A new measurement of $g_1^{\rm p}$

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Abstract. We present a new measurement of the spin-dependent structure function $g_1^{\rm p}$ of the proton from deep inelastic scattering of 190 GeV polarized muons on polarized ammonia from our 1996 run in the kinematic range $1 < Q^2 < 100$ GeV^2 and $0.003 < x < 0.7$. The new data are combined with our previous data on $g_1^{\rm p}$. A perturbative QCD evolution in next-to-leading order is used to compute $g_1^{\rm p}$ at a constant Q^2. At $Q^2 = 10$ GeV^2 assuming a Regge type low x behavior in the region ($x < 0.003$) we determine $\Gamma_1^{\rm p} = 0.149 \pm 0.006(sta) \pm 0.009(sys) \pm 0.005(evol)$ (Preliminary). Using published results on deuteron we test the Bjorken sum rule. The values of the first moments, both of proton and the deuteron, depend critically on the low x assumptions made for the behavior of the spin structure function. A preliminary analysis assuming a behavior consistent with QCD prediction in this region gives markedly different results.

Measurements of the spin-dependent structure function $g_1^{\rm p}$ of the proton are an important tool to study it's internal spin structure. In combination with similar measurements on deuteron and neutron targets, they allow us to verify the Bjorken sum rule [1] which is a fundamental result of QCD. We report on a new measurement of $A_1^{\rm p}$ by the Spin Muon Collaboration (SMC), obtained by scattering longitudinally polarized muons of 190 GeV energy on longitudinally polarized protons in a kinematic range $0.0008 < x < 0.7$ and 0.2 GeV$^2 < Q^2 < 100$ GeV^2 using solid ammonia as polarized target material. The choice of ammonia as the target material against butanol used previously by SMC [2,3] improved the dilution factor by $\approx 30\%$. The average longitudinal proton polarization in the polarized ammonia target was $P_{\rm p} = \pm 0.89$ with an overall accuracy $\Delta P_{\rm p}/P_{\rm p} = 2.8\%$. The data, collected in 1996 with the high-energy muon beam of the CERN SPS, complement earlier data taken in 1993 at the same beam energy using butanol [2,3] and improve our statistical precision by approximately by a factor of two.

The beam polarization was determined by measuring the cross-section asymmetry for the scattering of polarized muons on polarized atomic electrons [3,4]. For the beam of 190 GeV nominal energy, the average energy at the interaction vertex is 188 GeV, the polarization at this energy is $P_\mu = -0.77 \pm 0.03$.

When calculating $A_\parallel^{\rm p}$ we have to account for the contribution of polarized Nitrogen to the longitudinal asymmetry. In the shell model [5], Nitrogen is described as a spinless ^{12}C core with a valence proton and neutron responsible for the Nitrogen spin. The correction, expressed [6] in terms of the measured deuteron asymmetry $A_1^{\rm d}$ [7], was found to be up to 3% of $A_{\parallel}^{\rm p}$ and introduced a negligible systematic uncertainty.

The cross section longitudinal spin asymmetry for parallel and antiparallel configurations of beam and target polarizations $A_{\parallel}^{\rm p} = (\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow})/(\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow})$ is related to the virtual-photon proton asymmetries $A_1^{\rm p}$ and $A_2^{\rm p}$ by $A_{\parallel}^{\rm p} = D(A_1^{\rm p} + \eta A_2^{\rm p})$. The spin-dependent structure function $g_1^{\rm p}$ is given by $g_1^{\rm p} = \frac{F_2^{\rm p}}{2x(1+R)}(A_1^{\rm p} + \gamma A_2^{\rm p})$. The coefficients η and γ depend only on kinematic variables, the depolarization factor D depends, in addition, on the ratio of total photoabsorption cross sections for longitudinally and transversely polarized virtual photons $R = \sigma_{\rm L}/\sigma_{\rm T}$ [8,9].

In the kinematic region of our measurement, $A_2^{\rm p}$, η and γ are small, we therefore neglect the terms proportional to $A_2^{\rm p}$ in the expression of $g_1^{\rm p}$. We use

$$A_1^{\rm p} = (1+\gamma^2)\frac{g_1^{\rm p}}{F_1^{\rm p}} = 2x(1+R)\frac{g_1^{\rm p}}{F_2^{\rm p}} \tag{1}$$

The systematic uncertainty due to a possible residual $A_2^{\rm p}$ contribution is estimated using the SMC [10] and the E143 [31] measurements. The analysis is limited to the kinematic region with $x \geq 0.0008$ and $Q^2 \geq 0.2$ GeV^2. After applying suitable cuts to the data, 9.6×10^6 events remain for the final analysis from the 1996 measurement. The new results are in agreement with the 1993 data within the statistical error. The combined results for $A_1^{\rm p}$ are shown as a function of x and Q^2 in Fig. 1 along with the E143 [28] measurements. No Q^2 dependence of A_1 is visible within the accuracy of the present data.

Figure 2 shows $A_1^{\rm p}$ averaged over Q^2 as a function of x and compared to our 1993 results. The dominant systematic errors at low x are due to radiative corrections, time-dependent variation of the acceptance ratio for events from the upstream and the downstream target cells and uncertainties in $A_2^{\rm p}$. At large x, the dominant sources of systematic errors are uncertainties in the the ratio R and in the beam and target polarizations.

We compute $g_1^{\rm p}$ for data with $Q^2 \geq 1$ GeV^2 using Eqn. 1. In our previous publications we have used F_2 and R parameterization from NMC [13] and SLAC [14] respectively. Use of these suffers from the drawback that none of these measurements really extended in to the low x region that SMC explores. As such we had to extrapolate their parameterizations into such low x regions. Recently, new $F_2^{\rm p}$ data at smaller x became available from NMC [15], E665 [16], H1 [17] and ZEUS [18]. We performed a new fit of $F_2^{\rm p}$ which includes these new data, the data from SLAC [19], from NMC [13] and BCDMS [20] and covers the kinematic range $3.5 \times 10^{-5} < x < 0.85$ and $0.2 < Q^2 < 5000$ GeV^2. We use the same functional as used for the previous parametrization provided by NMC [13]. As in our previous publications we use for R in the high x region the SLAC parametrization [14]. For $x < 0.12$ we now use the R parametrization by NMC [15].

Figure 3 shows the $g_1^{\rm p}$ calculated from our new 1996 data using the two consistent sets of parametrizations of F_2 and R, the resulting differences in the values of g_1^p are negligible compared to the statistical uncertainties in the

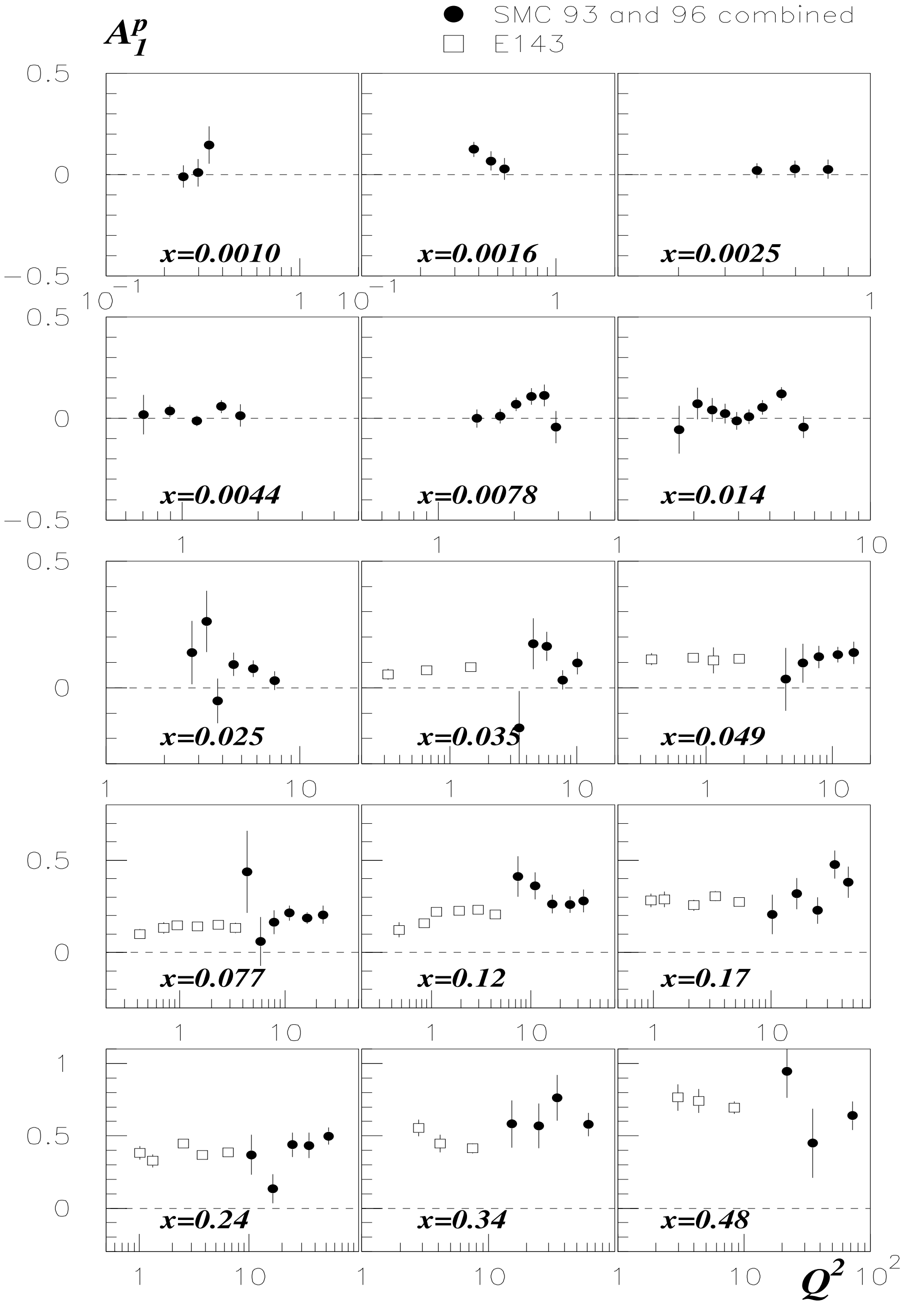

FIGURE 1. $A_1^{\rm p}$ as a function of Q^2 for different x bins for SMC 93+96 data compared to the E143 data.

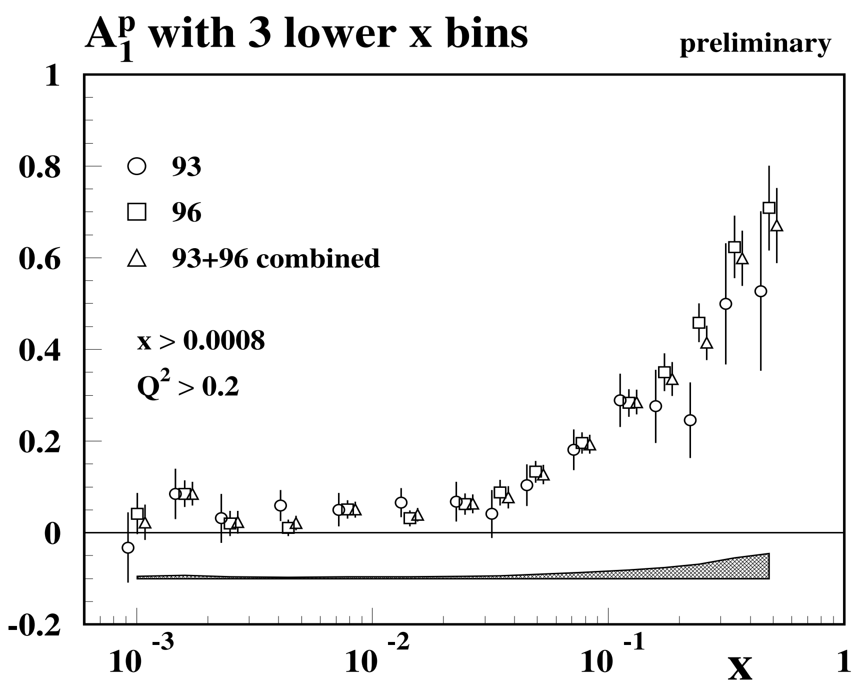

FIGURE 2. $A_1^{\rm p}$ versus x for SMC 93 and SMC 96

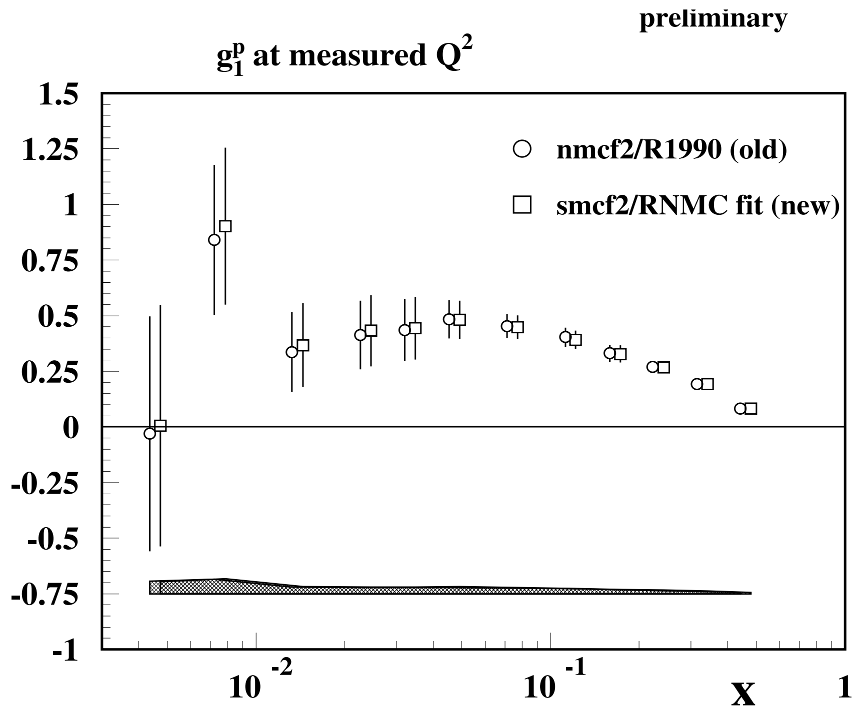

FIGURE 3. Comparison of $g_1^{\rm p}$ at measured Q^2 from SMC 1996 data using old and new F_2 and R parameterizations.

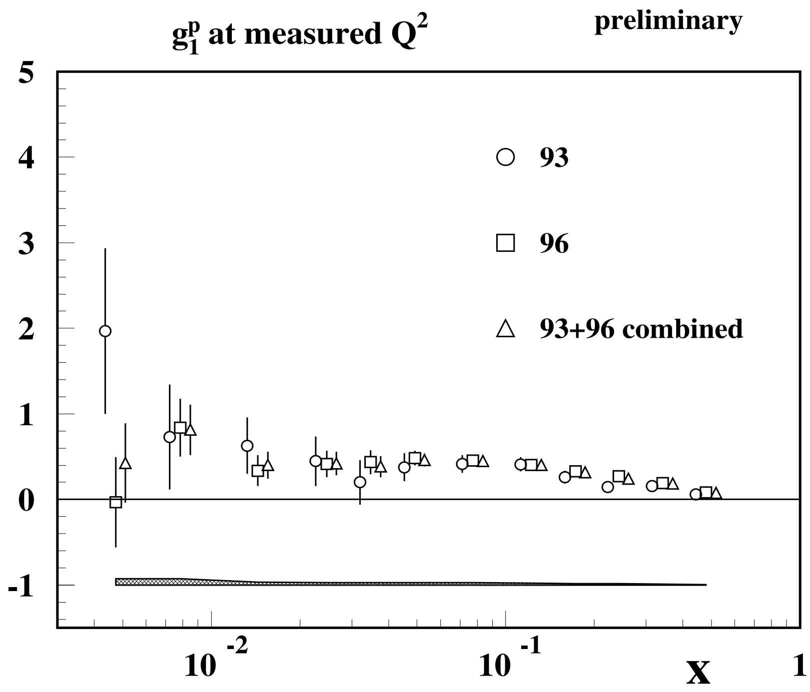

FIGURE 4. Comparison of g_1^p SMC 1993, 1996 and combined (1993 + 1996) data.

data. In Fig. 4 results for $g_1^{\rm p}(x)$ at the average Q^2 of each bin for 1996 data (open squares) are compared to our 1993 data (open circles). The new results agree with the previous ones, however they do not suggest a rise of $g_1^{\rm p}(x)$ at low x. The combined results are shown in same figure (open triangles).

We use our data in the kinematic region $Q^2 \geq 1$ GeV^2, $x \geq 0.003$ to evaluate $\Gamma_1^{\rm p}$ at a fixed Q^2 and to test the spin sum rules. Although no explicit Q^2 dependence of the asymmetry $A_1^{\rm p}$ ($\sim g_1/F_1$) is observed within the errors, different Q^2 behaviors of g_1 and F_1 are expected from perturbative QCD [21]

The Q^2 dependence of g_1 is estimated by a pQCD analysis [21] using DGLAP evolution equations [22,23] and QCD splitting and coefficient functions [24] at next-to-leading order (NLO) in the Adler–Bardeen (AB) factorization scheme [21]. We decompose the structure functions g_1 of the proton and of the neutron into a polarized quark singlet $\Delta\Sigma(x)$, quark nonsinglet $\Delta q_{\rm NS}^{\rm p}(x)$ and $\Delta q_{\rm NS}^{\rm n}(x)$ for proton and neutron respectively, and gluon $\Delta g(x)$ distributions. These four distributions Δf_j are parametrized at $Q^2 = 1$ GeV^2 as

$$\Delta f_j(x) = \eta_j N(\alpha_j, \beta_j, a_j) x^{\alpha_j}(1-x)^{\beta_j}(1+a_j x) \qquad (2)$$

The normalization factor N is fixed such that the parameter η_j is the first moment of the respective parton distribution, $\eta_j = \int_0^1 \Delta f_j(x) {\rm d}x$. For the proton and neutron non singlet distributions this first moment is known in terms of the flavor SU(3) coupling constants F and D, for which we use

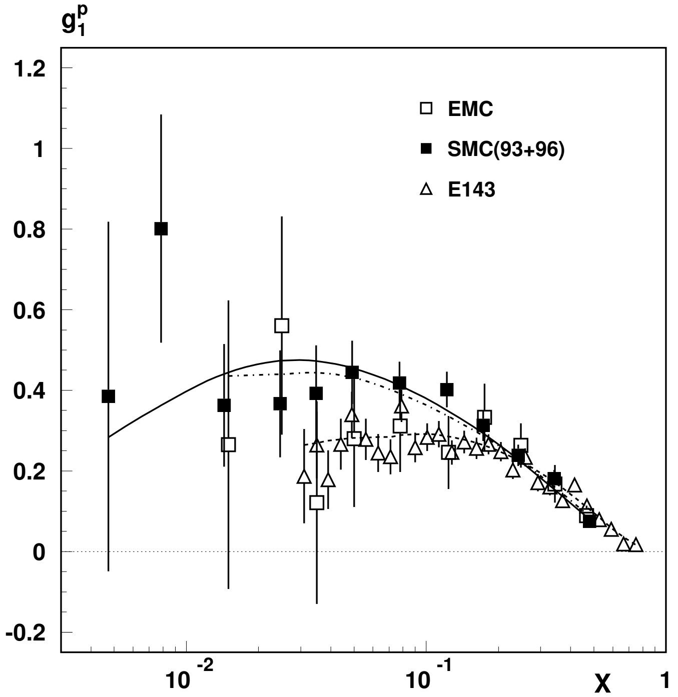

FIGURE 5. QCD fit to the world proton data

$F + D = g_A/g_V = 1.2601 \pm 0.0025$ [25] and $F/D = 0.575 \pm 0.016$ [26]. For the strong coupling constant, we use $\alpha_s(m_Z^2) = 0.118 \pm 0.003$ [25]. Since β_g is poorly constrained we set it to 4.0 as suggested by QCD counting rules [27]. In addition we set $a_g = a_{NS}^{p} = a_{NS}^{n} = 0$ since the QCD fit results in these parameters being consistent with zero and have large uncertainties. To determine the parameters of the parton distribution at $Q^2 = 1$ GeV^2 we evolve them to the Q^2 of the measurements, construct g_1 which is then fit to the data. In addition to the new data presented in this paper with $Q^2 > 1$ GeV^2 we use all the published data having $Q^2 \geq 1$ GeV^2 on proton, deuteron and neutron: SMC previous publications [3] and [7], the EMC [8], the SLAC [28–30,33] and the HERMES [34]. With 10 free parameters, the χ^2 of the fit is 97.5 for 123 degrees of freedom. The result of the fit for proton is shown in Fig. 5.

Starting from $g_1(x, Q^2)$ at the measured x and Q^2 of our experiment we obtain g_1 at a fixed Q_0^2 as follows:

$$g_1(x, Q_0^2) = g_1(x, Q^2) + [g_1^{\rm fit}(x, Q_0^2) - g_1^{\rm fit}(x, Q^2)],$$

where $g_1^{\rm fit}(x, Q_0^2)$ and $g_1^{\rm fit}(x, Q^2)$ are the values of g_1 evaluated at Q_0^2 and the Q^2 of the experimental measurement using the best fit parameters. We choose $Q_0^2 = 10$ GeV^2 which is close to the average Q^2 of our data. The uncertainty in the QCD evolution is evaluated and includes the uncertainties in the renormalization and factorization scales, the uncertainties in the assumed form of the initial polarized parton distributions at $Q_0^2 = 1$ GeV^2, the uncertainty in the quark mass thresholds, the uncertainties in the values of α_s, g_A, a_8 and the statistical and systematic errors of the input data used in the QCD analysis. One variable of particular interest is the first moment of the gluon distribution η_g. The QCD analysis and the error analysis presented here results in $\eta_g = 0.9 \pm 0.3(exp.) \pm 0.8(theo.)$ at $Q^2 = 1$ GeV^2. The theoretical uncertainties in the determination of $\eta_g = \Delta g$ are too large to make any definite statement on the sign of this quantity.

In the measured range $0.003 < x < 0.7$, the contribution to the first moment of the proton structure function is

$$\int_{0.003}^{0.7} g_1^p(x, Q_0^2)dx = 0.145 \pm 0.006 \pm 0.009 \pm 0.005 \qquad (Q_0^2 = 10 \text{ GeV}^2)$$

where the first uncertainty is statistical, the second is systematic and the third is due to the uncertainty in Q^2 evolution. To estimate the contribution to the first moment from the unmeasured high x region $0.7 < x < 1.0$, we assume $A_1^p = 0.7 \pm 0.3$ which is consistent with the data as well as with the bound $A_1 \leq 1$, it gives

$$\int_{0.7}^{1} g_1^p(x, Q_0^2)dx = 0.0015 \pm 0.0007$$

To estimate the contribution from the unmeasured low x region, we assume $g_1^p =$ constant at 10 GeV^2, consistent with Regge behavior $g_1^p \propto x^{-\alpha}$ $(-0.5 < \alpha < 0.0)$. This constant obtained from the 3 lowest x data points evolved to 10 GeV^2 leads to

$$\int_{0.0}^{0.003} g_1^p(x, Q_0^2)dx = 0.0028 \pm 0.0010 \quad \text{(Regge low x)}$$

where the error is the precision of the fit. However, we assign 100% uncertainty i.e. ± 0.0028, to this extrapolation.

The corresponding values for the first moment of g_1^p over the entire x range at $Q_0^2 = 10\text{GeV}^2$ is

$$\int_{0}^{1} g_1^p(x, Q_0^2 = 10\text{GeV}^2) = 0.149 \pm 0.006 \pm 0.009 \pm 0.005 \quad \text{(Regge low x)}$$

Assuming SU(3)$_f$ within the baryon octet [35] we determine the flavor singlet axial charge $a_0(Q^2) = a_u + a_d + a_s$ of the nucleon using the experimentally determined first moment of the proton from the equation

$$\Gamma_1^p(Q^2) = \frac{C_1^{NS}(Q^2)}{12}\left[a_3 + \frac{a_8}{3}\right] + \frac{C_1^S(Q^2)}{9} a_0(Q^2).$$

For a_3 and a_8 we take values calculated from the experimental measurements of g_A/g_V and F/D. The singlet and non-singlet coefficient functions C_1^S and C_1^{NS} have been calculated to 3rd and 4th order in α_s [36] respectively. Using the SMC proton data alone we get the value of a_0 and a_s to be 0.41 ± 0.11 and -0.06 ± 0.04 respectively. Combining this with our deuteron data they become 0.33 ± 0.07 and -0.08 ± 0.03 respectively. Both numbers point to clear violation of the Ellis-Jaffe sum rule.

In order to test the Bjorken sum rule, we calculate $\Gamma_1^{\rm n}$ from our deuteron data [7] using the relation $(\Gamma_1^{\rm p} + \Gamma_1^{\rm n}) = 2\Gamma_1^{\rm d}/(1 + 1.5\omega_D)$. We get $\Gamma_1^{\rm n} = -0.046 \pm 0.021$ at $Q^2 = 10$ GeV^2. For the Bjorken integral we get $\Gamma_1^{\rm p} - \Gamma_1^{\rm n} = 0.211 \pm 0.026$ which is in excellent agreement with the theoretical prediction of 0.187 ± 0.002 at $Q^2 = 10$ GeV^2.

An alternative method, presently under study, uses the QCD fit to calculate the low x contribution to the first moment of the structure function. Figure 6 and its inset show the $xg_1^{\rm p}$ vs. x at $Q_0^2 = 10$ GeV^2. The SMC data points (open squares) with the QCD fit (continuous line) are shown. In the region $x < 0.003$ the dot dashed line shows the Regge assumption discussed before. The dashed line indicates the calculation of the QCD best fit in this region. Note that the contribution to the first moment from this region assuming $g_1^{\rm p}$ behavior consistent with QCD gives a large negative contribution: -0.011 ± 0.010 (Preliminary). Detailed considerations of this approach and the theoretical uncertainties are in progress. Initial indications are that all conclusions regarding the spin sum rules based on the Regge type of low x behavior of the spin structure functions also hold in this approach. The behavior of the spin structure function in the region ($x < 0.003$) is however undetermined and will have to be explicitly measured in future experiments.

In summary, we have made a new measurement of the structure function g_1^p in the kinematic region $1 < Q^2 < 100$ GeV^2 and $0.003 < x < 0.7$. When combined with our old data this results in a factor ~ 2 reduction in the statistical uncertainty in $g_1^{\rm p}$. Following an analysis similar to the one in our previous publications we find that our data are in excellent agreement with Bjorken sum rule prediction. We note that the determination of the first moment of the structure function depends critically on the assumptions made for the behavior of the structure functions in low x unmeasured region. This uncertainty can only be reduced by direct measurements in this region. Further studies related to the effect of different assumptions in the low x region on the spin sum rules and other physical quantities are in progress.

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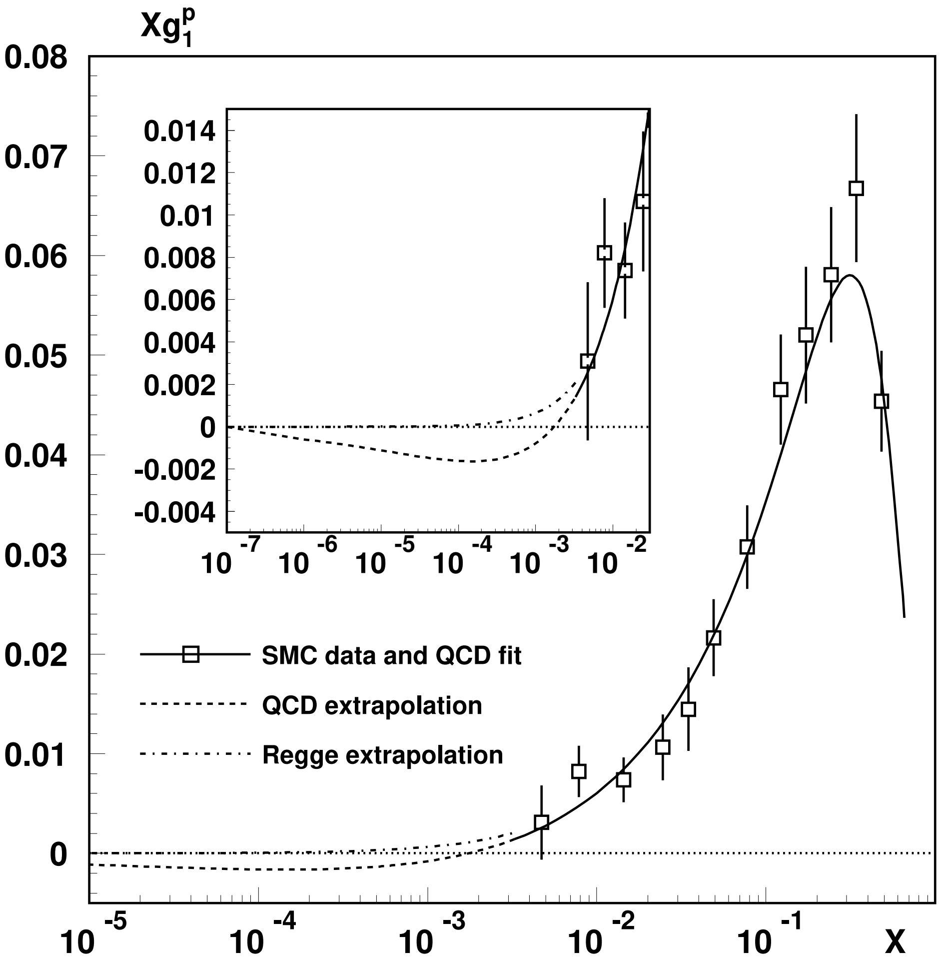

FIGURE 6. $xg_1^{\rm p}$ vs. x at $Q^2 = 10$ GeV^2. The SMC data are shown with the QCD fit (solid line), the low x extrapolation assuming Regge behavior in the region $x < 0.003$ is is always positive (dot dashed line), while the contribution to the first moment assuming a QCD-consistent behavior (dashed line) gives a large negative contribution. The inset shows the low x region in more detail.

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