Measurements of $R = \sigma_L/\sigma_T$ for $0.03 < x < 0.1$ and Fit to World Data[*]

The E143 Collaboration

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To be submitted to Physics Letters

Measurements were made at SLAC of the cross section for scattering 29 GeV electrons from carbon at a laboratory angle of 4.5°, corresponding to $0.03 < x < 0.1$ and $1.3 < Q^2 < 2.7$ GeV^2. Values of $R = \sigma_L/\sigma_T$ were extracted in this kinematic range by comparing these data to cross sections measured at a higher beam energy by the NMC collaboration. The results are in reasonable agreement with pQCD calculations and with extrapolations of the $R1990$ parameterization of previous data. A new fit is made including these data and other recent results.

hep-ex/9808028   26 Aug 1998

INTRODUCTION

The spin-averaged cross section for lepton nucleon scattering can be written in terms of the two components for virtual photon absorption: the longitudinal cross section $\sigma_L(x, Q^2)$, and the transverse cross section $\sigma_T(x, Q^2)$. Alternatively this can be expressed in terms of the structure functions F_2 and $R = \sigma_L/\sigma_T$

$$\frac{d\sigma(x, Q^2, \epsilon)}{dE'd\Omega} = \Gamma(x, Q^2, \epsilon)[\sigma_T(x, Q^2) + \epsilon\sigma_L(x, Q^2)]$$
$$= \sigma_{Mott}\frac{2MxF_2(x,Q^2)}{\epsilon Q^2}\left[\frac{1+\epsilon R(x,Q^2)}{1+R(x,Q^2)}\right] \tag{1}$$

where $Q^2 = 4EE'\sin^2(\theta/2)$ is the four-momentum squared of the virtual photon, $x = Q^2/[2M(E - E')]$ is the light-cone momentum fraction of the struck parton, Γ is the virtual photon flux, $\epsilon^{-1} = 1 + 2(1 + Q^2/4M^2x^2)\tan^2(\theta/2)$, and θ and E' are the scattered lepton scattering angle and momentum in the lab. R is determined by making cross section measurements at fixed (x, Q^2) as a function of ϵ by varying the beam energy and scattering angle. In the quark-parton model, R is sensitive to the spin of the struck partons: at large Q^2, R is zero for spin $1/2$ quarks while at finite Q^2 quark transverse momentum causes non-zero values. In pQCD calculations of R [1] the leading term is proportional to α_s times integrals over the quark and gluon distributions, and is thus sensitive to the gluon content of the nucleon. At low Q^2 and high x, target mass corrections [2] also contribute to R. Knowledge of R is important for extracting the unpolarized structure function F_2 from cross section measurements and the spin structure functions g_1 and g_2 from asymmetry measurements of polarized leptons on polarized nucleons.

Previously a good parameterization was made of the world data on R (known as $R1990$) [3], but the fit is limited in validity to $x > 0.07$, where input data existed. To extend our knowledge of R into the lower x region (where it is needed for the extraction of g_1) we made cross section measurements in the range $0.03 < x < 0.1$. This was part of SLAC experiment E143 [4], whose primarily goal was the measurement of g_1 for the proton and deuteron.

E143 CROSS SECTIONS

We measured the cross section for scattering of 29.1 GeV electrons from a 1.7 gm/cm^2 carbon target at the End Station A facilities of the Stanford Linear Accelerator Center. Scattered electrons in the momentum range of 6 to 25 GeV/c ($0.03 \leq x \leq 0.4$) were detected in a magnetic spectrometer at $\theta = 4.5°$. We used two threshold Čerenkov counters and a segmented lead glass shower counter to identify electrons. Electron momenta were determined from tracking in a multi-plane hodoscope system and independently from the energy deposited in the shower counter. The system was designed to measure the spin structure functions of the nucleons and thus could operate at high rates. Details are given in [4]. The acceptance of the spectrometer was calculated with a model that used magnetic measurements and survey information. Part of the acceptance of the spectrometer was also calibrated by re-measuring the already known cross section in the kinematic region $0.1 < x < 0.3$. These cross sections are accurately known at all values of ϵ from a fit to F_2^d by the NMC collaboration [5], a fit to the A-dependence of lepton-nucleon scattering [6], and previously measured values of R [3]. The central momentum of the spectrometer was then lowered in several steps to put scattered electrons corresponding to $0.03 < x < 0.1$ into the calibrated acceptance region. Small adjustments were made to the spectrometer acceptance model until the overlaps between spectra with different central momentum settings were in good agreement. The final corrections to the acceptance compared to the original model were in the few percent range. Thus the overall normalization of our results are tied to those of the NMC fit.

Absolute cross sections in the low x region for the carbon target were obtained taking into account the residual background contaminations, the experimental efficiency for detecting electrons, the trigger dead time, and the application of radiative corrections [7,8]. The results for carbon cross sections per nucleon are shown in Fig. 1a and Table I. The systematic errors include an overall normalization uncertainty of about 2.5% due the combined uncertainties in target thickness, beam charge and spectrometer acceptance. Other systematic errors increased with decreasing x, including detection efficiency, the spectrometer acceptance, and radiative corrections (about 3% at low x, decreasing to about 1% at the highest x). The Q^2 for the points in Fig. 1a vary approximately linearly with x as in Table I. The curve on Fig. 1a is the predicted cross section using the NMC fit to F_2^d [5], nuclear corrections [6], and $R1990$ [3]. The good agreement between data and model for $x < 0.1$ is an indication that the extrapolation of $R1990$ to $x = 0.03$ works reasonably well.

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RESULTS FOR R

To determine values for R, we used Eq. 1 with the E143 cross sections and those of NMC [5] at the same (x, Q^2) values, but at much higher beam energies (higher values of ϵ). Since our cross sections are normalized to NMC cross sections at higher values of x, the normalization uncertainties between the two experiments are negligible thus reducing the systematic uncertainty on R.

The results are shown in Fig. 1b and Table I together with various fits and calculations. The new data are in reasonable agreement with the $R1990$ parameterization (solid curve with dotted curves showing error band), plotted at the Q^2 values of E143, although there is a tendency for the data to be slightly higher than $R1990$ at low x and lower than $R1990$ at high x. The lower x data are also higher than a calculation of NNLO pQCD plus target mass corrections [9] (dashed) using the MRS-R2 [10] parton distribution with four flavors.

Since the $R1990$ was published, there has been a considerable body of new data on R from this experiment, from SLAC E140X [11], NMC [12], and CCFR [13] as well as final results from CDHSW [14]. The data were recorded on a variety of targets, but since $R^d = R^p = R^A$ [11,15] to high accuracy we will combine them into a single data set. The new data have extended the kinematic range to lower and higher values of x. Because $R1990$ has been used extensively outside its range of validity at low x, it is important to compare it to the new data. The confidence level for $R1990$ to match the data is 61%. For the region $x \leq 0.07$, outside the range of validity of $R1990$, the confidence level is 16%. We note that R_c, one of the three fits that were averaged to make $R1990$, has a confidence level of less than 1% to agree with the low x data, while the R_a and R_b are much more successful.

We have performed a new fit using the present data [3,11–14], but excluding data with errors greater than 0.5 or more than 3 standard deviations below zero. The final data set still included some values of R which, due to errors, were negative (unphysical). There were 237 points with a kinematic range of $0.005 \leq x \leq 0.86$ and $0.5 \leq Q^2 \leq 130$. Figure 2 shows the distribution of points as a scatter plot. More parameters were added to the general form of the $R1990$ fits to try to accommodate the new data at low x. Three 6-parameter models were used based on the previous three $R1990$ models:

$$R_a = \frac{a_1}{\log(Q^2/0.04)} \Theta(x, Q^2) + \frac{a_2}{\sqrt[4]{Q^8 + a_3^4}}[1 + a_4 x + a_5 x^2] x^{a_6} \ ,$$

$$R_b = \frac{b_1}{\log(Q^2/0.04)} \Theta(x, Q^2) + [\frac{b_2}{Q^2} + \frac{b_3}{Q^4 + 0.3^2}][1 + b_4 x + b_5 x^2] x^{b_6} \ ,$$

$$R_c = \frac{c_1}{\log(Q^2/0.04)} \Theta(x, Q^2) + c_2 \left[\left(Q^2 - Q_{thr}^2\right)^2 + c_3^2 \right]^{-1/2} \tag{2}$$

with

$$Q_{thr}^2 = c_4 x + c_5 x^2 + c_6 x^3$$

$$\Theta(x, Q^2) = 1 + 12 \left(\frac{Q^2}{Q^2 + 1}\right) \left(\frac{0.125^2}{0.125^2 + x^2}\right), \tag{3}$$

where the units of Q^2 are GeV^2. The coefficients of the fits are shown in Table II. As in the case of $R1990$, we define $R1998$ to be the average of the three fits. The error associated with the fitting is approximately given by:

$$\delta R(x, Q^2) = 0.0078 - 0.013x + \frac{0.070 - 0.39x + 0.70x^2}{1.7 + Q^2}.$$

This error is largest at low Q^2, reaching a maximum value for $x \sim 0.04$. A systematic error associated with the functional form can be assigned from the spread of the three fits. Long range correlated errors such as those due to radiative corrections will enhance the errors. The new fits result in a better agreement with the data, with a confidence level of 73% for all the data and 38% when restricted to $x \leq 0.07$.

Fig. 3 shows the measured values of R as a function of Q^2 in three ranges of x below $x = 0.10$, along with $R1998$ and the pQCD plus target mass calculation used above. The value of R decreases with Q^2 as had been observed [8] at higher values of x. At these low values of x, target mass effects make only a small contribution to the pQCD calculation. The pQCD curve is below the data at low Q^2 as previously noted. Fig. 4 shows the data as a function of x for three ranges of Q^2. R is not very strongly dependent on x in this Q^2 range, continuing the trend observed for

$x \geq 0.07$. The pQCD plus target mass calculation falls below the data at low Q^2 and low x, but otherwise is in quite good agreement. We note that $Q^2 \sim 1 \mathrm{GeV}^2$ is a rather low value for pQCD calculations.

In summary, our new measurements of R, as well as other recent results are consistent with extrapolations of the empirical parameterization R1990. The result are roughly consistent with pQCD plus target mass calculations. Our new fit to the data (R1998), although similar to R1990, better reflects the wealth of new data obtained over the last several years and is in better agreement with the low x data.

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[1] G. Altarelli & G. Martinelli, Phys. Lett. **76B**, 89 (1978).

[2] H. Georgi and D. Politzer, Phys. Rev. **D14**, 1829 (1976).

[3] L. W. Whitlow *et al.,* Phys. Lett. B250, 193 (1990).

[4] SLAC E143, K. Abe *et al.,* Phys. Rev. Lett. 74, 346 (1995); Phys. Rev. Lett. 75, 25, (1995); SLAC-PUB-7753 submitted to Phys. Rev. D.

[5] NMC, M. Arneodo *et al.,* Phys. Lett. **B364**, 107 (1995).

[6] J. Gomez *et al.,* Phys. Rev. D 49, 4348 (1994).

[7] Y. S. Tsai, Report No. SLAC–PUB–848, 1971; Rev. Mod. Phys. 46 (1974), 815; D. Y. Bardin et al., Yad. Phys. **29**, 499 (1979); D. Y. Bardin et al., Nucl. Phys. **B197**, 1 (1982).

[8] SLAC E140, S. Dasu *et al.,* Phys. Rev. Lett. 61, 1061 (1988) and references within.

[9] A. Bodek, S. Rock, and U. Yang, 1996 UR-1355 (Z. Phys. C to be published).

[10] A.D. Martin, R.G. Roberts, W.J. Stirling, Phys. Lett B387, 419 (1996).

[11] SLAC E140X, L.H. Tao *et al.,* Z. Phys. C70, 387 (1996).

[12] NMC, M. Arneodo *et al.,* Nucl. Phys. B483, 3 (1997)

[13] U.K. Yang *et al.,* University of Rochester Preprint UR-1534 (1998), Preprint archives hep-ex/9806023. The data at the lowest x bin were excluded (private communication, U. K. Yang)

[14] CDHSW, P. Berge *et al.,* Z. Phys. **C49,** 187 (1991).

[15] NMC, P. Amaudruz *et al.,* Phys.Lett. B294, 120 (1992); M. Arneodo *et al.,* Nucl. Phys. B487, 3 (1997); Nucl. Phys. B481, 23 (1996).

TABLE I. Cross sections for carbon from E143 in nb/GeV/sr (per nucleon) and R extracted from this experiment and NMC deuterium data with statistical and systematic errors.

x	Q^2 (GeV/c^2)	ϵ	$\sigma \pm$ stat $\pm$sys	$R \pm$ stat $\pm$sys
0.0325	1.32	0.474	61.91 $\pm$ .46 $\pm$ 3.7	0.45 $\pm$ 0.01 $\pm$ 0.07
0.0375	1.47	0.519	60.81 $\pm$ .50 $\pm$ 3.6	0.51 $\pm$ 0.02 $\pm$ 0.09
0.0450	1.67	0.578	62.82 $\pm$ .53 $\pm$ 2.9	0.40 $\pm$ 0.01 $\pm$ 0.10
0.0550	1.90	0.641	65.64 $\pm$ .62 $\pm$ 2.3	0.28 $\pm$ 0.01 $\pm$ 0.09
0.0650	2.11	0.692	66.76 $\pm$ .66 $\pm$ 2.1	0.29 $\pm$ 0.02 $\pm$ 0.10
0.0750	2.29	0.734	69.61 $\pm$ .73 $\pm$ 2.4	0.18 $\pm$ 0.02 $\pm$ 0.11
0.0850	2.46	0.767	70.23 $\pm$ .73 $\pm$ 1.8	0.26 $\pm$ 0.03 $\pm$ 0.10
0.0950	2.60	0.795	72.03 $\pm$ .70 $\pm$ 2.2	0.25 $\pm$ 0.03 $\pm$ 0.14
0.1050	2.73	0.818	74.46 $\pm$ .71 $\pm$ 2.1	0.17 $\pm$ 0.03 $\pm$ 0.13

TABLE II. Coefficients to 6-parameter fits a, b and c for R1998 with the corresponding χ^2/df for 231 degrees of freedom .

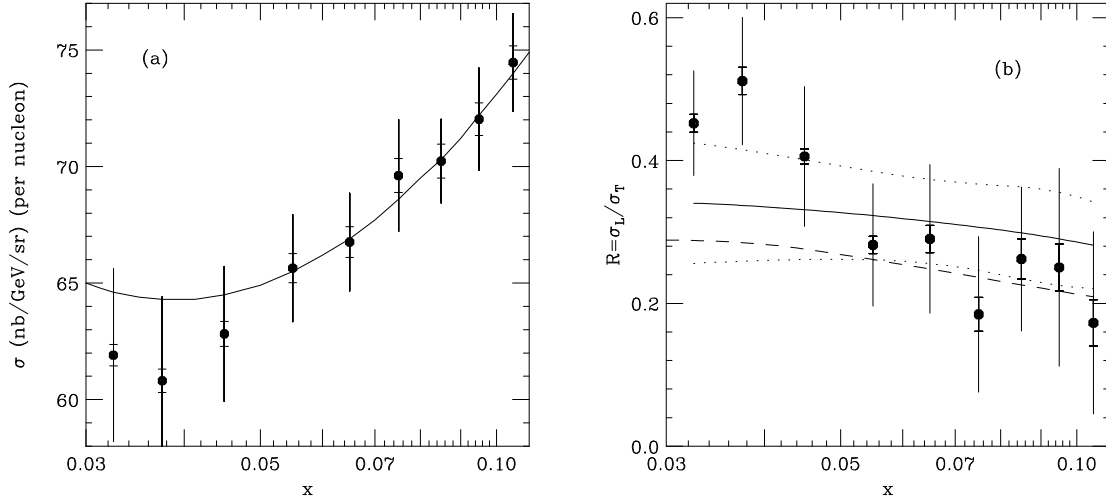| fit	1	2	3	4	5	6	χ^2/df
a	0.0485	0.5470	2.0621	-0.3804	0.5090	-0.0285	0.9
b	0.0481	0.6114	-0.3509	-0.4611	0.7172	-0.0317	0.9
c	0.0577	0.4644	1.8288	12.3708	-43.1043	41.7415	1.0

FIG. 1. (a) Cross sections from this experiment (E143) for 29.1 GeV electron scattering from carbon at 4.5°. Inner (outer) error bars are statistical (systematic). The curve is calculated using the NMC fit to F_2 [5], the R1990 fit to R [3], and the A-dependence of lepton-nucleon scattering [6]. (b) R extracted from this experiment (E143) combined with NMC. Inner (outer) error bars are statistical (systematic). The solid curve is the R1990 fit, with the dotted curves showing the error band evaluated at the Q^2 values of the data. The dashed curve is a pQCD calculation described in the text.
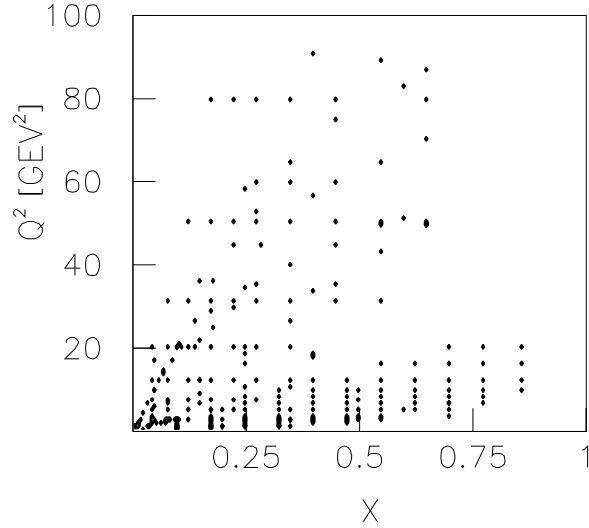

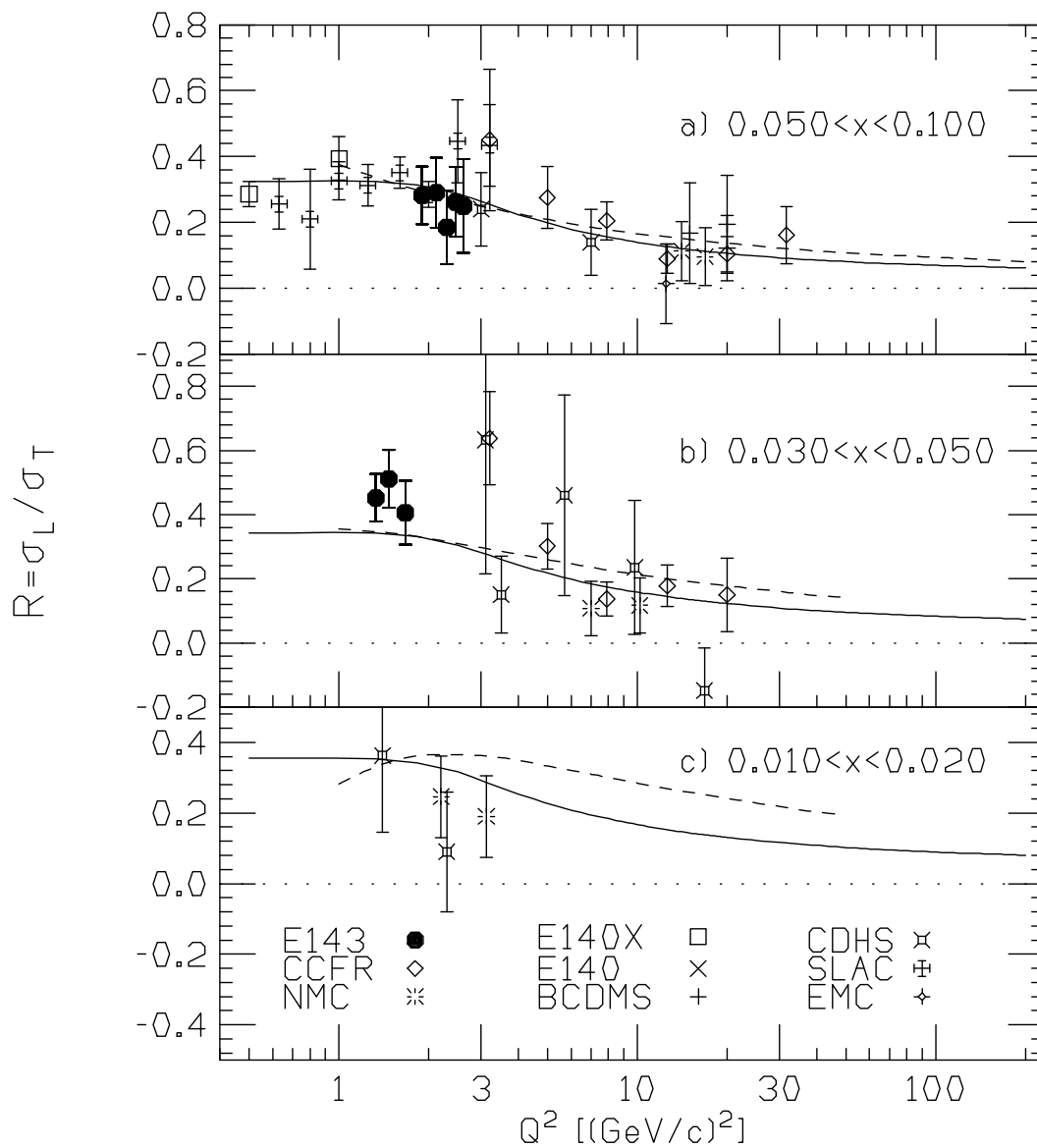FIG. 2. Kinematic distribution of data used for the R1998 fit.

FIG. 3. R as a function of Q^2 for: a) $0.05 \leq x \leq 0.10$; b) $0.03 \leq x \leq 0.05$; c) $0.01 \leq x \leq 0.02$. The solid curve is the average of the new fits, $R1998$, and the dashed curve is the NNLO pQCD calculation described in the text.
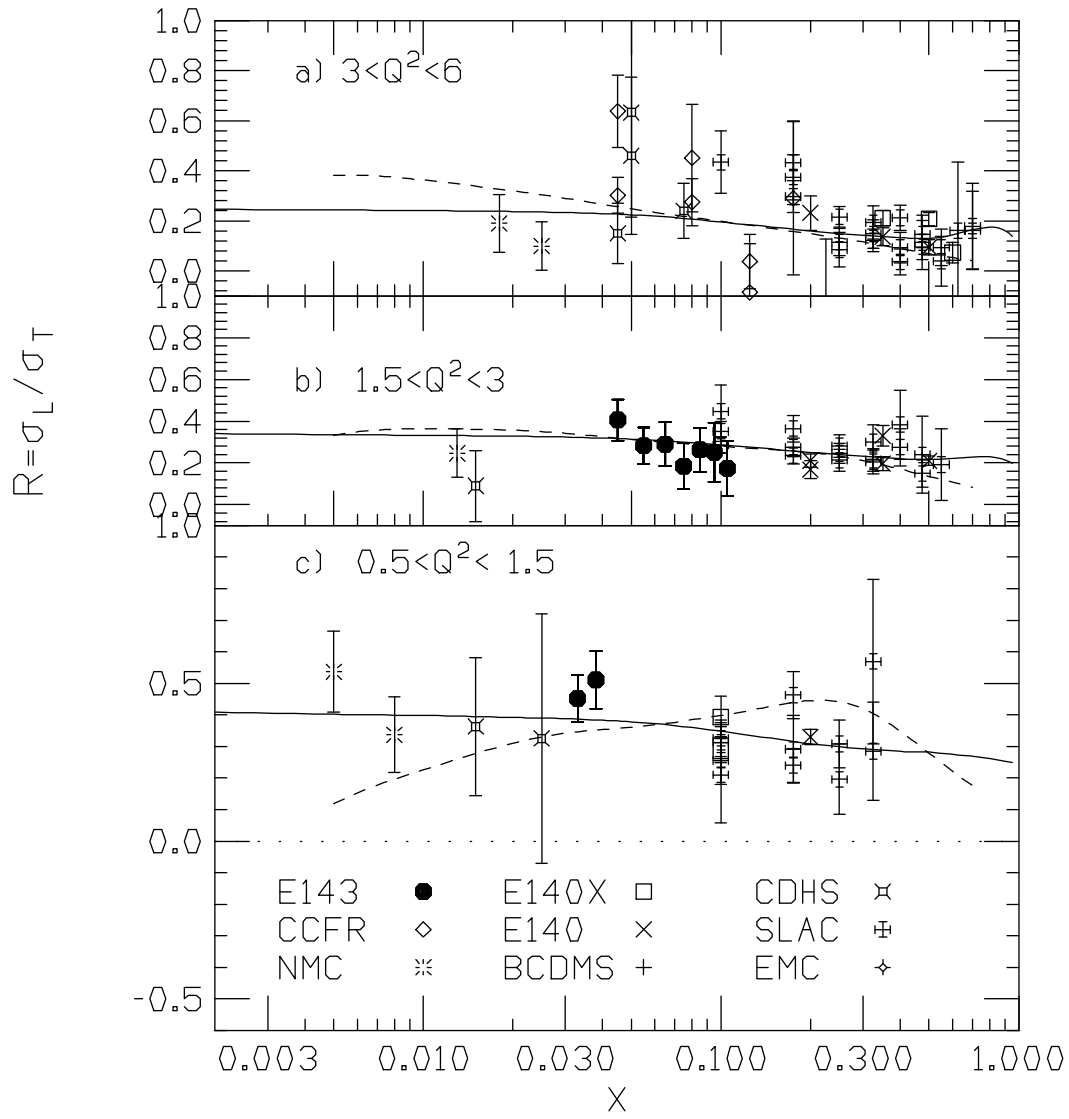
FIG. 4. R as a function of x for: a) $3 \leq Q^2 \leq 6 (\text{GeV/c})^2$; b) $1.5 \leq Q^2 \leq 3$ $(\text{GeV/c})^2$; c) $0.5 \leq Q^2 \leq 1.5$ $(\text{GeV/c})^2$. The solid curve is the average of the new fits, $R1998$, and the dashed curve is the NNLO pQCD calculation described in the text.