limit x of the integral, from which the result of eqn. (7) is derived. Note that the low x region below x = 0.1, measured for the first time by the EMC group, was decisive in leading to the violation of the Ellis-Jaffe sum rule. This combined experimental result eqn. (7) disagrees more strongly with the theoretical value of eqn. (4) - indeed by 3.5 standard deviations (combining statistical and systematic errors). Furthermore, assuming the Bjorken sum rule (1) and the experimental result of eqns. (6), and (7), we conclude that $\int_0^1 dx\ g_1^n(x)$ for the neutron is much larger than the value of eqn. (5) predicted by the Ellis-Jaffe sum rule.

Finally using the Bjorken polarization sum rule of eqn. (1), the experimental result of eqn. (6), and the quark-parton model relation of eqn. (3), we can deduce that the fraction of the proton spin carried by the u and d quarks is 0.068 ± 0.047 ± 0.103, an unexpectedly small value which implies that the spin of the proton is carried by gluons and/or orbital angular momentum. Further discussion of this conclusion is given in ref. 3.

A number of recent theoretical papers[9-22] have appeared discussing the violation of the Ellis-Jaffe sum rule and the smallness of the spin component of the proton carried by the quark spins. Several of the recent theoretical suggestions were discussed in this Fermilab Symposium.

2. POSSIBLE FUTURE MEASUREMENTS OF THE SPIN-DEPENDENT STRUCTURE FUNCTIONS OF THE NEUTRON AND PROTON.

2.1 Objectives

Although there has always been ample justification of a general nature to measure the spin-dependent structure functions of the nucleon (indeed a proposal was made at SLAC to measure the neutron asymmetry A_1^n in 1980-1982), the recent surprising EMC results that the Ellis-Jaffe sum rule for the proton is violated and that only a small fraction of the proton spin is carried by the quark spins have stimulated great interest in further measurements of the nucleon spin-dependent structure functions. The most important and fundamental measurement will be the neutron spin-dependent asymmetry $A_1^n(x)$, or the neutron spin-dependent structure function $g_1^n(x)$ and its first moment $\int_0^1 g_1^n(x)\,dx$. Improved precision in the measurement of $A_1^p(x)$ and $g_1^p(x)$ is also important. Furthermore the second independent spin-dependent asymmetry A_2 which determines the second spin-dependent structure function g_2 can and should also be measured.[1]

Measurement of both the proton and neutron spin-dependent structure functions g_1^p and g_1^n will allow a test of the fundamental Bjorken polarization sum rule eqn. (1). This sum rule follows directly from QCD in the scaling limit (with a correction from perturbative QCD) without any model dependent assumptions, and hence its verification would be an important test of QCD. Knowledge individually of the first moments of the proton and neutron spin-dependent structure functions will provide the basis for development of appropriate nucleon model-dependent sum rules and also for determining the contribution of quark spins to the nucleon spin. Knowledge of the spin-dependent structure functions as a function of x allows testing of detailed nucleon models.

Several possible experiments are currently being considered to measure the spin-dependent asymmetries $A_1^n(x)$ and $A_1^p(x)$. The first is an extension of the CERN EMC experiment, in which polarized muons are scattered from polarized protons and polarized deuterons.[23] The second would be a similar experiment at Fermilab. The third would be at HERA using a 35 GeV polarized electron beam in the electron ring and an internal polarized H or D gas target.[24] As compared to the CERN experiment the kinematic range of the HERA experiment will involve lower Q^2; its x range is not projected to extend below x = 0.025 but at high x statistical errors will be smaller. We discuss here briefly the CERN and Fermilab experiments.

2.2 A New CERN Experiment

The new CERN experiment would be very similar to the recent EMC experiment with the notable extension that the polarized target[25] would provide either polarized protons or polarized deuterons. The target material would be butanol or deuterated butanol. The cryostat and cryogenic system, microwave system, and proton NMR system of the CERN/EMC target will be used; a new solenoid with improved homogeneity will be constructed and will incorporate a transverse dipole field as well. The dipole together with the solenoid will allow rapid reversal of the magnetic field direction with the nucleon spins adiabatically following the field direction. Rotation of the spin direction relative to the magnetic field direction will also be done by changing the microwave frequency or possibly by adiabatic fast passage. Rapid reversal of the magnetic field and spin directions will eliminate the principal systematic error in the EMC experiment. Operating conditions for the polarized target are shown in Table 1. In the EMC experiment no measurement of the incident muon beam polarization P_μ was made; its value was determined to 10% accuracy by Monte Carlo calculation and with reference to an earlier measurement of

P_μ for this beam line.[26] In the new CERN experiment we aim to measure P_μ with an accuracy of 5% either by elastic muon-electron scattering similar to Moeller scattering[27] or from the spectrum of the decay electrons.[26] Considerable upgrading of the EMC spectrometer, including the on-line computer and data acquisition system and additional tracking chambers has been done by the NMC group which is presently using the spectrometer. Further improvements are planned for the new experiment.

Table 1. Operating Conditions for Polarized Target

Target Material	Butanol and deuterated butanol (Chemically doped)
Magnet Field	2.5 T
Temperature	0.5 K for dynamic mode 0.05 K for frozen spin mode
Polarization	0.8 for proton 0.4 for deuteron

Summary remarks on the CERN experiment are given in Table 2. Figures 3 and 4 give projected data points for $A_1^p(x)$ and $A_1^n(x)$.

Table 2. Summary Remarks on the New CERN Experiment*

(a) Polarized Muon Beam
Energy, E_μ = 100 GeV
Intensity, I, = 4×10^7 μ^+/pulse
Polarization, P_μ, = (80 ± 4)%
(To be measured by elastic μ-e scattering from magnetized iron or from spectrum of decay electrons).

(b) Polarized Target
Target material, butanol and deuterated butanol
P_p = (80 ± 2.4)%
P_d = (40 ± 1.2)%
(To be measured by standard NMR techniques)

Reversal of polarization
Frequency = once/day or faster by rotation of magnetic field
Frequency = once/week by rotation of spin
(By changing microwave frequency or by adiabatic fast passage)

(c) Spectrometer Acceptance and Efficiency
Data taking efficiency = 0.35
Events/muon = 1.1×10^{-6}
Improvements in data acquisition system, beam hodoscopes and reliability for NMC system as compared to EMC system account for an increase in data rate by a factor of 3.6.

(d) Expected Accuracies
Beam time = 220 days (2/3 for d and 1/3 for p)
24×10^6 μ DIS events

Statistical Errors:

For ΔA_1^p = 0.018 at x = 0.015 increasing to 0.087 at x = 0.55
(~1/2 size of EMC statistical errors)

For ΔA_1^n = 0.037 at x = 0.015 increasing to 0.314 at x = 0.55

$\Delta \int_0^1 g_1^p dx$ = 0.006 (~1/2 that of EMC)

$\Delta \int_0^1 g_1^n dx$ = 0.012

$\Delta \left(\int_0^1 g_1^p dx - \int_0^1 g_1^n dx\right)$ = 0.015 = 8% of theoretical value

Systematic Errors on the Integrals
Assume beam polarization measured to 5%
Assume target polarization measured to 3%
Assume error due to F_2 measurement 5%
Use the EMC values from R. Piegaia's thesis** (page 172) and interpolate to the values for the new experiment where necessary (as given above). Correlations are accounted for.

Source of Error	Type	$\int g_1^p dx$	$\int g_1^d dx$	$\int g_1^n = \int g_1^d - \int g_1^p$	$\int g_1^p - \int g_1^n = 2\int g_1^p - \int g_1^d$
P_μ	Multplicative	.0061	.0019	.0042	.0103
$P_{p,d}$	Multplicative	.0034	.0011	.0023	.0057
f & smearing	Multplicative	.0007	.00014	.0006	.0013
R_{QCD}	Multplicative	.0010	.00032	.0007	.0017
Rad.Cor. Uncert.	Multplicative	.0015	.00047	.0010	.0025
Uncert. in F_2	Multplicative	.0057	.0018	.0039	.0096
Neglect of A_2	Additive	.0080	.0080	0	.0080
Totals		.0122	.0085	.0063	.0175
		(10.7%)	(24%)	(8.1%)	(9.2%)
Values of integral assumed		0.114 (EMC measure)	.036	−0.078 (from Bj sum rule)	0.191

(e) Measurement of A_2
Possible with new solenoid-dipole magnet (0.5 T dipole field)
To be considered

(f) Radiative Corrections
Insignificant systematic error

(g) Time Scale and Manpower; Cost
Submit proposal to CERN in September or October.
Aim to be ready to start experiment in two years
Principal R & D jobs
(1) Polarized target (20 my)
(2) Polarimeter for muon beam (15 my)
(3) Drift chambers for spectrometer (15 my)

Cost
Polarized target (1.1 MSFr.)
Muon polarimeter (0.4 MSFr.)
Spectrometer (1.0 MSFr.)
Total: (2.5 MSFr.)

(h) Kinematic Range
Approximately same as for EMC experiment
x from 0.01 to 0.7
y < 0.85
Q^2 from 1.5 $(GeV/c)^2$ (at x = 0.01) to 70 $(GeV/c)^2$ (at x = 0.5)

*Based on material presented and discussed at the NMC collaboration meeting at CERN on July 15, 1988.
**Yale Ph.D. Thesis, 1988 (unpublished).

From Table 2 we see that a new CERN experiment should test for the first time the fundamental Bjorken polarization sum rule at the level of about 12%. Our first information on the neutron spin-dependent structure function would be obtained, and the first moment of $g_1^n(x)$ should be determined to about 18%. The new measurements of $A_1^p(x)$ should have only about 1/2 the statistical and systematic errors of the CERN EMC experiment and the first moment of $g_1^p(x)$ should be determined to about 12%.

2.3 A Fermilab Experiment

In view of the current interest in the nucleon spin-dependent structure functions, it is natural to consider an experiment at Fermilab using their polarized muon beam with E_μ up to about 500 GeV and the spectrometer developed for the E665 experiment. A long polarized target similar to the polarized target used in the EMC experiment would be required. Indeed such an experiment was discussed by the Yale group when we joined FNAL E665 in 1983, and discussion was initiated then with CERN about a loan of the CERN target to FNAL.

The principal advantage of a measurement at FNAL as compared to CERN is that the kinematic range could involve higher Q^2 values and extend to lower x values. The principal incremental capital equipment cost would be for the polarized target, provided a loan of the CERN target is not possible. In this Fermilab Symposium, H. Spinka of Argonne National Laboratory has discussed the cost and time scale for construction of a polarized target of 1 m length or of 3 m length.

V. Papavassiliou of Yale University has considered recently in some detail the kinematic range and statistical accuracy achievable using the CERN 1 m target in a Fermilab experiment to measure A_1^p and A_1^n in polarized

μ-p and μ-d deep inelastic scattering. Using the 450 GeV μ^+ beam in the high-intensity mode, which has an average polarization of -80% and a very wide momentum spectrum, for a 6 month data-taking run with 2 months for proton data and 4 months for deuteron data, it turns out as might be expected that the statistical accuracy is not high enough to compete with the CERN experiment discussed in section 2.2. - the number of events over most of the x range is less by a factor of about 5 to 10. However, the low x bins (x = 0.002 to 0.05) should be measurable with reasonably small errors, and such data would clearly be important to determine how A_1 extrapolates to x = 0. Analysis of a Fermilab experiment with a 120 GeV μ^+ beam and otherwise the same conditions as for the 450 GeV case indicates that data comparable to the new CERN experiment could be obtained.

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REFERENCES

1. V.W. Hughes and J. Kuti, Ann. Rev. Nucl. Sci. 33, 611 (1983).

2. M.J. Alguard et al., Phys. Rev. Lett. 37, 1261 (1976); 41, 70 (1978); G. Baum et al., Phys. Rev. Lett. 51, 1135 (1983).

3. J. Ashman, et al., (European Muon Collaboration), Phys. Lett. B206, 364 (1988).

4. J.D. Bjorken, Phys. Rev. 148, 1467 (1966); Phys. Rev. D1, 465 (1970).

5. J. Kodaira, Nucl. Phys. B165, 129 (1980).

6. J. Ellis and R. Jaffe, Phys. Rev. D9, 1444 (1974).

7. V.M. Belyaev, B.L. Ioffe and Ya. I. Kogan, Phys. Lett. 151B, 290 (1985).

8. V.W. Hughes, et al., "The Integral of the Spin-Dependent Structure Function g_1^p and the Ellis-Jaffe Sum Rule." Preprint, 7/22/88. To be published in Phys. Lett. B.

9. R.L. Jaffe, Phys. Lett. 193B, 101 (1987).

10. F.E. Close and R.G. Roberts, Phys. Rev. Lett. 60, 1471 (1988).

11. S.J. Brodsky, J. Ellis and M. Karliner, Phys. Lett. B206, 309 (1988).

12. J. Ellis and M. Karliner, CERN-TH-5095/88, "The Analysis of the Angular Momentum of the Proton."

13. G. Altarelli and G.G. Ross, CERN-TH-5082/88, "The Anomalous Gluon Contribution to Polarized Electroproduction."

14. A.V. Efremov and O.V. Teryaev, JINR preprint E2-88-287, "Spin Structure of the Nucleon and Triangle Anomaly."

15. M. Anselmino, B.L. Ioffe and E. Leader, NSF-ITP-88-94, "On Possible Resolutions of the Spin Crisis in the Parton Model."

16. J. Ellis, R.A. Flories and S. Ritz, CERN-TH-4812/87, "Implications for Dark Matter Particles of Searches for Energetic Solar Neutrino."

17. J. Ellis and R.A. Flores, CERN-TH-4911/87, "Realistic Predictions for the Detection of Supersymmetric Dark Matter."

18. D.B. Kaplan and A. Manohar, HUTP-88/Aowr; CTP#1590. "Strange Matrix Elements in the Proton from Neutral Current Experiments."

19. P. Hoodbhoy, R.L. Jaffe and A. Manohar, CTP#1608, "Novel Effects in Deep Inelastic Scattering From Spin One Hadrons."

20. J.Ph. Guillet Z. Phys. C39, 75, (1988).

21. G. Preparata, J. Soffer, Milan preprint (1988); A. Giannelli et al., Phys. Lett. 150B, 214 (1985).

22. G. Preparata, Milan preprint (1988), "Spin Physics: A Challenge to the Generally Accepted Picture of QCD".

23. V.W. Hughes, D. von Harrach, et. al., "Measurement of the Spin-Dependent Structure Functions of the Neutron and Proton", CERN Letter of Intent, CERN/SPSC 88-11; SPSC/I169; 20/4/88.

24. K. Rith, et. al., "Conceptual Studies for an Experiment to Measure the Spin Dependent Nucleon Structure Functions at HERA", 22/7/88.

25. S.C. Brown et al., Proc. of 4th Int. Workshop on Polarized Target Materials and Techniques, Bonn, ed. W. Meyer (1984), p. 102.

26. D. Bollini et al., Il Nuovo Cimento 63A, 441 (1981).

27. D.S. Cooper et al., Phys. Rev. Lett. 34, 1589 (1975).

28. D.J.E. Callaway and S.D. Ellis, Phys. Rev. D29, 567 (1984).

29. R. Carlitz and J. Kaur, Phys. Rev. Lett. 38, 673, 1102(E) (1977); J. Kaur, Nucl. Phys. B128, 219 (1977).

FIGURE CAPTIONS

Fig. 1. Compilation of all the data on A_1^p as a function of x. The EMC points[3] are shown as full circles while the SLAC points[2] are shown as open diamonds (experiment E-80) and open squares (E-130). Inner error bars are the statistical errors and the outer error bars are the total errors (statistical plus systematic added in quadrature). The systematic errors include uncertainties in the values of R and A_2.

Fig. 2. Results for $\int g_1(x)dx$. Full circles: computed from the EMC data.[3] Open triangles: computed from the SLAC data, merging the two experiments.[2,8] The solid curve was computed from a fit to the EMC A_1 data. Inner (outer) error bars are the statistical (total) errors.

Fig. 3. Projected data points for $A_1^p(x)$ in a new CERN experiment. The total errors are based on Table 2. The projected points are plotted with the same central values as obtained in the EMC experiment.[3]

Fig. 4. Projected data points for $A_1^n(x)$ in a new CERN experiment. The total errors are based on Table 2. The projected points are plotted with their central values lying on a predicted curve due to Callaway and Ellis.[28] The parameters of their model are chosen to satisfy the Bjorken polarization sum rule and the first moment $\int_0^1 g_1^p(x)dx$ determined by the EMC experiment. Prior to the EMC experiment[3] the Carlitz-Kaur[29] model was expected to give the correct form for $g_1^n(x)$.

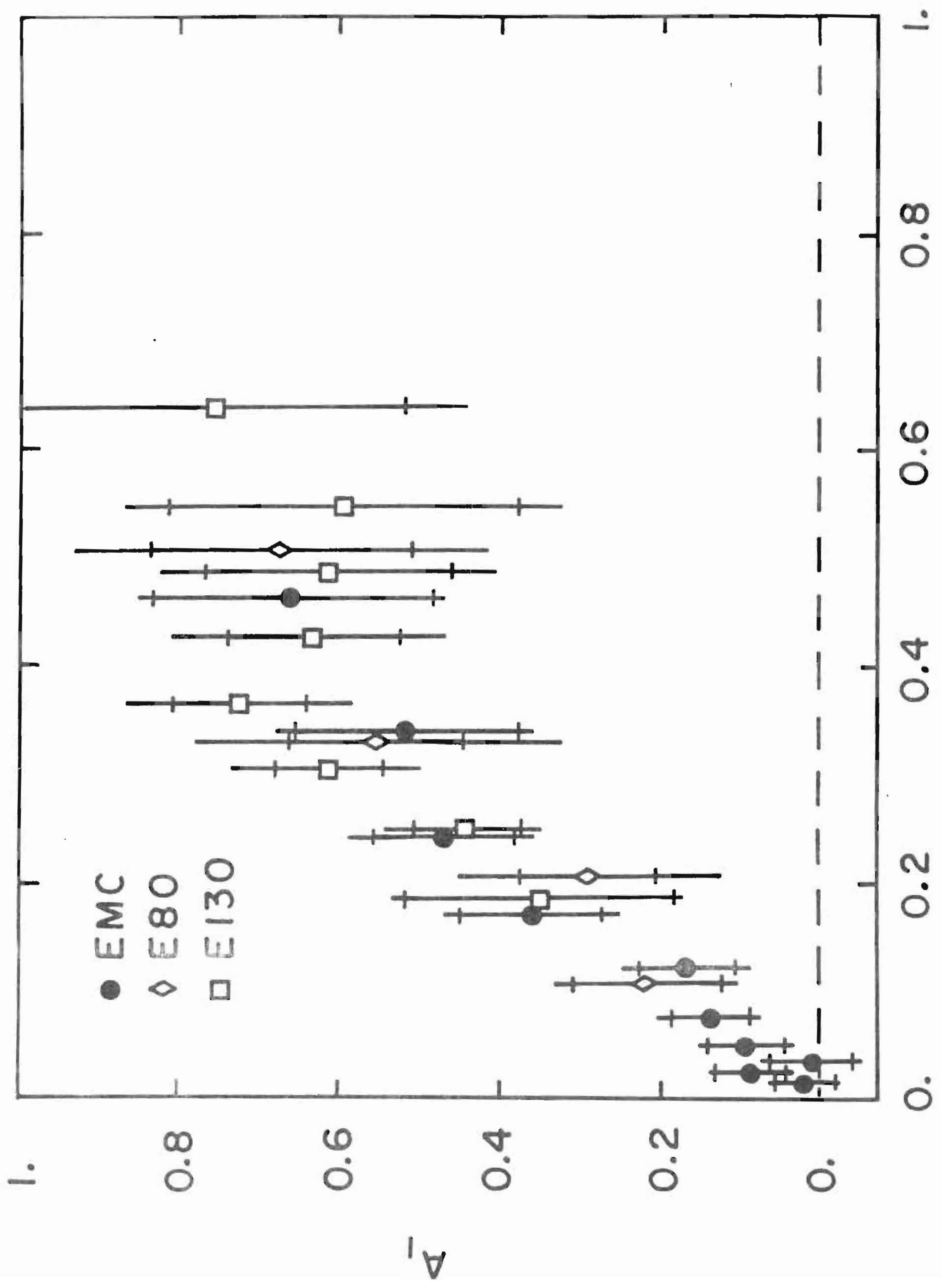

Figure 1

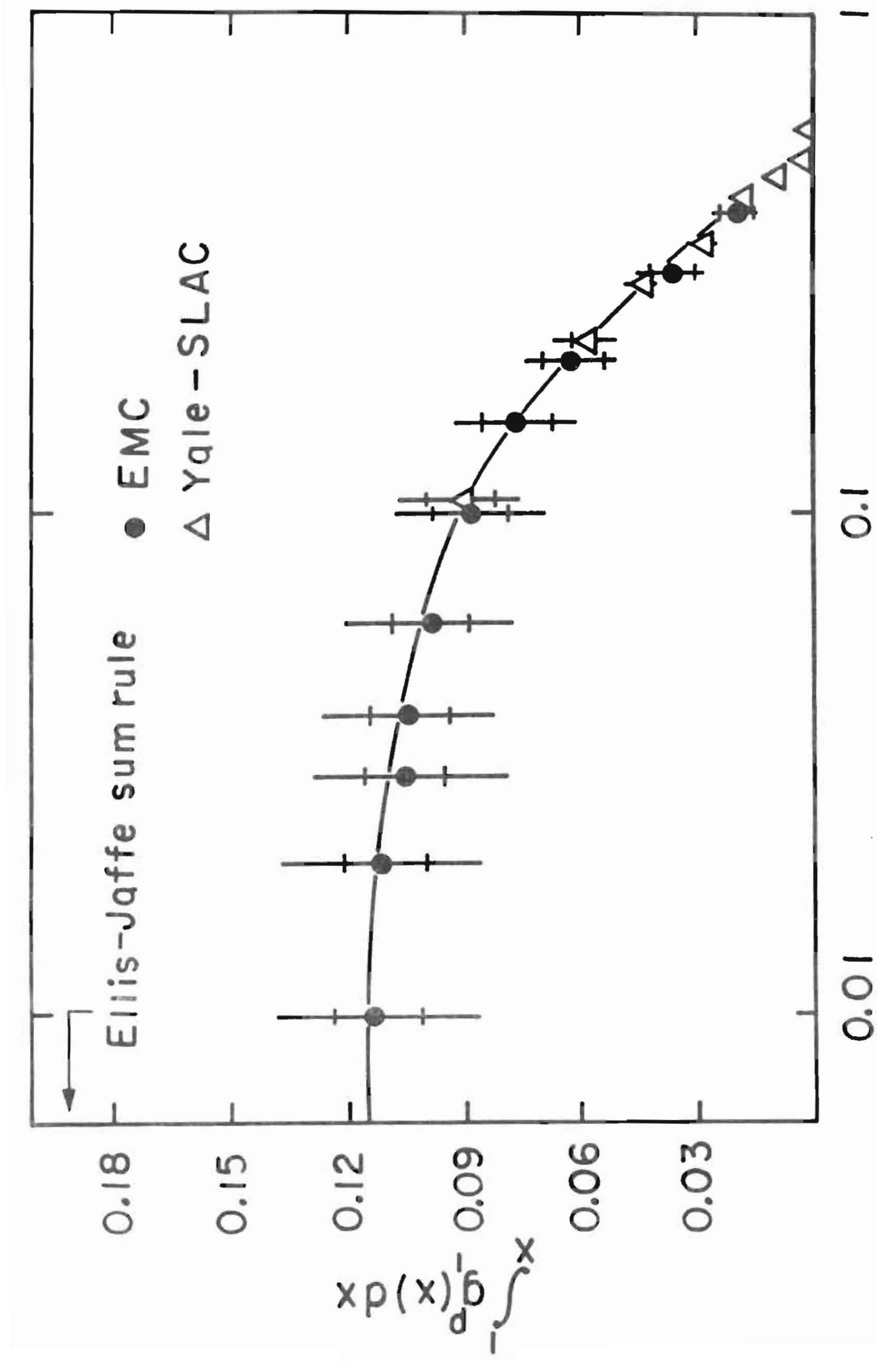
Ellis-Jaffe sum rule
● EMC
△ Yale-SLAC
0.18
0.15
0.12
0.09
0.06
0.03
$\int_x^1 g_1^p(x)dx$
0.01
0.1
1
x

Figure 2

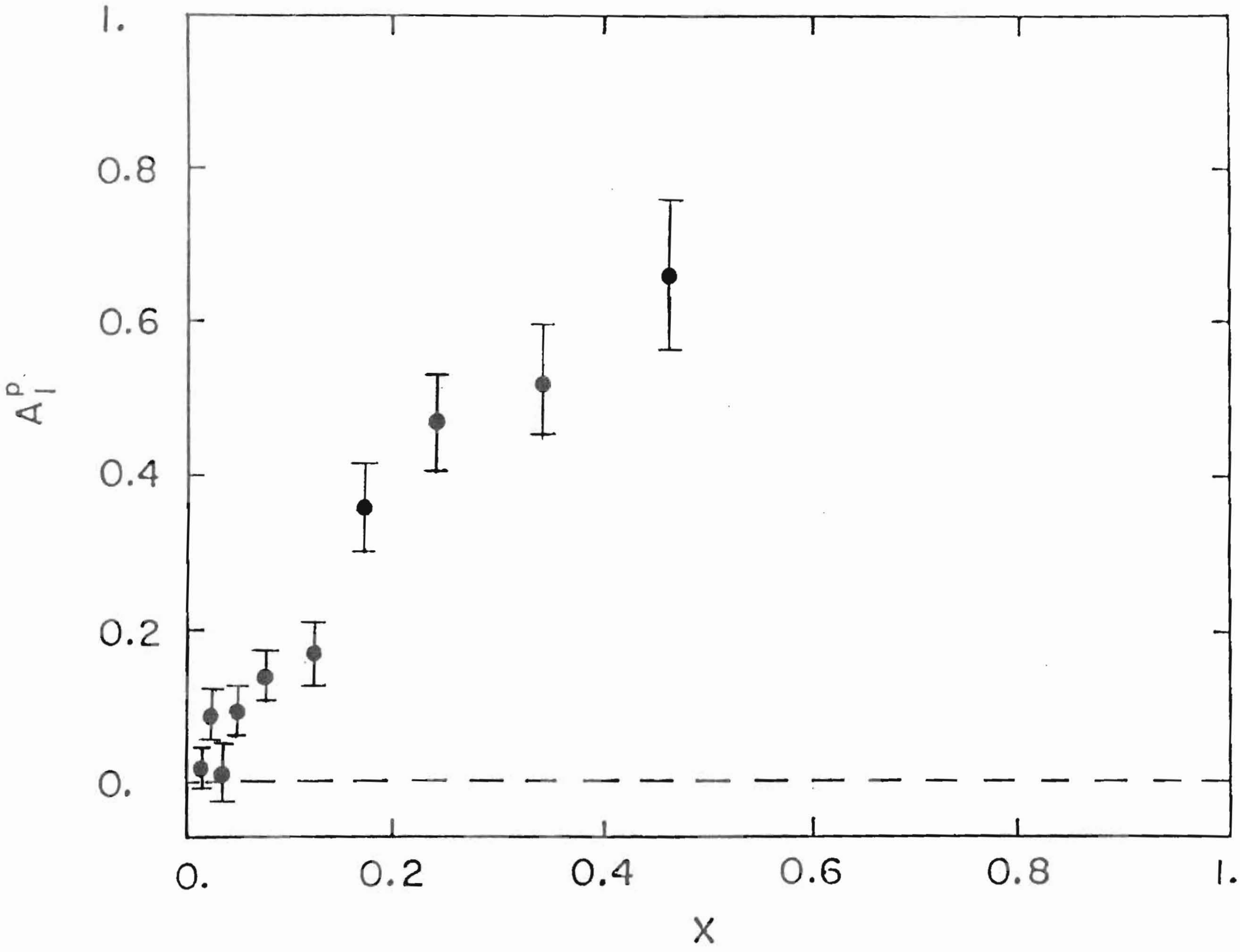

Figure 3

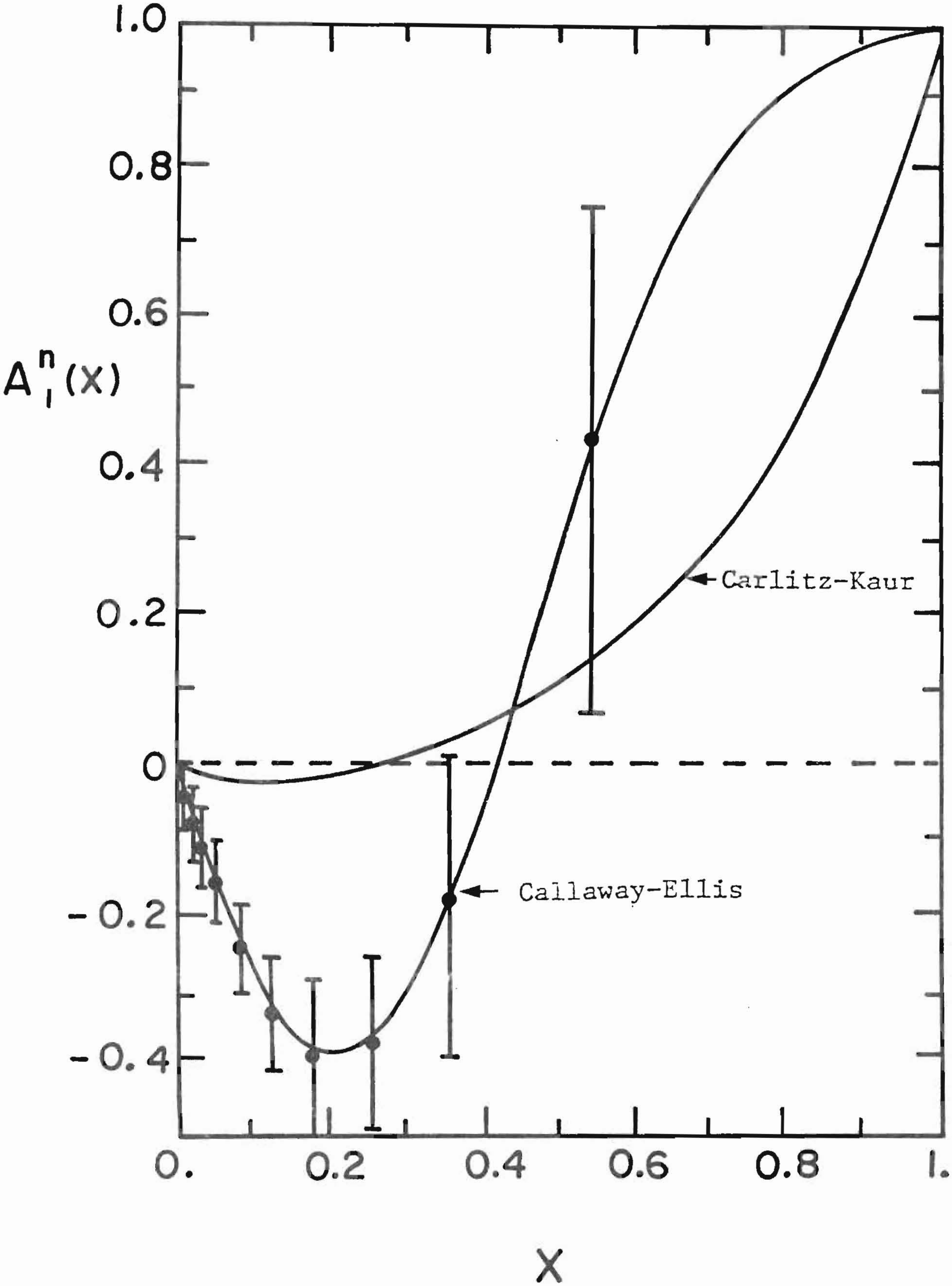
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
$A_1^n(X)$
Carlitz-Kaur
Callaway-Ellis
0.
0.2
0.4
0.6
0.8
1.
X

Figure 4