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Nucleon Spin: Summary

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Nucleon Spin: Summary

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Abstract

This talk summarises the discussions during the conference on the spin structure of the nucleon held at Erice; July 1995. The summary focuses on where we have come, where we are now, and the emerging questions that direct where we go next in the quest to understand the nucleon spin.

We have spent a stimulating week discussing the status of the "nucleon spin puzzle". At least we are agreed that neither is there nor, apparently, was there ever, any spin "crisis". We are also agreed that this field has been, and continues to be, rich in opportunity and the unexpected. I have always believed that the essential clues are implicit in an apparent paradox that shows up when one looks at the data in two complementary ways. On the one hand, experiment measures directly the polarisation asymmetry $A_1(x,Q^2)$. World data on both proton and neutron are in remarkable agreement with the "pre- historic" pre-dictions of quark models refs (1,2,3), at least for $x \gtrsim 0.1$. This would appear to "confirm" the quark spins as primarily responsible for generating the nucleon spin (fig 1).

However, when we construct $g_1^p(x,Q^2) \equiv A_1^p(x,Q^2)F_1^p(x,Q^2)$ and integrate it, it falls short of the value expected by the Ellis-Jaffe sum rule [4]; typically for SMC in 1994 at $Q^2 = 10GeV^2$

$$I^p_{expt} = 0.136 \pm 0.011 \pm 0.011; I^p_{theory} = 0.176 \pm 0.006.$$

The discrepancy is some $2\frac{1}{2}\sigma$; the net quenching of inferred spin Δq is roughly $\Delta q \simeq 9(I^p_{theory} - I^p_{expt})$ and hence a shortfall of 0.04 in the integral magnifies into a quenching of Δq by some 40%. It is this dramatic shortfall that has excited so much interest. How is it that data presented one way (the $A_1(x,Q^2)$) appear to agree so well with theory whereas the $\int dx g_1^p(x,Q^2)$ appears to give a rather different message?

This meeting has sharpened understanding of this and helped to focus on the leading current questions.

First, construction of $g_1^p(x \to 0)$ is a particularly delicate issue, as has repeatedly been stressed. Here are some issues that need study.
(i) Experiment measures $A(x,Q^2)$. This is Q^2 independent to good accuracy at $x \gtrsim 3 \times 10^{-2}$ and is assumed to remain so even for $x < 10^{-2}$. QCD evolution suggests this is not in general true, and the Q^2 dependence is a major issue.
(ii) The above yields $A(x) \simeq$ constant as $x \to 0$
(iii) The constant $A(x)$ is then multiplied by $F_1(x,Q^2)$ that rises as $x \to 0$. To be pedantic, we know that $F_2(x,Q^2)$ from NMC and HERA show a marked rise; more information on unpolarised structure, in particular on $R(x,Q^2) \equiv \sigma_L/\sigma_T$ and on the normalisation of NMC and HERA data sets may be needed before we can be entirely certain that there are no subtle errors creeping in here.

But one certain conclusion is that at $x < 0.1$ we cannot lose. Either $g_1^p(x \to 0)$ behaves smoothly as has been assumed with the result that Δq is quenched (hence theoretically challenging) or if Δq is not quenched there will be interesting behaviour to be measured at small x.

In this summary I shall start at large x where we know what is going on but don't understand why.

It is remarkable that the x-dependences of the polarisation asymmetries in the valence region $A_1(x > 0.2)$ confirm the quark model predictions [1, 2] for proton neutron and deuteron systems. It is worth remembering that these predictions were based initially on the assumption that the Pauli principle correlates the spins and flavours of the valence quarks as in the familiar case of constituent quarks in spectroscopy. These initial predictions were then modified in light of the emerging unpolarised $F_2^n(x)/F_2^p(x)$ and theoretical ideas concerning the relationship between constituent and current quarks [2].

The region $x \rightarrow 1$ probes the deep valence structure of the current quarks. An untested prediction [2] is that $A^n(x \rightarrow 1) \equiv A^p(x \rightarrow 1)$. When $x < 0.3, A^n(x < 0.3) < 0$; thus an issue is whether A^n becomes positive when $x \gtrsim 0.4$. The data error bars are too large to tell, hence the challenge is to measure if

$$\bullet A^n(x \gtrsim 0.4) > 0$$

This would at least be a qualitative indicator that the neutron is "readjusting" so as to catch the large positive asymmetry of the proton. The next question concerns the magnitude of $A^N(x \rightarrow 1)$. If a single quark carries all the helicity in this limit [3, 5] then $A(x \rightarrow 1) \rightarrow 1$. If its spin is quenched in line with the 25% quenching of g_A/g_V then $A(x \rightarrow 1) \rightarrow 3/4$. However if a single flavour dominates (as suggested by $F_2^n/F_2^p(x \rightarrow 1)$) but it retains the naive SU(6) values, one has $A(x \rightarrow 1) \rightarrow 2/3$.

Thus for the proton a first test may be

$$\bullet Is A^p(x \rightarrow 1) > 2/3 \ ?$$

Showing whether $A > 3/4$ will be more difficult.

Do not overlook that CEBAF may be able to study $A(Q^2, W^2)$ in this region of x but with W^2, the invariant mass squared of the hadronic system, tending towards the resonance region. It will be interesting to have predictions on the x and Q^2 dependence in this limit where the spin response of the nucleon may be probed in some detail.

To the extent that the polarisation of valence quarks is canonical, at least insofar as the asymmetry is concerned, we should confidently expect predictions for **asymmetries** of polarised Λ etc. to apply in the valence region. In turn the question arises as to what is quenching the valence quarks' contribution to the net polarisation.

In 1977 Sivers and I already noted that the evolution equations of QCD imply a nontrivial polarisation of the sea. First, helicity conservation implies that a polarised valence quark will bremstrahlung a gluon that will itself be polarised with the same polarisation as that of the initial quark. Hence, since $\Delta q_v > 0$ then $\Delta G > 0$ also, at least at $0(\alpha_s)$. We found that

$$\frac{\Delta G(x \to 1)}{G(x)} \equiv \frac{G^+(x) - G^-(x)}{G^+(x) + G^-(x)} \simeq \frac{1-(1-x)^2}{1+(1-2)^2}$$

which has been discovered independently more recently [7]. Experiment E704 at Fermilab [6] suggests that $\Delta G(x < 0.3)$ is small: this may be compatible with the above since the gluon asymmetry is small there. Measurement of $\Delta G(x > 0.3)$ may be critical.

The next stage in our paper was to study the implication for $\Delta q_{sea}(x)$. A polarised evolution $G^\uparrow(x) \to q\bar{q}$ indeed gives no net helicity in the sea but it does yield a local non-zero effect. The gluon gives in general $q(x_1)\bar{q}(x - x_1)$ where $0 \leq x_1 \leq x$. The hard tail $x_1 \to x$ has $\Delta q = \Delta\bar{q} > 0$ while the soft region $x_1 \to 0$ compensates with $\Delta q = \Delta\bar{q} < 0$. This contrasts with non-perturbative effects such as a sea driven by $J^p = 0^-$ meson clouds, for which $\Delta\bar{q} < 0$ (e.g. Isgur here [8]).

Hence the challenge is to test whether, for the hard component at least,

- $\Delta\bar{q}(x\ large) > 0$
- $\Delta\bar{q}(x) < 0$

The sharpest probe, in theory, is to tag fast K^- in the current fragmentation region. The idea [9] exploits the fact that $K^-(s\bar{u})$ contains members of the initial proton's sea and so, to the extent that the leading hadron in a jet contains the quark (or antiquark) that was struck by the current probe, the K^- is a direct tag for the sea. A polarisation asymmetry for the leading K^- will translate into a polarised sea for the proton. These questions are beginning to be answered by SMC and will be a major component of the HERMES programme.

Finally in this study of how the proton's spin is decomposed we have the "sum rule"

$$\frac{1}{2} = \sum \Delta q + \Delta G + L_z$$

where L_z is the "orbital angular momentum" of the constituents. Discussions here show that there is some confusion as to what "L_z" means. An example is given by QCD evolution where $G^{\uparrow}(q\bar{q})_{\lambda=0}$ with ($\lambda = 0$) denoting the net helicity of the $q\bar{q}$. The gluon-$q\bar{q}$ vertex contains an $e^{i\phi}$, where ϕ is the azimuthal angle of the $q\bar{q}$ plane relative to the gluon helicity and $< L_z >\simeq i\frac{d}{d\phi}$ represents the transmutation of gluon helicity into the orbital angular momentum of the $q\bar{q}$ (see e.g. ref [10]). So in some sense $< L_z >$ measures the number of polarised gluons that has transmogrified into $q\bar{q}$.

Experimentalists are encouraged to seek ϕ dependence of the hadron production [11]; the theoretical and practical question is then how to disentangle how much of this is background from resonance decay or from quark-hadron fragmentation.

Sum Rule Sensitivity and F/D

Differences between I^p_{exp} and I^p_{theory} are magnified ninefold when interpreted as a quenching of Δq: consequently any apparently minor adjustment to the left hand side (I^p_{exp}) or right hand side (F/D) of the EJ sum rule can have an order of magnitude impact on the inferred magnitude of Δq.

One unresolved question is the interpretation of F/D when SU(3) is broken. Experimental data on hyperon decays may still have something to offer. For example

$$\frac{g_A}{g_V}(n \to p) = F + D \equiv \frac{g_A}{g_V}(\Xi \to \Sigma)$$

so it will be interesting to see if this equality is preserved when β-decay occurs in the presence of spectator strange quarks. Secondly, for the case of strangeness changing decays in the hadronic axial current

$$A_\mu = g_A \gamma_\mu \gamma_5 - g_2 \frac{\iota \sigma_{\mu\nu} q^\nu \gamma_5}{m_i + m_j}$$

it has been assumed that $g_2 = 0$. While this is assured in the limit $m_i = m_j$ (such as $n \to p$) it is not necessarily so for $\Delta S = 1$. The Hsueh et al analysis of Σn made a fit [12] allowing for $g_2 \neq 0$ and found a rather different value for g_A than that taken from the Particle Data Group [13] and used in the extraction of F/D $= 0.575 \pm 0.016$ [14]. In addition to these uncertainties there are systematic uncertainties due to phase space and form factors [15].

Further precision studies of hyperon decays may be warranted if the quantitative precision on Δq becomes an important issue. For example, if Δq is quenched it will be of interest to determine whether $\Delta q \simeq 0.3$ which may be in the region of "ΔG and the anomaly" [16] or whether $\Delta q \to 0$ as in Skyrmion models [17].

My opinion is that one should continue to use F/D $\simeq$ 0.58 and 3F-D $\simeq$ 0.6 until proven wrong to do so.

$x \to 0$ Questions

Historically extrapolation has used Regge with an a_1 trajectory whose intercept $\alpha(a_1) \simeq 0$. However, Roberts and I [18] originally noted that diffractive behaviour in spin dependence is a poorly understood area and that an $(x \log^2 x)^{-1}$ behaviour is allowed within the general Regge analyses. So the first question is, for Regge

- What extrapolation should one use?
- Up to what value of Q^2 is Regge legitimate?

Complementary to this is a renewed interest in the $x \to 0$ evolution of $g_1^p(x, Q^2)$ and the rise [18, 19]

$$\bullet g_1 \sim \exp \sqrt{\ln 1/x}$$

Some recent analyses suggest that there may be a rise even in the non-singlet contribution [20]. The questions here include

- At how small a value of x do such ideas apply?

Kuti [21] has reanalysed the Regge theory and confirms the "in principle" presence of $(x \ln^2 x)^{-1}$ but finds that its coefficient vanishes in the Reggeon calculus. To settle the question of Regge behaviour empirically we need to fix Q^2 at a small value common to SMC as $x \to 0$ and SLAC at $x \simeq 0.1$ say, and establish the energy dependence at fixed Q^2.

As to whether/when Regge applies it is important to recall the historical origins of its application to deep inelastic. When scaling was first observed, Regge theory was a leading idea. It was noted that one could force a marriage between the two if the Regge residue had a magic behaviour.

$$F_1(x, Q^2) \sim \beta(Q^2)\nu^\alpha \to x^\alpha \; if \; \beta(Q^2) \sim (Q^2)^{-\alpha}$$

To my knowledge such a behaviour has not been derived from Reggeon field theory! This may be a question of interest to some, but suppose instead that $\beta(Q^2) \sim (Q^2)^{-(\alpha+1)}$ in which case Regge applies as $Q^2 \to 0$ but is rapidly overtaken by

QCD evolution (to which it might have no immediate relation). Thus the energy dependence of low Q^2 data may be quite different to that at high Q^2: HERA data on $F_2(x, Q^2)$ may give insight into this general question.

Until these questions are better understood we may gauge the "theoretical" systematic errors on Δq by extrapolating with

- x^α
- $(x \ln^2 x)^{-1}$
- $\ln x$
- $\exp \sqrt{\ln 1/x}$

The resulting range on Δq may be larger than other errors and this at least would highlight what are the most important issues. Even so, they are unlikely to raise Δq to the naive valence of $\simeq 0.6$ when one treats both proton and neutron (deuteron) target data simultaneously (see later).

The Erice Statement

It is agreed that one plot $xg_1(x)$ against $\log x$ or one plots $g_1(x)$ against x when attempting to visualise the measurement of sum rules

$$I \sim \int dx g_1(x) = \int d(\ln x) x g_1(x).$$

Plotting $g_1(x)$ against $\log x$ is to be used only for making propaganda and will be recognised as such.

I shall now show g_1^p and g_1^n plotted against $\log x$! This expands the $x < 10^{-1}$ region and highlights a marked difference between the proton and neutron (fig 2). This is an interesting area demanding further study. I will motivate this by recalling why the deuteron target has interest.

The generic sum rules have the structure for target A.

$$I^A = aI_3 + bI_8 + c\Delta q$$

Using F/D $\simeq 0.58$ to relate I_8 to (g_A/g_V) and including QCD corrections we may write

$$I^A = A(\frac{g_A}{g_V}) + B\Delta q$$

Very approximately (ignoring $0(\alpha_s)$)

$$I^p \simeq \frac{1}{10}(\frac{g_A}{g_V}) + \frac{1}{9}\Delta q$$
$$I^n \simeq -\frac{1}{15}(\frac{g_A}{g_V}) + \frac{1}{9}\Delta q$$

so that

$$I^{p-n} = \frac{1}{6}(\frac{g_A}{g_V})$$
$$\frac{1}{2}I^{p+n} = \frac{1}{60}(\frac{g_A}{g_V}) + \frac{1}{9}\Delta q$$

Thus the $p-n$ difference is the Bjorken sum rule for which Δq vanishes and $p+n$ is the best for emphasising Δq. In 1988 we expected [14] that for the deuteron the $g_1^d(x > x_c) > 0$ where $x_c \lesssim 0.1$. The predicted (and now empirical) $g_1^n < 0$ as $x \to 0$ gave the possibility that $g_1^d(x < x_c) < 0$. If so one would have an upper limit on Δq without any need to worry about extrapolating to $x = 0$.

$$\int_{x_c}^1 dx g_1^d(x, Q^2) \leq \int_0^1 dx g_1^d(x, Q^2)$$

Using the present data gives $\Delta q \lesssim 0.25$.

However there is a catch. We assumed that $g_1^d(x \to 0)$ does not oscillate, i.e. does not become positive at even smaller x. In this context the SMC datum $x = 5 \times 10^{-3}$ is tantalising (fig 3). The challenge will be to reduce the errors on this datum to see whether $g_1^d(x \simeq 5 \times 10^{-3}) > 0$. If $g_1^p(x \to 0)$ is indeed rising due to a singlet (diffractive) dominant contribution, then g_1^d will have to become positive too.

The fact that $g_1^p \neq g_1^n$ for $x \gtrsim 5 \times 10^{-3}$ shows that there is substantial non-singlet, non-diffractive, contribution still present. Indeed one may note that to a reasonable approximation that

$$g_1^n \simeq -g_1^p$$

in a substantial region. Kuti and Roberts [22] have even noted that an extreme simultaneous fit would allow a_1 exchange with $\alpha \simeq 0.3$. This large intercept is required to accommodate the rise in $g_1^p(x \to 0)$ and would give $\int_{0.003}^0 g_1^p(x) \simeq 0.025$ with consequent extra contribution to $\Delta q \simeq 0.2$ and elevating the total Δq towards the naive quark model value. This would be a dramatic conclusion if confirmed. Problems include why a_1 exchange totally dominates f_1 (in unpolarised Compton scattering the analogous $a_2 : f_2$ is only in ratio 1:5).

$g_2(x)$

The Burkhardt-Cottingham sum rule $\int dx g_2(x,Q^2) = 0$ needs to be tested but how much effort is needed to confirm zero is zero? The main challenge will be to measure or limit $\bar{g}^2(x,Q^2)$ where

$$\bar{g}_2(x,Q^2) \equiv g_2(x,Q^2) - [\int_x^1 g_1(y,Q^2) d\ln y - g_1(x,Q^2)]$$

This is a unique and **direct** measurement of twist 3 contributions: other tests of higher twist tend to rely on model dependent fits to data.

$b_1(x)$

For $J = 1$ targets this can be non-zero. However, before investing too much experimental effort on the deuteron bear in mind that, to the extent that the deuteron is made of two independent spin 1/2 components, $b_1(x) \to 0$. There is a parton model sum rule [23]

$$\int dx b_1(x) = \lim_{t\to 0} tF_Q(t) + \frac{1}{9}\delta Q \to \frac{1}{9}\delta Q$$

where $F_Q(t)$ denotes the quadrupole moment of the target and δQ is the quadrupole polarisation of the sea $\equiv q_\uparrow^0 - \frac{1}{2}(q_\uparrow + q_\downarrow)^1$ where the superscripts denote the target $\hat{z}$ polarisation and q denotes $q + \bar{q}$ number. There are further spin dependent structure functions, such as $h_1(x)$ [24] which may be probed at polarised RHIC or by the HMC collaboration at CERN within a few years.

The $Q^2 \to 0$ Polarisation Asymmetries

To my knowledge it was Gilman in 1971 [25] who first questioned how the Bjorken sum rule and predictions of a large **positive** $A_1(x)$ for the proton would match with the requirements of the DHG sum rule [26] that $\langle A \rangle < 0$ for $Q^2 = 0$. We discovered that the quark model predicted that a rapid change from $A < 0$ to $A > 0$ would occur in the resonance region, a phenomenon that was subsequently confirmed by experiments in 1973 for the prominent $N^*(1520)$ and $N^*(1690)$ [27]. The change in sign occurs for $Q^2 < 0.5$ GeV^2 for the latter and possibly even by Q^2=0.3 GeV^2 for the former. In the $\Delta(1230)$ we expect that the resonance excitation cross section drops very fast with Q^2, revealing the πN S-wave background (with $A > 0$).

The only direct measurements of total asymmetries through the N^* region show $A(Q^2 \geq 0.5 \text{ GeV}^2) > 0$. However, even this is at too large a Q^2 for our purposes! It is necessary to understand how the asymmetry changes sign as a function of Q^2 and W^2 . If it changes sign at Q^2=0.3 GeV^2 for all W, then it will be irrelevant as a higher twist phenomenon that potentially affects the interpretation of the Ellis-Jaffe sum rules. [28]. However, if the sign change occurs at (approximately) constant Q^2/W^2 , then the region $x \lesssim 0.2$ could exhibit interesting non-perturbative Q^2 dependence at values of $Q^2 \gtrsim$ 1 GeV^2

The programme at CEBAF should provide some insights. In addition to the above it promises to probe the spin dependence of transitions $p \rightarrow N^*$ in detail, thereby revealing the electric and magnetic response as a function of quantum numbers (angular momentum or multipoles). This will be a fine detail probe of the constituent valence nucleon structure whose relation with the deep response of valence current quarks may reveal the profound and poorly understood transformation from constituent to current quarks.

HERA and Gluemorons

The rapidity gap events at HERA may be interpreted on rather general grounds as due to the proton offering up a colour singlet non-baryonic system whose misconstructure is then probed by the virtual photon. This "Pomeron" may be made primarily of glue or of quarks. Let's refer to these extreme possibilities as "Gluemeron" or "Quarkball". The question is: how on general grounds can one distinguish between these two broad classes?

The answer [29] is to focus not on the x-dependence of the object's $F_1(x,Q^2)$ but its Q^2 dependence, specifically

$$\frac{dp}{dQ^2} \equiv \frac{d}{dQ^2}\int_0^1 dx F_2(x,Q^2)$$

For a quarkball (think of the familiar proton as an example) this falls gradually to an asymptotic value, whereas for a glueball or a gluemoron it should rise rather rapidly to this asymptopia.

The essential reason is that quarks shed momentum by gluon bremstrahlung whereas gluons feed momentum into $q\bar{q}$. Hence in regions of x where quarks dominate, the $\frac{dF_2(x)}{dQ^2} < 0$ with increasing Q^2; by contrast $\frac{dF_2(x)}{dQ^2} > 0$ in regions of gluon dominance.

Gluon dominance is anticipated as $x \to 0$ for all systems and hence $\frac{dF_2(x\to 0)}{dQ^2} > 0$ in general. For a quarkball this is compensated at large x where valence quarks dominate with the consequence that $\frac{dp}{dQ^2} < 0$ overall. For a gluemeron however, the "valence" gluons cause $\frac{dF_2(x>0.3)}{dQ^2} > 0$ which is quite opposite to that of a quarkball.

Eventually data at HERA may quantify the $\frac{dp}{dQ^2}$. However it is already apparent at $x \simeq 0.6$ that $\frac{dF_2(x=0.6)}{dQ^2} \not< 0$ and is probably positive. Thus it seems likely that there is strong indication that the Pomeron is a gluemeron, independent of particular model dependent assumptions as to x dependence.

Having established the gluemeron, we may look forward 25 years to polarised HERA. In addition to measuring $g_1^p(x < 10^{-4})$ it may also probe the spin structure of polarised gluemerons.

If the gluemeron has $J = 0$ there will be no spin asymmetry. If it has $J \neq 0$ we will need to know the probability that it is offered up with helicity parallel or antiparallel to the probe. Suppose we have solved this and are doing polarised deep inelastic scattering from a polarised gluemeron as the latter evolves into $q\bar{q}$ with Q^2.

Will the asymmetry be positive (the $q\bar{q}$ remember the gluemeron polarisation), zero (the gluon helicity turns into L_z in evolution) or negative (the anomaly reads $-\alpha\Delta G$). I asked several theorists to choose among these three and there was a roughly equal split between four answers.

It is 25 years since theorists first predicted the valence polarisation for quarkballs and it may be 25 years before we know the answer for gluemerons. Vote now.

A Moral for Fundamental Curiosity Driven Research

Many politicians believe that you have to be able to see the endgame if any research is to be worthwhile. We all know counter-examples from Maxwell, Faraday, X- rays etc. I added one to my list this week in the opening address by Vernon Hughes who nearly 40 years ago "was stimulated by parity violation" to make polarised electrons "with no obvious use". Who would fund such blue skies today? "Then in 1968 quarks became real!" The rest, as they say, is history.

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Figure Captions

Figure 1. Predictions for $A^{p,n}$ in the valence region compared with recent data. The curves (ref 1) correspond to $A_1^p = (\frac{19-6R}{15})\xi$, $A_1^n = (\frac{2-3R}{5R})\xi$ with $R = F_1^n/F_1^p$ and ξ=1 (solid), ξ=0.75 (dashed). See ref 2 (ii) for more details

Figure 2. g_1^p and g_1^n versus $\log x$

Figure 3. g_1^d versus $\log x$

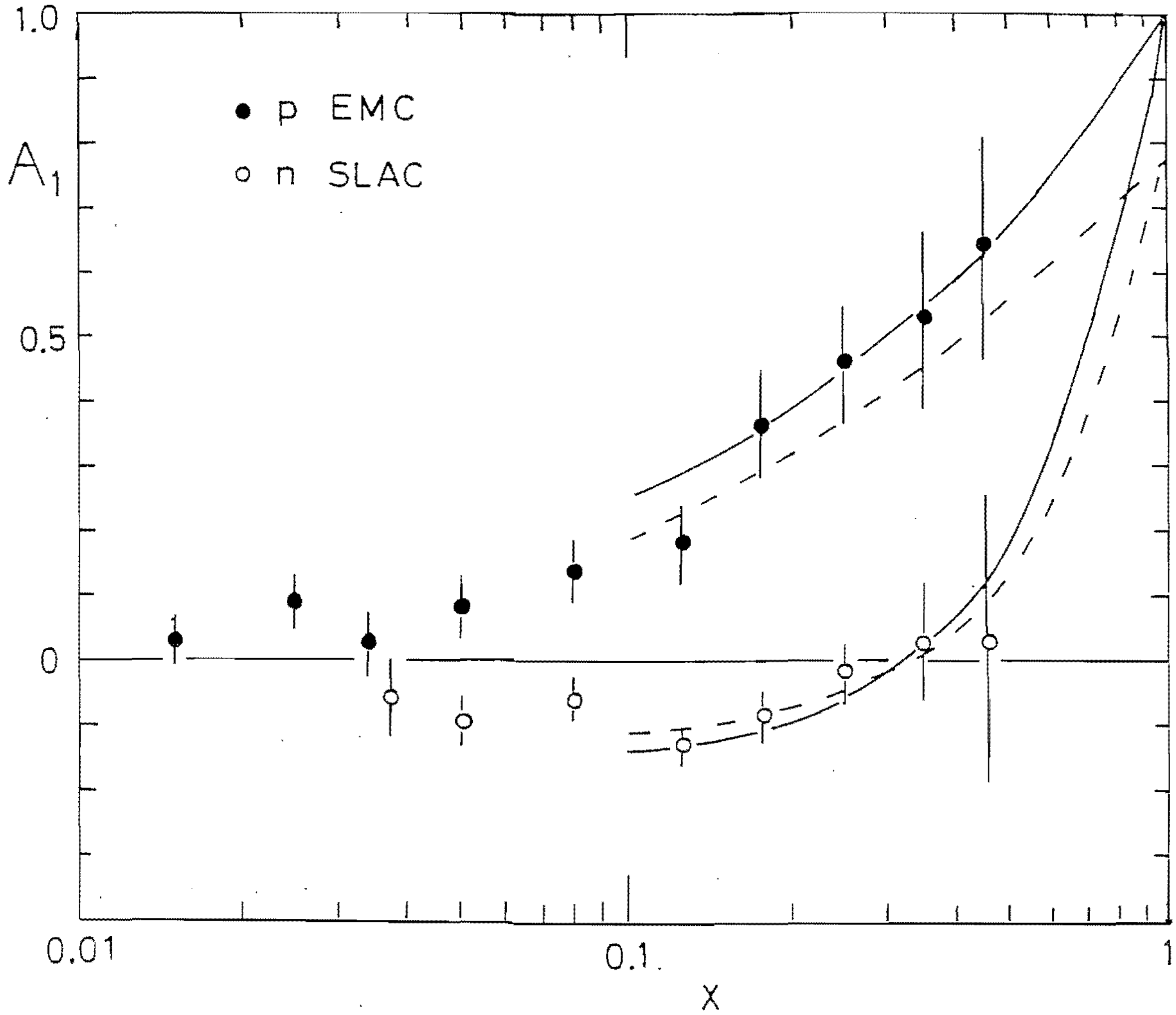
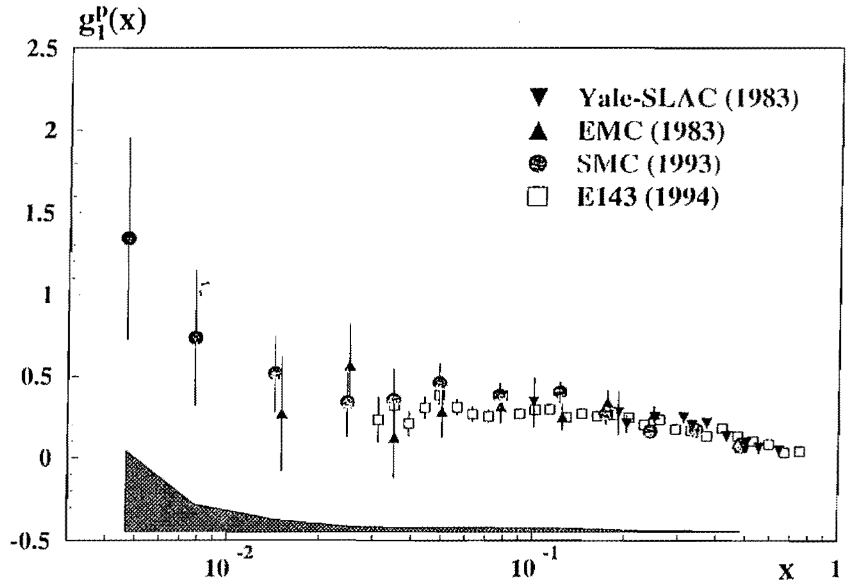
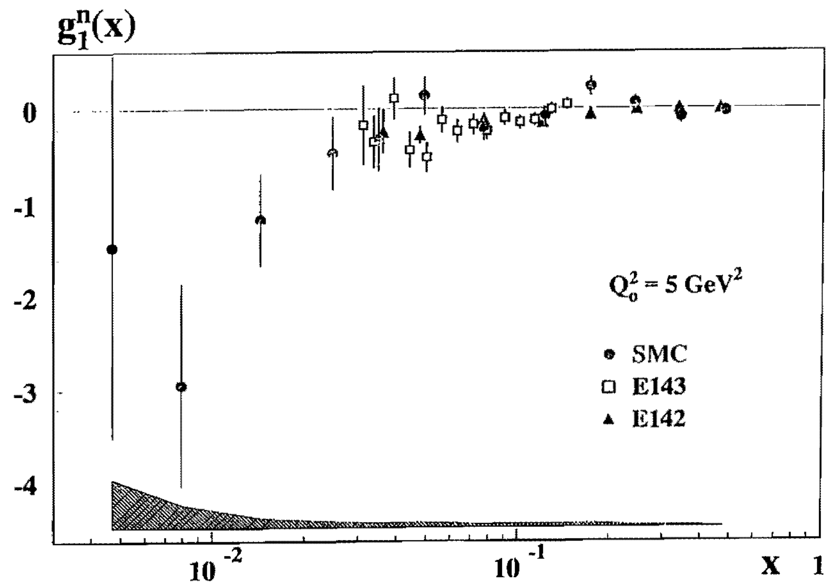


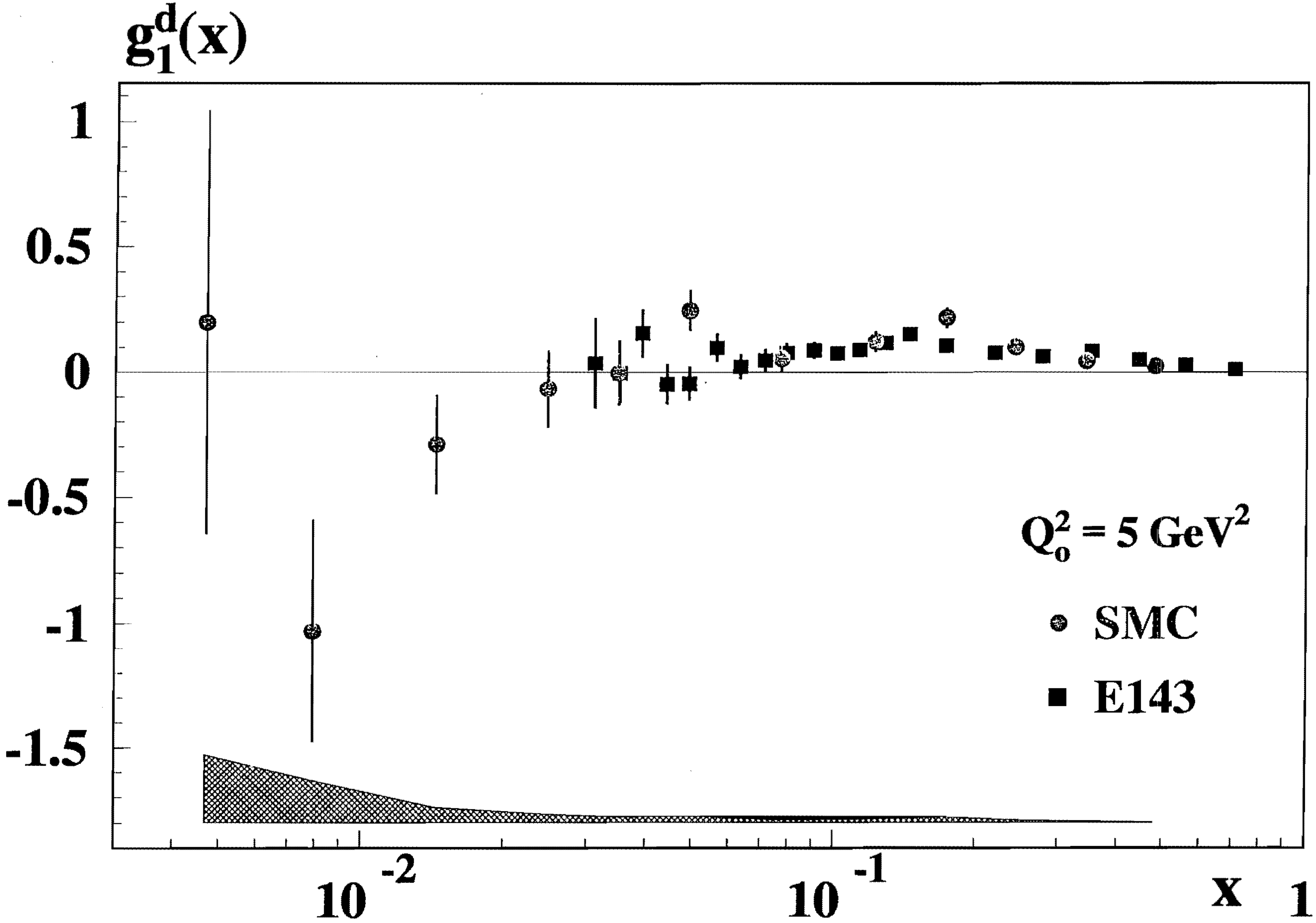
Fig. 1



$g_1^p(x)$
2.5
2
1.5
1
0.5
0
-0.5
Yale-SLAC (1983)
EMC (1983)
SMC (1993)
E143 (1994)
10^{-2}
10^{-1}
x
1



$g_1^n(x)$
0
-1
-2
-3
-4
$Q_o^2 = 5\ GeV^2$
SMC
E143
E142
10^{-2}
10^{-1}
x
1



$g_1^d(x)$
1
0.5
0
-0.5
-1
-1.5
10^{-2}
10^{-1}
x
1
$Q_o^2 = 5\ GeV^2$
SMC
E143