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SPIN STRUCTURE FUNCTIONS *

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ABSTRACT

We review the theory and phenomenology of deep inelastic polarized lepton-nucleon scattering in the light of recent data with a deuteron target from the SMC at CERN and a Helium 3 target from the E142 experiment at SLAC. After including higher-order perturbative QCD corrections, mass corrections and updated estimates of higher-twist effects, we find good agreement with the basic Bjorken sum rule, and extract a consistent set of values for the quark contributions to the proton spin:

$$\Delta\Sigma \equiv \Delta u + \Delta d + \Delta s = 0.27 \pm 0.11$$

$$\Delta u = 0.82 \pm 0.04 \;, \quad \Delta d = -0.44 \pm 0.04 \;, \quad \Delta s = -0.11 \pm 0.04$$

which are consistent with chiral soliton models and indications from lattice estimates. We also mention the prospects for future experiments on the spin structure of the nucleon.

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1. Introduction

Polarized lepton-nucleon scattering is characterized by two spin-dependent structure functions $G_{1,2}$, as follows:

$$\frac{d^2\sigma^{\uparrow\downarrow}}{dQ^2 d\nu} - \frac{d^2\sigma^{\uparrow\uparrow}}{dQ^2 d\nu} = \frac{4\pi\alpha^2}{Q^2 E^2}\left[M_N(E + E'\cos\theta)G_1(\nu, Q^2) - Q^2 G_2(\nu, Q^2)\right] \quad (1)$$

According to the naïve parton model, these structure functions have simple scaling behaviours in the Bjorken scaling limit

$$x = \frac{Q^2}{2M_N\nu} \quad \text{fixed}, \quad Q^2 \to \infty \quad (2)$$

given by

$$\begin{aligned} \frac{\nu}{M_N^2} G_1(\nu, Q^2) &\equiv g_1(x, Q^2) \to g_1(x) \\ \left(\frac{\nu}{M_N^2}\right)^2 G_2(\nu, Q^2) &\equiv g_2(x, Q^2) \to g_2(x) \end{aligned} \quad (3)$$

These scaling structure functions can be related to the distributions of quarks with spins parallel and antiparallel to that of the target nucleon

$$\begin{aligned} g_1^p(x) &= \frac{1}{2}\sum_q \; e_q^2[q_\uparrow(x) - q_\downarrow(x) + \bar{q}_\uparrow(x) - \bar{q}_\downarrow(x)] \quad (4) \\ &= \frac{1}{2}\sum_q \; \Delta q(x) \end{aligned}$$

For comparison, in the Bjorken scaling limit the unpolarized structure function can be written as

$$F_2(x) = \sum_q e_q^2 x[q_\uparrow(x) + q_\downarrow(x) + \bar{q}_\uparrow(x) - \bar{q}_\downarrow(x)] \quad (5)$$

Polarized lepton-nucleon scattering experiments actually measure the polarization asymmetry

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \quad (6)$$

where $\sigma_{3/2}$ and $\sigma_{1/2}$ are the cross-sections for scattering with the spin of the photon parallel and antiparallel to the spin of the longitudinally-polarized nucleon. In the Bjorken scaling limit, the polarization asymmetry in Eq. (6) can be written as

$$A_1(x) = \frac{\sum_q \; e_q^2 \; [q_\uparrow(x) - q_\downarrow(x) + \bar{q}_\uparrow(x) - \bar{q}_\downarrow(x)]}{\sum_q \; e_q^2 \; [q_\uparrow(x) + q_\downarrow(x) + \bar{q}_\uparrow(x) + \bar{q}_\downarrow(x)]} \quad (7)$$

Thus the asymmetry measurements in polarized lepton-nucleon scattering experiments must be combined with independent measurements of the unpolarized structure functions in other experiments in order to extract $g_{1,2}$, as we discuss later.

Much of the interest in deep inelastic polarized lepton-nucleon scattering arises from its relationship to axial current matrix elements. Neglecting for the moment perturbative QCD complications in the singlet axial current sector, one can represent the different quark axial currents matrix elements as follows:

$$\langle p|A^q_\mu|p\rangle = \langle p|\bar{q}\gamma_\mu\gamma_5 q|p\rangle = \langle p|\bar{q}_R\gamma_\mu q_R - \bar{q}_L\gamma_\mu q_L|p\rangle = \Delta q \cdot S_\mu(p) \tag{8}$$

where $q_{L,R} \equiv 1/2(1 \mp \gamma_5)q$, S_μ is the nucleon spin four-vector, and

$$\Delta q \equiv \int_0^1 dx[q_\uparrow(x) - q_\downarrow(x) + \bar{q}_\uparrow(x) - \bar{q}_\downarrow(x)] \tag{9}$$

of particular interest is the flavour-singlet axial current

$$A^0_\mu = \sum_{q=u,d,s} \bar{q}\gamma_\mu\gamma_5 q : \qquad \langle p|A^0_\mu|p\rangle = \sum_{q=u,d,s} \Delta q \cdot S_\mu(p) \tag{10}$$

where $\Delta\Sigma \equiv \sum_q \Delta q$ is naïvely interpreted as the sum of the quark contributions to the proton spin.

It is worthwhile to recall here the general spin decomposition of the proton

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \Delta G + \langle L_z\rangle \tag{11}$$

where the three terms on the right-hand side represent the contributions of quarks, gluons and orbital angular momentum to the proton helicity in the infinite momentum frame, loosely referred to simply as the proton spin. We note in passing that the contribution of L_z is not negligible in nuclei such as the deuteron and ^{3}He, as we shall discuss in more detail later on.

The first pieces of experimental information about the Δq came from charged-current weak interactions. In particular, neutron β-decay, together with an innocent $SU(2)$ isospin transformation, leads to[1]

$$\Delta u - \Delta d = F + D = 1.2573 \pm 0.0028 \tag{12}$$

where F and D are the two independent irreducible matrix elements of the axial currents in $SU(3)_f$. Hyperon β-decays, together with a somewhat less innocent $SU(3)$ flavour transformation yield[2]

$$\frac{\Delta u + \Delta u - 2\Delta s}{\sqrt{3}} = \frac{3F - D}{\sqrt{3}} = 0.34 \pm 0.02 \tag{13}$$

We note in passing that the same hyperon β-decays yield

$$F/D = 0.58 \pm 0.02 \tag{14}$$

to be compared with the values of 2/3 in the naïve constituent quark model and 5/9 in chiral soliton model.

As we shall see, equations (11) and (12) together provide two equations for the three unknowns $\Delta u, \Delta d$ and Δs. As we shall discuss in more detail later on, polarized lepton-nucleon scattering provides a third equation which enables $\Delta u, \Delta d$ and Δs to be determined. However, it is interesting to observe[3,4] that there is an alternative source of the third equation. Elastic $\overset{(-)}{\nu}\ p \to \overset{(-)}{\nu}\ p$ scattering depends on the Z^0 coupling to the proton, which has a piece proportional to the axial current $\bar{u}\gamma_u\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d - \bar{s}\gamma_\mu\gamma_5 s$. Thus, the axial Z^0 coupling in the $Q^2 \to 0$ limit measures the combination $\Delta u - \Delta d - \Delta s$. The experimental data presently available[5] enable only a rough estimate to be made:

$$\Delta s = -0.15 \pm 0.09 \tag{15}$$

but a new, high-precision experiment is now being prepared, which should enable Δs to be measured with an accuracy of ± 0.03 (syst.) ± 0.03 (stat.) [6]

Deep-inelastic polarized lepton-nucleon scattering should obey certain sum rules, of which the most basic is that derived by Bjorken[7]

$$\int_0^1 dx \Big[g_1^p(x,Q^2) - g_1^n(x,Q^2) \Big] = \frac{1}{6}(\Delta u - \Delta d) \times \left(1 - \frac{\alpha_s(Q^2)}{\pi}\right) + \ldots \tag{16}$$

where we have indicated explicitly the leading-order perturbative QCD correction and the dots represent subasymptotic corrections, which will be discussed in more detail later. This sum rule, derived by Bjorken in the late 1960's, was the original motivation for scaling in the Bjorken limit. It is an essential prediction of QCD,[8] and all QCD theorists would have to eat their collective hat it if turned out to be violated.

It is possible to derive additional sum rules only by making further dynamical assumptions. Precisely because such additional assumptions are necessary, the theoretical foundation of such additional sum rules is much less firm than that of the Bjorken sum rule. Specifically, it was proposed in Ref. [9] that $\Delta s = 0$, in which case

$$\int_0^1 dx\ g_1^p(x,Q^2) = \frac{1}{18}(4\Delta u + \Delta d)\ \left(1 - \frac{\alpha_s(Q^2)}{\pi}\right) + \ldots \quad = 0.17 \pm 0.01 \tag{17}$$

at $Q^2 = 10.7$ GeV^2. The assumption of Ref. [9] was based on intuition provided by the naïve constituent quark model. It seemed reasonable at the time to assume that there were no strange quarks in the proton, and if there were, that surely they would have no net polarization. The original motivation for writing down the sum rule was that a new generation of experiments with polarized beam and target was about to start at SLAC, and it would be helpful to have some qualitative idea of what could be seen in those experiments. Nowadays, we are clear that this sum rule is not a fundamental test of QCD, but depends on an assumption about a non-perturbative hadronic matrix element, that could be and indeed seems to be wrong.

2. Polarized Proton Data

Pioneering experiments were carried out in 1976-1983 by a SLAC-Yale collaboration,[10,11,12] yielding the estimate

$$\int_0^1 g_1^p(x,Q^2) = 0.17 \pm 0.05 \tag{18}$$

This result was inconclusive as a test of the sum rule in Eq. (16), because of the large error bars, a large part of which was due to the extrapolation to $x = 0$. The next round came in 1987, with the EMC result[13,14]

$$\int_0^1 g_1^p(x,Q^2) = 0.126 \pm 0.010 \text{ (syst.) } \pm 0.015 \text{ (stat.)} \ , \quad \langle Q^2 \rangle = 10.7 \text{ GeV}^2 \tag{19}$$

which is significantly different from the prediction of Ref. [9] evaluated in Eq. (17) with the updated values of F and D, in (12) and (13). This experiment actually measured polarized muon-proton scattering over the range $0.01 < x < 0.7$, extending down to lower values of x than in the SLAC-Yale experiments. The EMC data showed a substantial deviation at low x from the predictions of some theoretical models that had been assumed by the SLAC-Yale collaboration. However, the EMC behaviour at low x is consistent with expectations based on Regge behaviour

$$g_1^p(x) \simeq \sum_i x^{-\alpha_i(0)} \beta_i^\gamma \beta_i^N \tag{20}$$

where β_i^γ and β_i^N are the couplings to the photon and nucleon of the i-th Regge trajectory, and the $\alpha_i(0)$ are the corresponding Regge intercepts. A knowledge of meson spectra and exchanges leads us to expect[15] $\alpha_i(0) \simeq 0$ to -0.5, whilst a fit to the low-x region of the EMC data yields[3]

$$g_1^p \sim x^{-\delta} : \quad \delta = -0.07^{+0.42}_{-0.32} \ \text{ for } \ x < 0.2 \tag{21}$$

This consistency gives us no reason to doubt the EMC value of the sum rule shown in Eq. (19). One would expect similar low-x behaviour in the neutron structure function.

The EMC polarized muon-proton data provide a third equation

$$\frac{1}{2}\left(\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right)\left(1 - \frac{\alpha_s(Q^2)}{\pi}\right) + \ldots = 0.126 \pm 0.010 \text{ (syst.) } \pm 0.015 \text{ (stat.)} \tag{22}$$

with which we can determine[16,13] the three quark contributions to the proton spin

$$\begin{aligned} \Delta u &= \ \ 0.78 \pm 0.06 \\ \Delta d &= -0.47 \pm 0.06 \\ \Delta s &= -0.19 \pm 0.06 \end{aligned} \tag{23}$$

We see that $\Delta s \neq 0$, and the sum rule of Ref. [9] is clearly violated. Adding together the different contributions in Eq. (23), we find that the total contribution of quarks to the proton spin is

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.12 \pm 0.17 \tag{24}$$

which is consistent with zero. This has sometimes been referred to in the literature as the "spin crisis". This is an exaggeration. The result in Eq. (24) is certainly a surprise for our original naïve understanding of non-perturbative QCD, but does not conflict with any rigorous result of perturbative QCD.

3. Theoretical Interpretation

By now we are familiar with competing models of hadronic structure: the naïve constituent quark model on the one hand, and the chiral soliton models on the other hand. Certain aspects of baryon and nuclear phenomenology are better described by the former, and others by the latter class of models. Neither holds a monopoly of truth.

In the naïve non-relativistic quark model (NRQM) one thinks of the proton or neutron as a composite of three relatively heavy, slow-moving constituent quarks, with $m_{p,n} \simeq 3m_q$ and $m_q \simeq 300$ MeV. In particular, the spin of the proton or neutron is obtained by combining naïvely the spins of the three non-relativistic constituent quarks, which can be depicted schematically as

$$p, n^{\Uparrow} = q^{\Uparrow} q^{\Uparrow} q^{\Downarrow} \tag{25}$$

The NRQM yields good values for the anomalous magnetic moments of the proton and neutron, and has been very successful in describing hadron spectroscopy. However, the model can be justified rigorously in QCD only for very heavy quarks such as the b or t.

Other aspects of hadron physics, in particular the low-energy interactions of pions, are well described by approximate chiral symmetry, which would become exact if the quark masses in the underlying QCD Lagrangian were to vanish. The small physical value of the pion mass is related to the smallness of the u and d quark masses

$$m_\pi^2 = \langle 0|\bar{q}q|0\rangle \, \frac{m_u + m_d}{f_\pi^2} \tag{26}$$

The chiral symmetry picture can be extended to nucleons with the aid of the $1/N_c$ expansion,[17,18] an expansion in the inverse of the number of colours in QCD. This combination justifies a view of the nucleon as a soliton "lump" of light pseudoscalar meson fields[19,20,21] – a "skyrmion". This model gives good or acceptable values for the ratios of proton and neutron magnetic moments[20] and successful predictions[22,23] of meson-nucleon scattering phase shifts. In the Skyrme model, the proton wave function may be viewed as

$$|p\rangle \simeq V(t) U(r) V^{-1}(t) \; ; \quad U = \exp[iF(r)\hat{r}\cdot r] \tag{27}$$

where $V(t)$ is a time-dependent $SU(3)$ flavour matrix which represents a slow collective rotation in the flavour space. As it is based on an effective chiral Lagrangian, it is expected to be good for reproducing the "soft" (low momentum transfer) properties of nucleons, such as axial current matrix elements. According to this picture, the proton contains many relativistic quarks, and the angular momentum of the nucleon is due to the slow collective rotation of the soliton, parametrized by $V(t)$ in (27). As was pointed out in Ref. [24], it is a general feature of such chiral soliton models that the nucleon matrix elements of the flavour-singlet axial current Eq. (8) are identically zero, implying that the net contribution of quarks to the proton or nucleon spin vanishes,

$$\langle N|A^0_\mu|N\rangle = 0 \quad \Longrightarrow \quad \Delta\Sigma = \sum_q \Delta q = 0 \tag{28}$$

This result follows directly from the topology of the flavour group manifold, and has nothing to do with the perturbative $U(1)$ axial anomaly of Eq. (30) below. In the Skyrme model and its simple extensions there are no gluons, and therefore $\Delta G = 0$ identically. Thus the angular momentum sum rule of Eq. (17) becomes[3]

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(=0) + \Delta G(=0) + \langle L_z\rangle \; (=\frac{1}{2}) \tag{29}$$

in such chiral soliton models. Of course, orbital angular momentum can only take integer values in any given parton state, so that the statement $L_z = 1/2$ refers to the expectation value of the orbital angular momentum carried by the quarks, after appropriate statistical weighting of all the states contributing to the proton wave function. The fact that L_z is not an integer in such a strongly-coupled system should not come as a surprise. After all, even in the weakly-bound deuteron there is a 5 % admixture of the D-wave in the nuclear wave function. The prediction Eq. (29) is valid in the large-N_c limit and for massless quarks. We expect in general corrections coming from $1/N_c$ terms and from finite quark masses, especially the strange quark mass, $m_s \simeq 150$ MeV $\simeq \Lambda_{QCD}$. Estimates indicate[24,25,26] that these could modify the prediction of Eq. (29) by $\lesssim 30$ %.

We would like to emphasize that the above-mentioned soliton picture of the nucleon is not necessarily in conflict with the NRQM. The fact that $\Delta s \neq 0$ experimentally (23) and Eq. (24) could be reconciled with the NRQM if constituent quarks have internal structure.[27,28,29,30,31] It is possible to model this structure in a type of chiral model where the chiral field carries both flavour and colour.[28,30,31] The constituent quarks then emerge as solitons in such a chiral model, just as the nucleon emerges as a soliton in the usual chiral Lagrangian. It is also possible to model the chiral constituent quarks in the Nambu-Jona-Lasinio model, with similar results.[32]

Shortly after the EMC results were published, an important theoretical observation was made.[33,34,35] Consider the flavour-singlet axial current A^0_μ. This current is conserved at the classical level if one neglects the small current quark masses, just like the flavour non-singlet currents. However, it has a non-zero divergence at the quantum level, due to the one-loop triangle anomaly

$$\partial^\mu A^0_\mu = \frac{\alpha_s}{\pi} \; N_f \; \mathrm{tr} \; F_{\mu\nu}\tilde{F}^{\mu\nu} \; , \quad \tilde{F}^{\mu\nu} \equiv \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta} \tag{30}$$

where $F_{\mu\nu}$ is the gauge field strength tensor in QCD. The intuitive meaning of Eq. (30) is that the anomaly induces a mixing between gluons and the flavour-singlet axial current of quarks. For this reason, the helicities carried by each flavour $\Delta u, \Delta d$ and Δs undergo additive renormalization,

$$\begin{aligned} \Delta u &\longrightarrow \widetilde{\Delta u} = \Delta u - (\alpha_s/2\pi)\Delta G \\ \Delta d &\longrightarrow \widetilde{\Delta d} = \Delta d - (\alpha_s/2\pi)\Delta G \\ \Delta s &\longrightarrow \widetilde{\Delta s} = \Delta s - (\alpha_s/2\pi)\Delta G \end{aligned} \tag{31}$$

Despite appearances, these corrections are *not* suppressed by a power of α_s. The reason is that $\Delta G \sim \log Q^2$. Whereas α_s decreases as Q^2 increases, ΔG increases, and the product $\Delta\Gamma \equiv (\alpha_s/2\pi)\Delta G$ is Q^2-independent in leading order. Recall also that, since the ΔG term is the same for all flavours, it does not contribute to flavour non-singlet matrix elements, for example $\widetilde{\Delta u} - \widetilde{\Delta d} = \Delta u - \Delta d$.

Some physicists have proposed[34] that this effect could rescue the NRQM intuition, by making $\Delta s = 0$ compatible with experiment. This is possible in principle, because experiment only tells us the value of $\widetilde{\Delta s}$. If ΔG were large enough, one could have $\Delta s = 0$, with the observed non-zero value of $\widetilde{\Delta s}$ induced by the gluon term alone. However, this would require $\Delta G \simeq 4$ (in units of $\hbar$) at $Q^2 = 10$ GeV^2, which seems rather unlikely. The angular momentum sum rule of Eq. (17) would then read

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta q + \Delta G(\simeq 4) + \langle L_z \rangle \quad (\simeq -4) \tag{32}$$

which is rather counter-intuitive. On top of this, the anomaly interpretation has to face an additional difficulty. A detailed calculation of the relevant box diagram shows[36] that the contribution of ΔG to the first moments of $\Delta q(x)$ tends to concentrate at low values of x. Since the EMC experiment covers only a limited range of x, the contribution of gluon polarization to the *observed* Δq is actually much smaller than suggested by Eq. (32), and hence an even larger value of ΔG is required.

We stress again that the chiral soliton model and the anomaly interpretation of the EMC data are two physically distinct possibilities. The former is based on the topology of the $SU(3)$ flavour group, whereas the latter is based on quantum breakdown of the classical $U_A(1)$ symmetry. It is possible in principle to distinguish between them by measuring the gluon polarization in the nucleon. The required experiments are difficult, but are within the reach of current experimental techniques.

4. Analysis of New Data[37]

When attempting to check experimentally a QCD prediction for a sum rule, one has to deal with the following problem, due to a very basic mismatch between the theory and what is actually measured. Theoretical predictions for sum rules are always formulated at a fixed value of Q^2. A generic sum rule in QCD typically reads

$$\Gamma(Q^2) = \Gamma_\infty \left[1 + \sum_{n\geq 1} c_n \left(\frac{\alpha_s(Q^2)}{\pi}\right)^n\right] + \sum_{m\geq 1} \frac{d_m}{(Q^2)^m} \tag{33}$$

where Γ_∞ is the asymptotic value of the sum rule for $Q^2 \to \infty$, the c_n are the coefficients of the perturbative corrections, and the d_m are coefficients of the so-called mass and higher-twist corrections. On the other hand, in a typical experiment, data are taken at *variable* values of Q^2, with a significant and monotonic correlation between the range of Q^2 and the value of x, as shown schematically in Fig. 1. This results from the finite kinematical range of any given experiment. Moreover, as has already been mentioned, polarized lepton-nucleon scattering experiments measure directly the polarization asymmetry defined in Eq. (6), rather than the polarized structure functions shown in Eq. (1).

To overcome this limitation and correct simultaneously for the above-mentioned x-dependence of the range of Q^2, it is convenient to use the experimental fact[13,14] that $A_1(x, Q^2)$ seems approximately independent of Q^2, and reconstruct the polarized structure function $g_1(x, Q^2)$ using

$$g_1(x, Q^2) = \frac{A_1(x, Q^2) F_2(x, Q^2)}{2x[1 + R(x, Q^2)]} \simeq \frac{A_1(x) F_2(x, Q^2)}{2x[1 + R(x, Q^2)]} \tag{34}$$

where $R(x, Q^2)$ is the ratio of longitudinal to transverse virtual photon cross-sections. One can take $F_2(x, Q^2)$ and $R(x, Q^2)$ from previous high-precision parametrizations of unpolarized data. Equation (34) and the assumption of Q^2-independence of A_1 imply that the Q^2 dependence of $g_1(x, Q^2)$ is determined by the Q^2-dependences of $F_2(x, Q^2)$ and of $R(x, Q^2)$. In particular, the higher-twist effects well known to occur in F_2 and R at low Q^2 will show up in g_1. Clearly, the approximation of Eq. (34) is most reliable at $Q^2 = \langle Q^2 \rangle$, but we will also need to make the same assumption at other values of Q^2, in order to combine the proton and neutron data, which have been taken at different values of Q^2.

The procedure of Eq. (34) has been used previously by the EMC to interpret their polarized μ-p data. Now one must reevaluate those asymmetry data, incorporating more recent parametrizations of $F_2(x, Q^2)$ by the NMC,[38] and of $R(x, Q^2)$ from SLAC.[39] We use these to evaluate

$$\Gamma_1^p(Q^2) \equiv \int_0^1 dx\; g_1^p(x, Q^2) \tag{35}$$

at different values of Q^2 as seen below

$$\begin{array}{cc} Q^2(\mathrm{GeV}^2) & \Gamma_1^p(Q^2) \\ & \\ 2.0 & 0.124 \\ 4.6 & 0.125 \\ 10.7 & 0.128 \end{array} \left.\vphantom{\begin{array}{c}1\\1\\1\end{array}}\right\} \quad \pm 0.013 \pm 0.019 \tag{36}$$

The first two values of Q^2 are chosen for comparison with the recent SMC data[40] at $\langle Q^2 \rangle = 4.6$ GeV^2 and E142 data[41] at $\langle Q^2 \rangle = 2$ GeV^2. The last value of Q^2 is that used previously by the EMC,[13,14] and our value of $\Gamma_1^p(Q^2 = 10.7$ GeV$^2)$ is well within the errors they originally quoted.

We apply the same procedure to re-interpret the E142 polarized e-^{3}He data,[41] interpreted as e-n asymmetry data after the nuclear structure corrections discussed below. When we rescale to fixed $Q^2 = 2$ GeV^2, using the NMC[38] and SLAC[39] parametrizations mentioned earlier, we find

$$\int_{0.03}^{0.6} dx \; g_1^n(x, Q^2{=}2 \text{ GeV}^2) = -0.022 \pm 0.006 \text{ (stat.)} \; \pm 0.006 \text{ (syst.)} \tag{37}$$

whose central value is again very close to that quoted by the E142 collaboration.

No experiment can measure the full range $0 \leq x \leq 1$, and every experiment must make some assumption in order to extrapolate to the full x range. Non-perturbative models of neutron structure suggest that $A_1^n(x) \to 1$ as $x \to 1$, but there is no indication of this from perturbative QCD. Therefore, we prefer to be agnostic and allow the asymmetry to vary within the possible kinematic range $|A_1^n(x)| \leq 1$. We then find a high-x contribution to Γ_1^n for the E142 experiment of

$$\Delta\Gamma_1^n = 0.000 \pm 0.003 \tag{38}$$

The extrapolation of the E142 data to $x = 0$ is *a priori* more uncertain than that of the SMC, because of a larger lower limit on x (0.03 to be compared with 0.006). Motivated by the polarized proton data discussed in Section 2, we assume the following plausible Regge form for the low-x extrapolation

$$g_1^n(x) = Ax^\alpha \quad : \quad 0 \leq \alpha \leq 0.5 \tag{39}$$

which yields a low-x contribution to the E142 integral of

$$\Delta\Gamma_1^n = -0.006 \pm 0.006 \tag{40}$$

Putting together Eqs. (37), (38) and (40), we arrive at the following final estimate of the polarized neutron integral at $Q^2 = 2$ GeV^2

$$\Gamma_1^n(Q^2{=}2 \text{ GeV}^2) = -0.028 \pm 0.006 \text{ (stat.)} \; \pm 0.009 \text{ (syst.)} \tag{41}$$

which is consistent within errors with the value quoted by the E142 collaboration.

In the case of the SMC experiment, which used the procedure (34) with up-to-date parametrizations of $F_2(x,Q^2)$ and $R(x,Q^2)$, we find

$$\Gamma_1^n(Q^2{=}4.6\ \mathrm{GeV}^2) = -0.076 \pm 0.046\ (\mathrm{syst.})\ \pm 0.037\ (\mathrm{stat.}) \tag{42}$$

The only difference from their published paper is due to the re-evaluation in Eq. (36) of the original EMC proton data, that are used in a subtraction.

Before using the above numbers, some comments are in order on the corrections due to the nuclear structure of ^{3}He and deuterium. Naïvely, one would view the ^{3}He nucleus as containing a pair of protons with paired spins, and an odd neutron which carries all the nuclear spin. However, a general description of the ^{3}He nuclear wave function contains 10 components. This can be simplified for most practical purposes to a three-component description with a D-wave component that varies between 8.6 and 9.8 % (a typical estimate and comprehensive discussion can be found in Ref. [42]) an S' component that varies in strength between 1.4 and 1.7 %, and the rest made up by the conventional S-wave component. The above numbers lead to the following plausible estimates for the mean polarizations of protons and neutrons in the ^{3}He nucleus in the Bjorken scaling limit

$$p_p = (-2.5 \pm 0.3)\%\ , \quad p_n = (87 \pm 2)\% \tag{43}$$

This then yields the following relation between the integrals of the polarized structure functions for neutrons, ^{3}He and protons

$$\Gamma^n = (1.15 \pm 0.02)\Gamma^3 + (0.057 \pm 0.009)\Gamma^p \tag{44}$$

Calculations indicate that this nuclear structure correction is almost independent of x in the Bjorken scaling limit, and the above estimates indicate that uncertainties in this nuclear structure correction are not important in the analysis of the E142 data. However, one caveat should be mentioned. The above estimates are in the Bjorken scaling limit, and there may well be large effects at finite Q^2, which could lead to significant corrections to the E142 data.[43] Similar effects are also possible in principle for the deuteron,[44] but should be less important, as it is a simpler nucleus and the SMC data are at larger values of Q^2.

We conclude this section by mentioning an interesting bound on $g_1^n(x,Q^2)$, derived in Ref. [45]. The idea of this bound is to eliminate $\Delta u(x,Q^2)$ between $g_1^p(x,Q^2)$ and $g_1^n(x,Q^2)$. Neglecting higher-twist effects, one finds

$$\left|4g_1^n(x,Q^2) - g_1^p(x,Q^2)\right| = \left|\frac{15}{18}\ \Delta d(x,Q^2) + \frac{3}{18}\ \Delta s(x,Q^2)\right| \le \frac{15}{18} d(x,Q^2) + \frac{3}{18} s(x,Q^2) \tag{45}$$

When using this equation, one cannot simply assume that the deuteron structure function is the sum of proton and neutron structure functions, but must include the deuteron nuclear structure correction

$$\Gamma_1^p(Q^2) + \Gamma_1^n(Q^2) \simeq \frac{\Gamma_1^d(Q^2)}{1 - 1.5\omega_D} \tag{46}$$

where ω^D is the probability of finding the deuteron in a D-wave, $\omega^D \simeq 0.058$, and one must also bear in mind the existence of smearing at large x. We choose to express Eq. (45) in terms of the following directly measured quantities: $A_1^p(x)$, $A_1^n(x)$, $R(x,Q^2)$, and $\xi(x,Q^2) \equiv F_2^N(x,Q^2)/F_2^p(x,Q^2)$

$$\left|4A_1^n(x,Q^2)\xi(x,Q^2) - A_1^p(x,Q^2)\right| \leq \left[1 + R(x,Q^2)\right] \left[4\xi(x,Q^2) - 1\right] \qquad (47)$$

To check the inequality, one should evaluate all the terms using the same fixed value of Q^2. As seen in Fig. 2a, we find that the SLAC E142 data are highly consistent with this inequality at $Q^2 = 2$ GeV^2, whereas Fig. 2b indicates that there is a very marginal disagreement ($\ll 1\sigma$) between the SMC and EMC data at $Q^2 = 4.6$ GeV^2. We emphasize that this discrepancy cannot be considered significant, in view of the large experimental errors and the possible existence of higher-twist and mass corrections.

5. More Theoretical Interpretation[37]

Combining the EMC and E142 data we find

$$\Gamma_1^{p-n}(Q^2 = 2\ \text{GeV}^2) = 0.152 \pm 0.014 \pm 0.021 \qquad (48)$$

whilst combining the EMC and SMC data we find

$$\Gamma_1^{p-n}(Q^2 = 4.6\ \text{GeV}^2) = 0.201 \pm 0.048 \pm 0.042 \qquad (49)$$

These evaluations at fixed Q^2 of the Bjorken sum rule integral must be compared with the theoretical prediction

$$\begin{aligned}\Gamma_1^{p-n}(Q^2) = \quad & \frac{1}{6}\Big\{g_A\Big[1 - \frac{\alpha_s(Q^2)}{\pi} - 3.58\Big(\frac{\alpha_s(Q^2)}{\pi}\Big)^2 - 20.2\Big(\frac{\alpha_s(Q^2)}{\pi}\Big)^3 + \ldots\Big] \\ & \quad - \frac{8}{9Q^2}\Big(\ll U^{NS} \gg + \frac{1}{2}m_N^2 \ll V \gg\Big)\Big\} \\ & + \frac{4}{9}\,\frac{m_N^2}{Q^2}\,\int_0^1 dx\ x^2 g_1^{p-n}(x,Q^2) + \ldots\end{aligned} \qquad (50)$$

where we have included the full set of perturbative QCD corrections calculated in Ref. [46], as well as the leading higher-twist term and the leading target-mass corrections.[47,48,49,50] The higher-twist term is obtained from

$$\langle N|U_\mu^{NS}|N\rangle \equiv S_\mu \ll U^{NS} \gg \qquad (51)$$

where

$$U_\mu^{NS} \equiv \bar{u}g\tilde{G}_{\mu\nu}^a\gamma_\nu\ \frac{1}{2}\lambda^a u - (u \to d)\ :\ \tilde{G}_{\mu\nu}^a \equiv \epsilon_{\mu\nu\alpha\beta}G_a^{\alpha\beta} \qquad (52)$$

and an analogous expression for $\ll V \gg$.[48] The first estimate of the matrix elements $\ll U^{NS} \gg$ and $\ll V^{NS} \gg$ was given in Ref. [48]. This initial estimate has been criticized as either too small[51] or too large.[49] Following this criticism, the calculation in Ref. [48] has been recently re-checked by one of the authors and the most recent estimate[50] is

$$-\frac{8}{9Q^2}\Big(\ll U^{NS} \gg + \frac{1}{2} m_N^2 \ll V \gg \Big) \simeq -\frac{0.1}{Q^2} \tag{53}$$

to which we assign the same error as was quoted[48] previously, namely $\pm 0.15\,\mathrm{GeV}^2/Q^2$. In the following we will use the value given in Eq. (53), while keeping in mind the possibility that it might change in either direction.

Eq. (53) makes a significant correction to the Bjorken sum rule at $Q^2 = 2$ GeV^2, but is negligible compared with the SMC errors at $Q^2 = 4.6$ GeV^2. The integral in the target mass correction in Eq. (51) is evaluated to be 0.0168 at $Q^2 = 2$ GeV^2 and 0.0130 at $Q^2 = 4.6$ GeV^2. Using a recent determination of $\alpha_s(Q^2)$ from τ decays[52] and incorporating all the finite-Q^2 corrections in Eq. (50), we find the following theoretical predictions

$$\Gamma_1^{p-n}(Q^2 = \ \ 2 \text{ GeV}^2) = 0.160 \pm 0.014 \tag{54a}$$

$$\Gamma_1^{p-n}(Q^2 = 4.6 \text{ GeV}^2) = 0.177 \pm 0.007 \tag{54b}$$

as seen in Fig. 3. Confronting these with the experimental values shown in Eqs. (48) and (49), we conclude that *the Bjorken sum rule is satisfied within one standard deviation.*

The perturbative QCD and higher-twist machinery used above can be cross-checked[53] with the Gross-Llewellyn Smith sum rule. The CCFR collaboration has recently published a new evaluation[54] of this sum rule at $Q^2 = 3$ GeV^2

$$\int_0^1 dx\ F_3^{\bar{\nu}p+\nu p}(x, Q^2 = 3 \text{ GeV}^2) = 2.50 \pm 0.018 \pm 0.026 \tag{55}$$

to be compared with the naïve prediction of 3 in the quark-parton model. Including perturbative QCD corrections[46] and higher-twist effects,[55] one finds[53] for the right-hand-side of Eq. (55)

$$3\Big[1 - \frac{\alpha_s(Q^2)}{\pi} - 3.58\Big(\frac{\alpha_s(Q^2)}{\pi}\Big)^2 - 19.0\Big(\frac{\alpha_s(Q^2)}{\pi}\Big)^3 - \frac{8}{27}\ \frac{\ll O^s \gg}{Q^2} + \ldots\Big] \tag{56}$$

where the higher-twist coefficient is given by

$$\langle P|O^s_\mu|P\rangle \equiv 2p_\mu \ll O^s \gg \tag{57}$$

where

$$O^s_\mu = \bar{u}\ \tilde{G}_{\mu\nu}\gamma_\nu\gamma_s u + \bar{d}\ \tilde{G}_{\mu\nu}\gamma_\nu\gamma_s d \tag{58}$$

The higher-twist coefficient has been estimated[55] as

$$\ll O^s \gg = 0.33 \text{ GeV}^2 \tag{59}$$

with a precision of perhaps 50%. Figure 4 shows that there is very good agreement between experiment, Eq. (55), and theory, Eq. (56), and it is claimed that this agreement may even be improved by including the higher-twist effect. These data have in fact been used to determine[53]

$$\alpha_s(m_z) = 0.115 \pm 0.006 \tag{60}$$

in the $\overline{\mathrm{MS}}$ renormalization scheme, in good agreement with other determinations from deep-inelastic scattering, LEP and elsewhere.

One way of stating the agreement of the polarized structure function data with the Bjorken sum rule is to extract an effective value of g_A. This is done by subtracting the higher-twist and mass corrections from the data, and then removing the perturbative QCD correction factors. Following this procedure, we find from the EMC and SMC data

$$g_A = 1.43 \pm 0.45 \tag{61}$$

and from the EMC and SLAC E142 data

$$g_A = 1.20 \pm 0.22 \tag{62}$$

Combining all three experiments we find

$$g_A = 1.24 \pm 0.20 \tag{63}$$

and conclude that *the Bjorken sum rule is verified to within 16 %.*

Given this high degree of consistency with the fundamental Bjorken sum rule, we now proceed to extract the different quark contributions to the nucleon spin. We do this by using the EMC proton data, the SMC proton plus neutron data after making the deuteron D-wave correction, and the E142 data for the neutron after making the ^{3}He wave function correction discussed earlier. The higher-order perturbative corrections to the singlet integral $\Gamma^{p+n}(Q^2)$ are not available, but the mass corrections and leading higher-twist effect have been calculated. The latest updated estimate[50] of the latter is $\simeq 0.1\,\mathrm{GeV}^2/Q^2$ with a large error, which we take here to be the same as in Ref. [48].

As in the extraction of the effective value of g_A, we first subtract from the data the theoretical values of the $1/Q^2$ corrections, and then remove the perturbative QCD factors. We denote the resulting moments with a tilde, $\tilde{\Gamma}_1$, to distinguish them from the raw experimental quantities Γ_1. Following this procedure, we find

$$\tilde{\Gamma}_1^p(Q^2 = 10.7\ \mathrm{GeV}^2) = \frac{1}{2}\,(\frac{4}{9}\ \Delta u + \frac{1}{9}\ \Delta d + \frac{1}{9}\ \Delta s) = \quad 0.138 \pm 0.023 \tag{64a}$$

$$\tilde{\Gamma}_1^n(Q^2 = \ \ 2.0\ \mathrm{GeV}^2) = \frac{1}{2}\,(\frac{1}{9}\ \Delta u + \frac{4}{9}\ \Delta d + \frac{1}{9}\ \Delta s) = -0.045 \pm 0.016 \tag{64b}$$

$$\tilde{\Gamma}_1^{n+p}(Q^2 = \ \ 4.6\ \mathrm{GeV}^2) = \frac{1}{2}\,(\frac{5}{9}\ \Delta u + \frac{5}{9}\ \Delta d + \frac{2}{9}\ \Delta s) = \quad 0.051 \pm 0.055 \tag{64c}$$

Combining these results with neutron-β decay

$$g_A = \Delta u - \Delta d = 1.2573 \pm 0.0028 \tag{65}$$

and hyperon beta-β assuming $SU(3)$ as discussed in Section 2, we find three independent estimates of the sum of the quark contributions to the proton spin

$$\Delta\Sigma \equiv \Delta u + \Delta d + \Delta s = \begin{cases} 0.15 \pm 0.21, & (\text{EMC}, Q^2 = 10.7\ \text{GeV}^2) \quad (66a) \\ 0.08 \pm 0.25, & (\text{SMC}, Q^2 = 4.6\ \text{GeV}^2) \quad (66b) \\ 0.39 \pm 0.14, & (\text{EMC}, Q^2 = 2.0\ \text{GeV}^2) \quad (66c) \end{cases}$$

The different determinations of $\Delta\Sigma$ and Δs are plotted in Fig. 5, where we see a high degree of consistency. The world average of $\Delta\Sigma$ is

$$\Delta\Sigma = 0.27 \pm 0.11 \tag{67}$$

with individual contributions of

$$\Delta u = 0.82 \pm 0.04\ , \quad \Delta d = -0.44 \pm 0.04\ , \quad \Delta s = -0.11 \pm 0.04 \tag{68}$$

We see that the total quark contribution to the proton spin is positive but small, and that the strange quark contribution is significantly non-zero.

In this context it is interesting to note that Δs being nonzero is a part of an intriguing pattern[56]: experiment indicates that certain strange-quark bilinear operators, such as $\bar{s}\gamma_\mu\gamma_5 s$ have relatively large matrix elements in the proton, while others are very small. The presence of a substantial non-valence component of $\bar{s}s$ pairs in the proton has some striking consequences. One of these is the evasion of the OZI rule in the couplings of $\bar{s}s$ mesons to baryons,[57] leading to surprisingly large branching ratios for ϕ production in $\bar{p}p$ annihilation at rest.[58]

At this point we note that there are three possible attitudes towards three higher-twist effects: one is simply to ignore them, like the ostrich. Another is to treat the coefficient of the higher-twist correction as a free parameter,[59] setting its value through the requirement that the EMC, SMC and E142 results for $\Delta\Sigma$ are consistent with each other, in which case the available data yield

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.38 \pm 0.48 \tag{69}$$

We have taken a third approach, which is to use the best available theoretical calculations to produce Eq. (68).

6. Conclusions and Prospects

A wealth of new data on polarized lepton-nucleon structure functions are now being accumulated. All the data available so far are consistent with QCD, and the Bjorken sum rule is verified with a precision of about 16 %. There is good convergence between the different measurements of the quark contributions to the proton spin, which are summarized in Eqs. (67) and (68). We note that the value of $\Delta\Sigma$ is qualitatively consistent with the predictions of chiral soliton models[24] and lattice simulations.[60,61,62,63] The most recent lattice calculation[63] finds $\Delta\Sigma = 0.10 \pm 0.21$.

We welcome the more precise data on polarized lepton-proton and -neutron structure functions that will become available shortly, including data on the interesting structure function g_2. We emphasize that cleaner tests of QCD are possible at higher Q^2, corresponding to higher beam energies, since the higher-twist and mass corrections vanish asymptotically. Therefore, other things being equal, preference should be given to running with higher-energy beams.

Also of interest for the future are data on polarization asymmetries for final-state particles. Measuring π^+/π^- asymmetries should confirm the values of Δu and Δd discussed above, whereas measuring K^+/K^- asymmetries should probe Δs directly. Particularly interesting would be polarization asymmetries for charmed final states, including the J/ψ, which would probe ΔG directly.

Forthcoming deep inelastic experiments include a continuation of the SMC experiment using protons in 1993 and other targets in subsequent years, the SLAC E142 experiment taking data on proton and deuteron targets in 1993, and the SLAC E143 experiment taking data on proton and deuteron targets with a 50 GeV beam in 1995.[64] A particularly interesting newcomer will be the Hermes experiment at HERA[65] using proton, deuteron and ^{3}He targets from 1995 onwards. This experiment will have particular advantages for studying final-state asymmetries. In the longer term, there is a proposal[66] to perform polarized lepton-nucleon scattering experiments in LEP. Finally, we mention the ambitious project for injecting polarized protons into RHIC and colliding beams each of 250 GeV. Measuring jet and Drell-Yan asymmetries one should be able to measure Δq and ΔG directly.[67]

Polarized lepton-nucleon scattering experiments have already provided us with plenty of interest and some surprises. We are sure that this field will continue to excite the community of physicists for the foreseeable future.

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FIGURE CAPTIONS

Fig. 1 In any given polarized lepton-nucleon scattering experiment, the range of Q^2 probed is different in different bins of the Bjorken variable x_{B_j}.

Fig. 2 The difference between the right-hand and left-hand sides of the bound.[47] The actual errors are slightly larger than those indicated by the error bars, as the latter refer to the error in the left-hand side only. (a) E142 data,[41] combined with EMC data,[13] rescaled to $Q^2 = 2$ GeV^2; (b) SMC data,[40] combined with EMC data,[13] rescaled to $Q^2 = 4.6$ GeV^2.

Fig. 3 Experimental tests at $Q^2 = 2$ GeV^2: E142 and EMC, $Q^2 = 4.6$ GeV^2: SMC and EMC, of the Bjorken sum rule, including perturbative QCD corrections (dot-dashed lines) and higher-twist corrections (solid lines). The asymptotic value $g_A/6$ is denoted by a dotted line.

Fig. 4 Experimental test[54] at $Q^2 = 3$ GeV^2 of the Gross-Llewellyn Smith sum rule including perturbative QCD corrections (dot-dashed lines) and higher-twist corrections (solid lines).

Fig. 5 The allowed regions in the $\Delta\Sigma - \Delta s$ plane, corresponding to the linear constraints (64) and (13). Continuous lines: $\Delta\Sigma - 3\Delta s = 3F - D$; dots: $\tilde{\Gamma}_l^p(Q^2)$ constraint; dot-dash: $\Gamma_l^n(q^2)$; dashes: $\tilde{\Gamma}_l^p(q^2) + \tilde{\Gamma}_l^n(q^2)$.

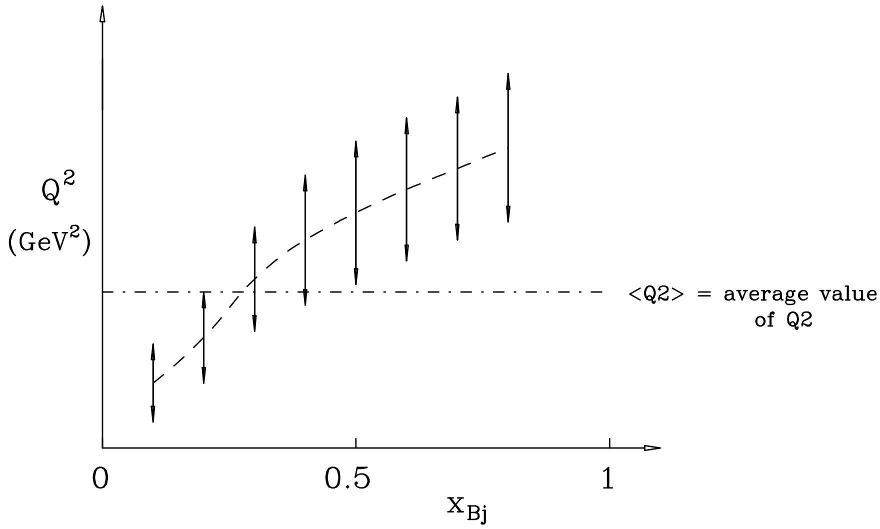


Fig. 1

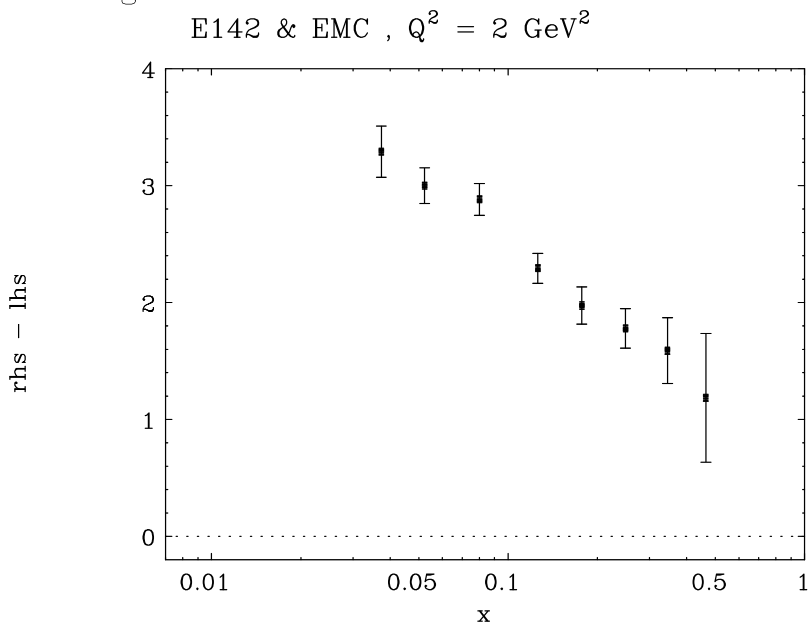
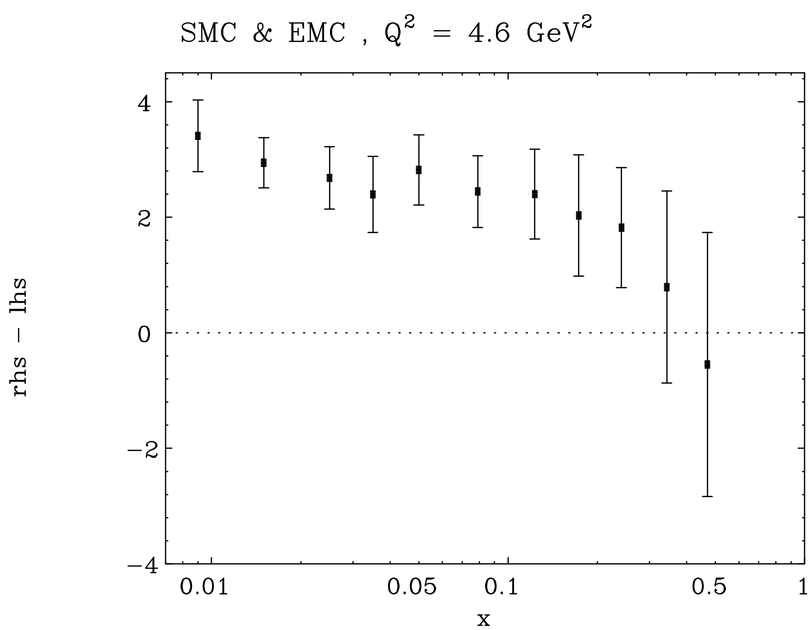


Fig. 2(a)



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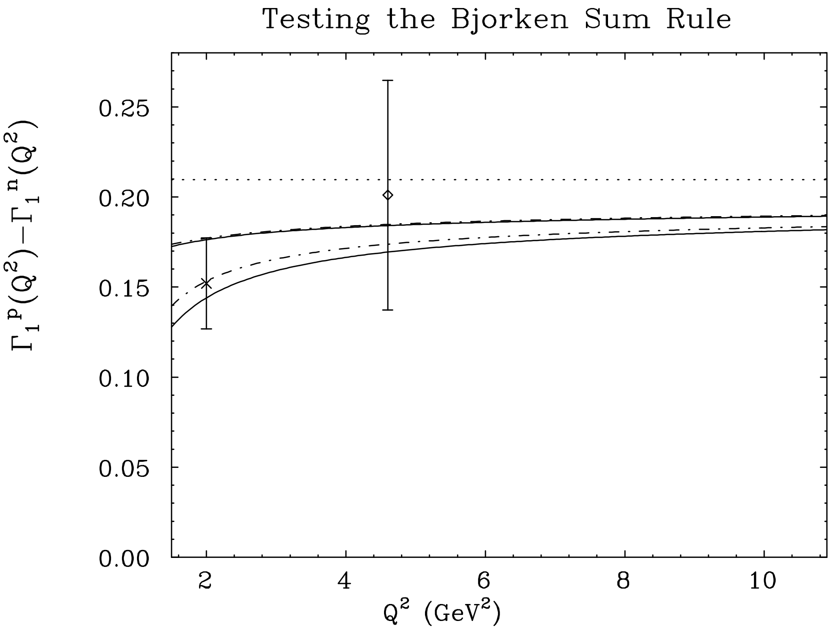

Fig. 3

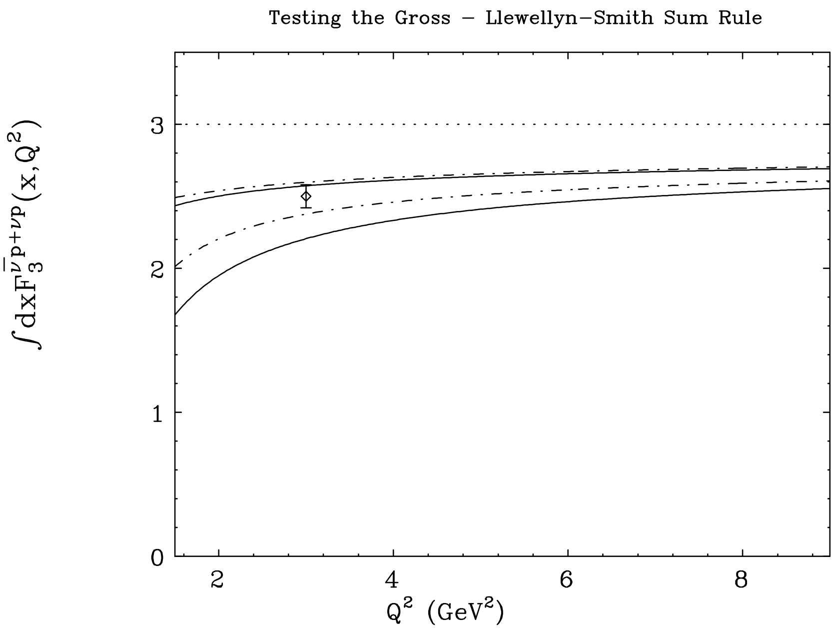

Fig. 4

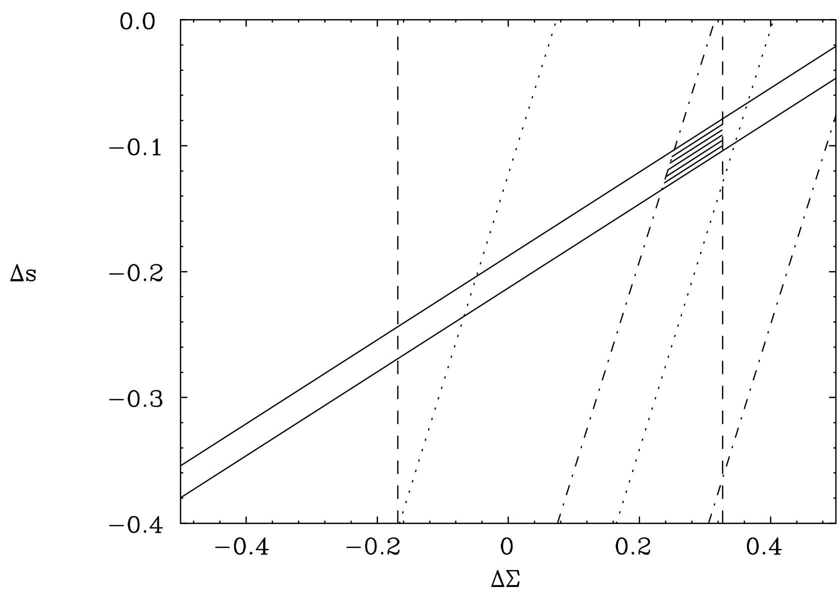

Fig. 5