The Spin Structure of the Nucleon After 10 Years of Experiments

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Testing QCD through Spin Observables

in Nuclear Targets

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- **Parton distributions from QCD analysis**
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The Spin Dependent Structure Function g_1

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{\sum e_f^2 \left[q_f^{\uparrow}(x) - q_f^{\downarrow}(x)\right]}{\sum e_f^2 \left[q_f^{\uparrow}(x) + q_f^{\downarrow}(x)\right]}$$

WITH

$$g_1(x) = \frac{1}{2} \sum e^2 \Delta q(x)$$

$$F_1(x) = \frac{1}{2} \sum e^2 q(x)$$

$$F_2(x) = 2x F_1(x)$$

$$g_1(x) = A_1(x) F_1(x) = \frac{A_1(x) F_2(x)}{2x(1 + R(x))}$$

Sum Rule

$$\Delta q = \int_0^1 \Delta q(x) dx$$

$$\Gamma = \int_0^1 g_1(x) dx = \frac{1}{2} \sum e^2 \Delta q$$

SPIN CONTENT EQUATIONS (QPM)

For proton and neutron, with isospin symmetry

$$\Gamma_1^p = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right]$$

$$\Gamma_1^n = \frac{1}{2}\left[\frac{4}{9}\Delta d + \frac{1}{9}\Delta u + \frac{1}{9}\Delta s\right]$$

$$\Delta u - \Delta d = F + D = g_A = 1.2601 \pm 0.0025$$

More general - expressed in terms of the
axial charge matrix elements a_3, a_8 and a_o:

$$\Gamma_1^p = \int_0^1 g_1^p(x)\,dx =$$

$$C_{NS}\,\frac{1}{12}\left(a_3 + \frac{1}{3}a_8\right) + C_S\,\frac{1}{9}a_o$$

Where C_{NS} and C_S are the high order QCD corrections following S. A. Larin.
Phys. Lett. B 334 (1994) 192.

Assuming exact SU(3):

$$a_3 = F + D = g_A$$
$$a_8 = 3F - D = \Delta u + \Delta d - 2\Delta s = 0.580 \pm 0.016$$

➨ $$\Gamma_1^p = \int_0^1 g_1^p(x)\,dx = \frac{1}{12}g_A + \frac{1}{36}(3F-D) + \frac{1}{9}a_o$$

➨ $$\Gamma_1^n = \int_0^1 g_1^n(x)\,dx = -\frac{1}{12}g_A + \frac{1}{36}(3F-D) + \frac{1}{9}a_o$$

$$\Gamma_1^d = \frac{1}{2}(\Gamma_1^p + \Gamma_1^n)\,(1-1.5\omega_D)$$ *(Correction for D state probability in deuteron G.S.)*

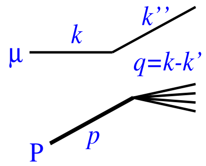
The Bjorken sum rule

A fundamental result in perturbative QCD

$$\Gamma_1^{\mathrm{p}} - \Gamma_1^{\mathrm{n}} = \frac{1}{6}\left|\frac{g_A}{g_V}\right| \cdot C_1^{\mathrm{NS}}(Q^2)$$

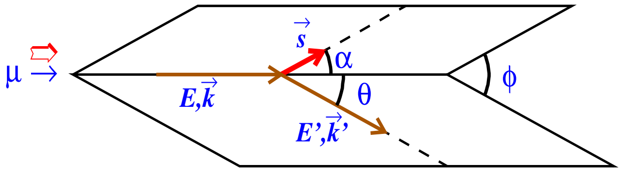
$C_1^{\mathrm{NS}}(Q^2)$ has been calculate to 4th order in α_s

POLARIZED DEEP INELASTIC SCATTERING



$$Q^2 = -q^2 \qquad x = Q^2/2M\nu$$

$$\nu = E - E' \qquad y = \nu/E$$



$$\frac{d^3\sigma(\alpha,\phi)}{dx\,dy\,d\phi} = \frac{e^4 ME}{4\pi^2 Q^4}\Big[xy^2 F_1 + (1-y)\,F_2 + h\cos\alpha\, xy\,[(y-2)\,g_1 + y\gamma^2 g_2] - h\sin\alpha\, xy\cos\phi\,\gamma\,(1-y)^{1/2}(y\,g_1 + 2\,g_2)\Big]$$

Longitudinal polarization:

$$\sigma_{(\alpha=0)} - \sigma_{(\alpha=180)} \propto g_1 + \gamma^2 g_2 \qquad (\gamma^2 \sim 0.01 \text{ at } 100\,\mathrm{GeV})$$

Transverse polarization:

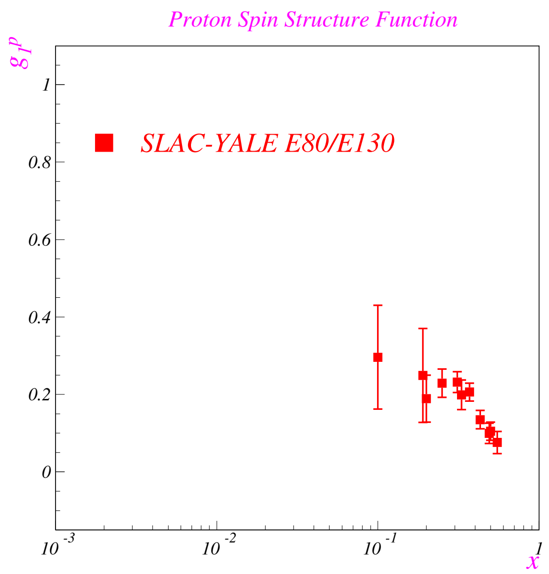
$$\sigma_{(\alpha=90)} - \sigma_{(\alpha=270)} \propto y\,g_1 + 2\,g_2$$

SLAC-YALE E80/E130 Experiment

G. Baum *et al*; Phys. Rev. Lett. **51** (1983) 1135.

First measurements of spin-dependent asymmetries

- Polarized 16.2 and 22.7 GeV electron beams
- Butanol polarized target
- Kinematic range (rather limited):
  $0.18 \leq x \leq 0.7$
  $3.5\ \mathrm{GeV}^2 \leq Q^2 \leq 10\ \mathrm{GeV}^2$



Estimate the first moment $\Gamma_1^p = \int_0^1 g_1(x)\mathrm{d}x$:

Use the Regge prediction $A_1 \propto x^{1.14}$ for low x

$A_1 = \sqrt{x}$ (fit) for large x

$$\int_0^1 g_1(x)\mathrm{d}x = 0.17 \pm 0.05$$

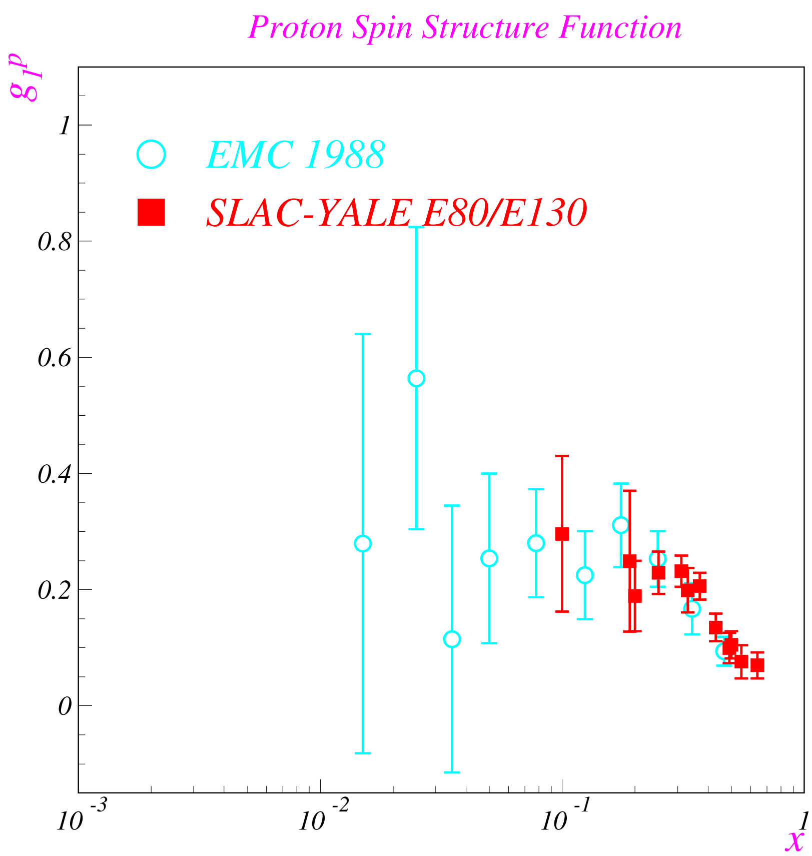
Consistent with the Ellis-Jaffe sum rule

The EMC Experiment at CERN

J. Ashman *et al:* Phys. Lett. **B206** (1988) 364;
Nucl. Phys. **328** (1989) 1.

Extend the kinematic range to lower x

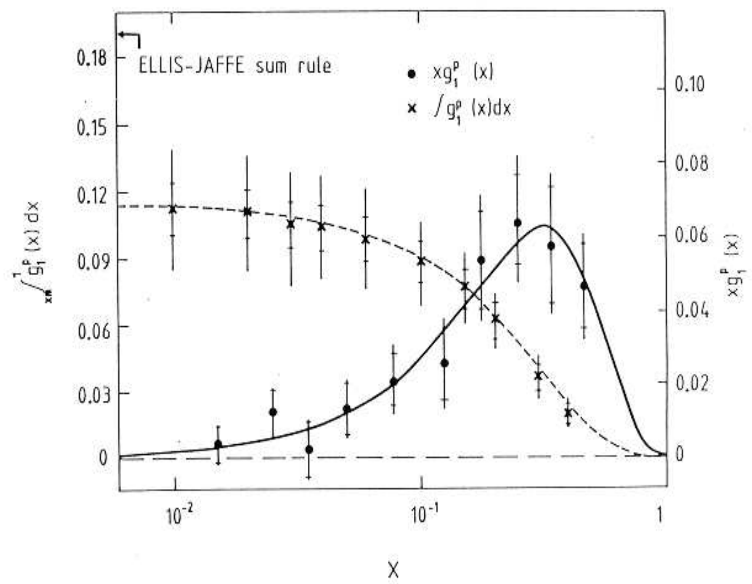
- High energy (100, 120 200 GeV) muon beams, naturally polarized and double cell butanol polarized target
- Kinematic range:
  $0.01 \leq x \leq 0.7 \qquad 1.5\ \mathrm{GeV}^2 \leq Q^2 \leq 70\ \mathrm{GeV}^2$



The EMC Experiment at CERN (Cont.)

The Spin Crisis

(E. Leader and M. Anselimo Z. Phys. C **41** (1988) 239.



$$\int_0^1 g_1(x)\mathrm{d}x = 0.114 \pm 0.012 \pm 0.026$$

Inconsistent with the Ellis-Jaffe sum rule

$$\Gamma_1^{\mathrm{p}} = 0.189 \pm 0.005$$

CONCLUDE:

Only a small fraction of the proton spin is carried by the spin of the quarks $(14 \pm 9 \pm 21)\%$

The next generation of experiments (1988-2000)

- Extend the kinematic range (Low x)
- Reduce uncertainties:
  Better statistics.
  Reduce systematic errors
  (Beam and target polarization; false asymmetries)
- Test experimentally the fundamental Bjorken Sum Rule
  Measure the proton and neutron spin structure functions.

EXPERIMENTS

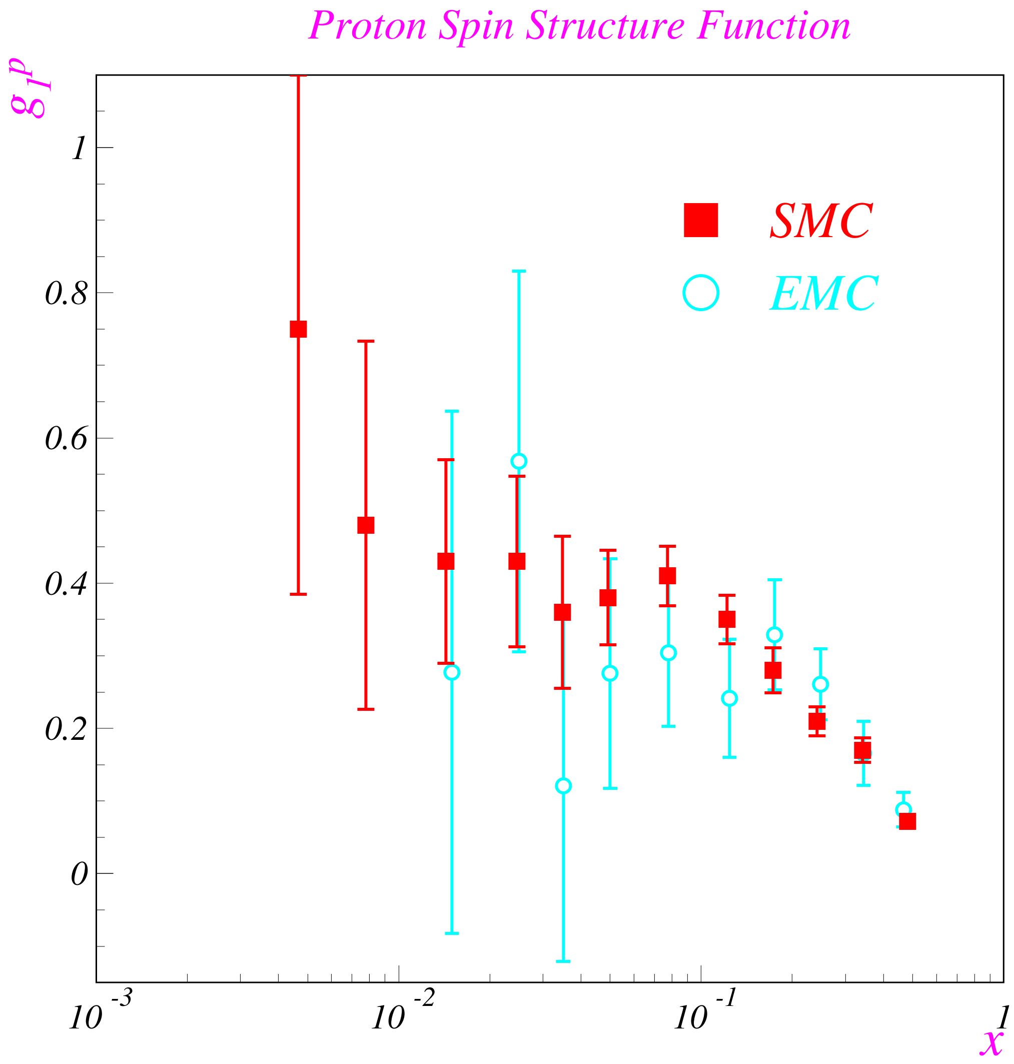
- The Spin Muon Collaboration at CERN:
  Measure the proton and the deuteron
- E142, E154 at SLAC:
  Measure the neutron from polarized ^{3}He
- E143 and E155 at SLAC:
  Measure the proton and the deuteron
- HERMES at DESY:
  Measure ^{3}He, proton and deuteron;
  good semi-inclusive set-up

THE SMC experimental set-up: Spectrometer

The SMC experimental set-up:
polarized target

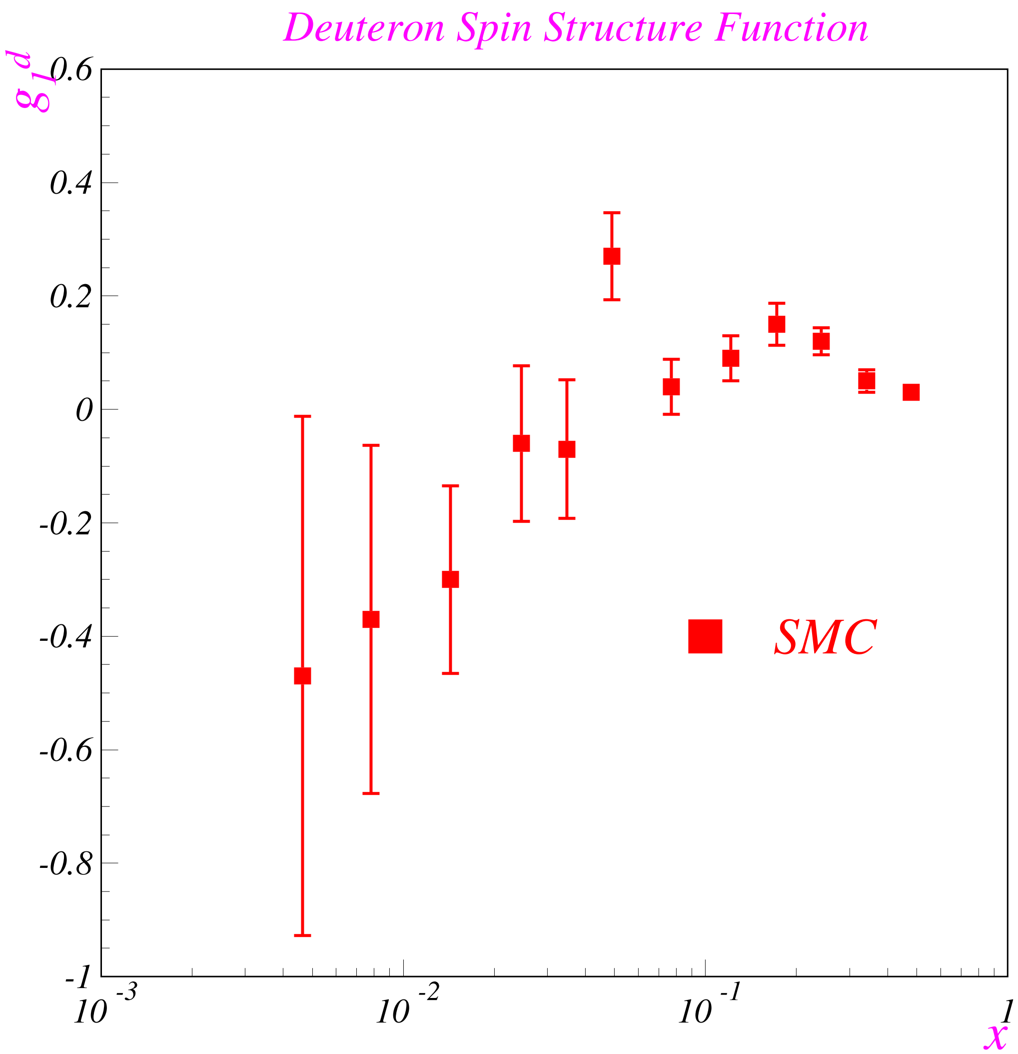
SMC proton data

At measured Q^2

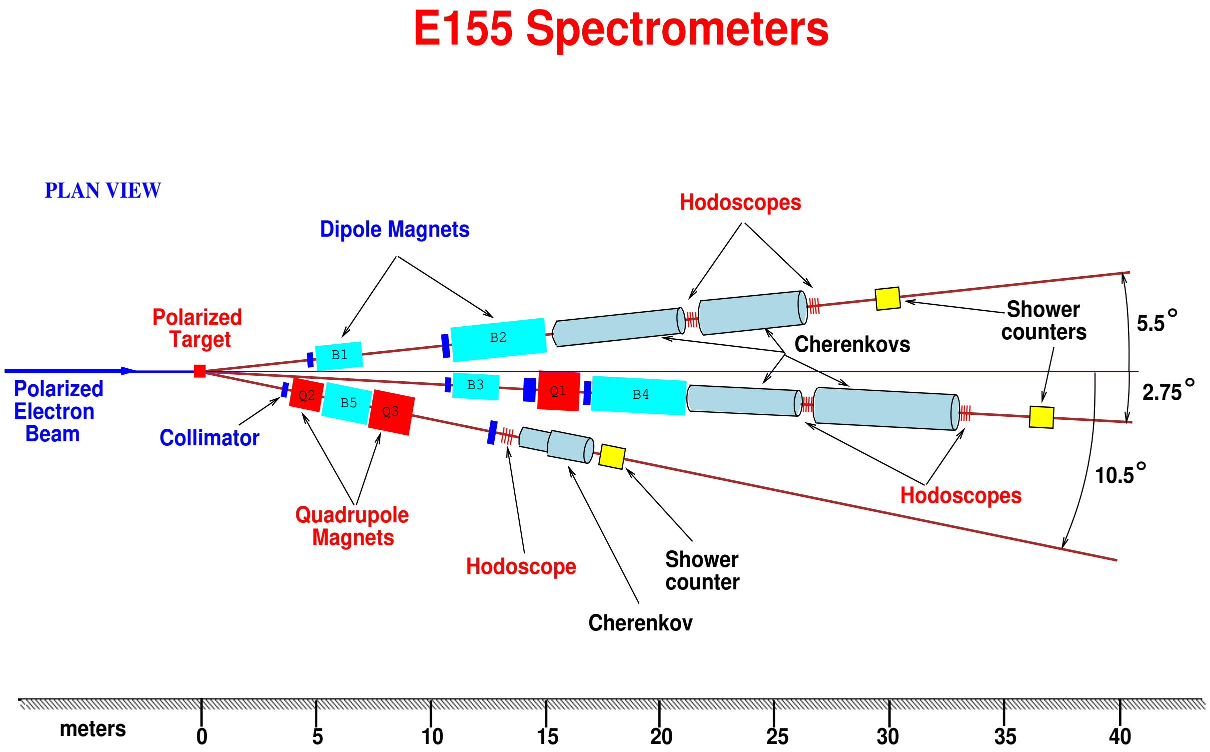


SMC deuteron data

At measured Q^2

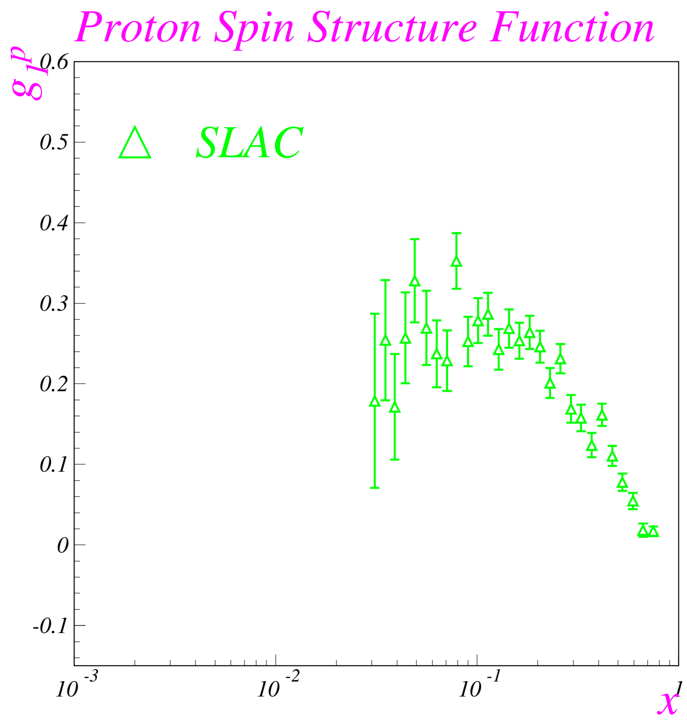


SLAC Experimental set-up (E155)

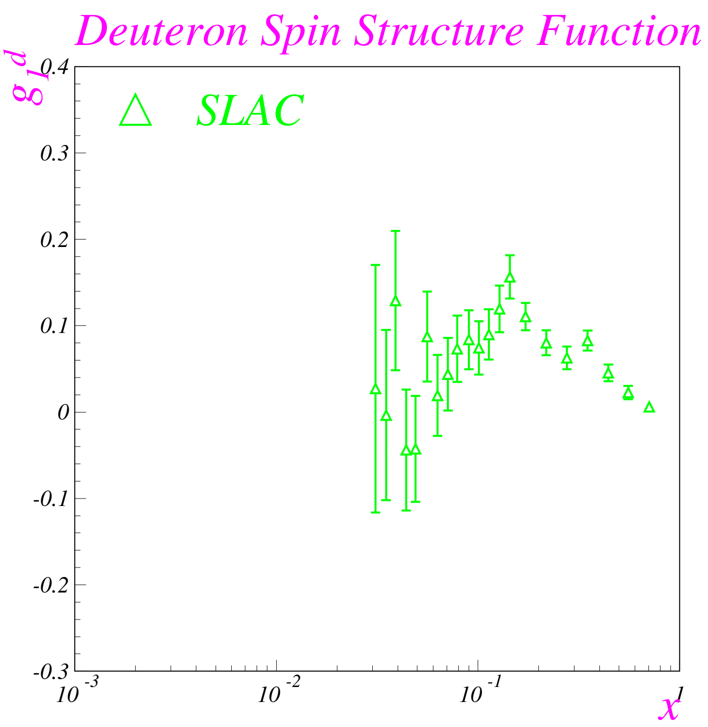


SLAC E143 Experiment

- Polarized 9.7, 16.2 and 29.1 GeV electron beams
- $^{15}NH_3$ (or $^{15}ND_3$) polarized target
- Kinematic range:
  $0.03 \leq x \leq 0.8$
  $0.3\ \mathrm{GeV}^2 \leq Q^2 \leq 10\ \mathrm{GeV}^2$
  $< Q^2 > = 3\ \mathrm{GeV}^2$



SLAC E143 Experiment (Cont.)



New analysis: Phys. Rev. D **58** 112003 (1998)

At $Q_0^2 = 3$ GeV^2 (assuming scaling):

$$\Gamma_1^{\mathrm{p}} = \int_0^1 g_1 \mathrm{d}x = 0.133 \pm 0.003 \pm 0.009$$

$$\Gamma_1^{\mathrm{d}} = \int_0^1 g_1 \mathrm{d}x = 0.047 \pm 0.003 \pm 0.006$$

(Average over different behaviors for low x)

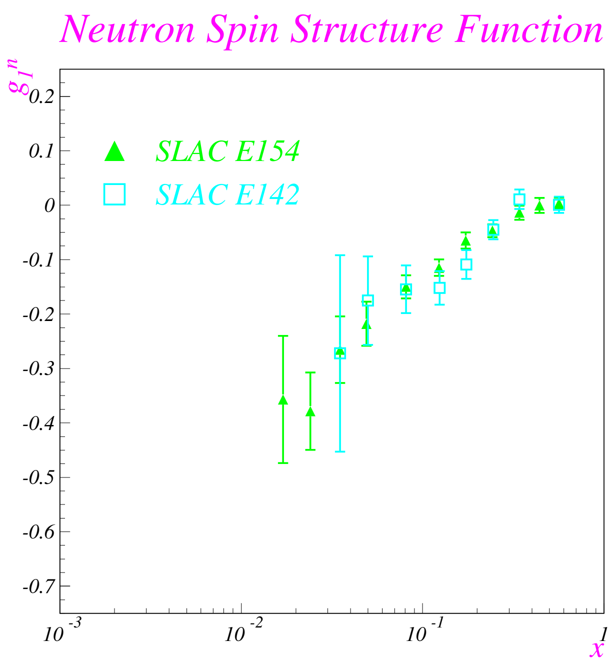
$$\Gamma_1^{\mathrm{p}} - \Gamma_1^{\mathrm{n}} = 0.164 \pm 0.023$$

Consistent with the Bjorken sum rule:

$$\Gamma_1^{\mathrm{p}} - \Gamma_1^{\mathrm{n}} = 0.177 \pm 0.004$$

SLAC E154 Experiment

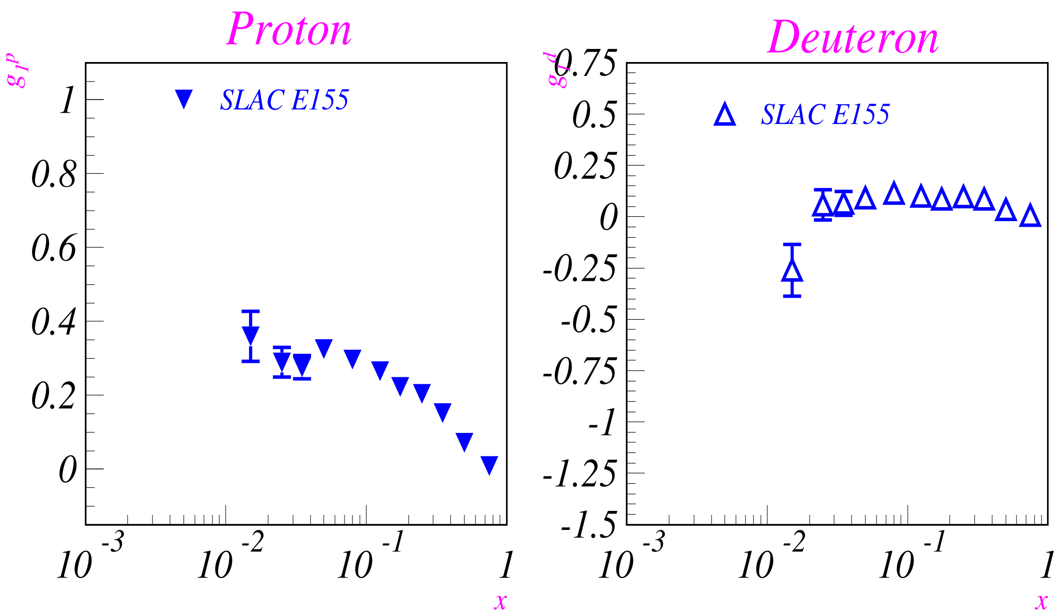
- Polarized 48.3 GeV electron beam
- ^3H_e polarized gas target
- 2 spectrometers at 2.75^o and 5.5^o
- Kinematic range:
  $0.014 \leq x \leq 0.7$
  $1.0\ GeV^2 \leq Q^2 \leq 17\ GeV^2$
  $< Q^2 > = 5\ GeV^2$



Data in good agreement with g_1^n from
E142, E143 and SMC
At $Q_0^2 = 5\ GeV^2$ (assuming scaling):
Γ_1^n = -0.041 $\pm$ 0.004 $\pm$ 0.06
(with Regge extrapolation for low x)

SLAC E155 Experiment

- Polarized 48.3 GeV electron beam
- Polarized $^{15}NH_3$ and ^{6}LiD targets
- 3 spectrometers at 2.75^o 5.5^o and 10.5^o
- Kinematic range:
  $0.01 \leq x \leq 0.9$ $\quad 1.0\ \mathrm{GeV}^2 \leq Q^2 \leq 40\ \mathrm{GeV}^2$



Data in good agreement with E143 and SMC

Fit the Q^2 dependence to evolve the data to 5 GeV^2.

Use pQCD fits (E154 and SMC) for the low x extrapolation.

At $Q_0^2 = 5\ \mathrm{GeV}^2$

$$\Gamma_1^d = 0.0266 \pm 0.0025 \pm 0.071$$

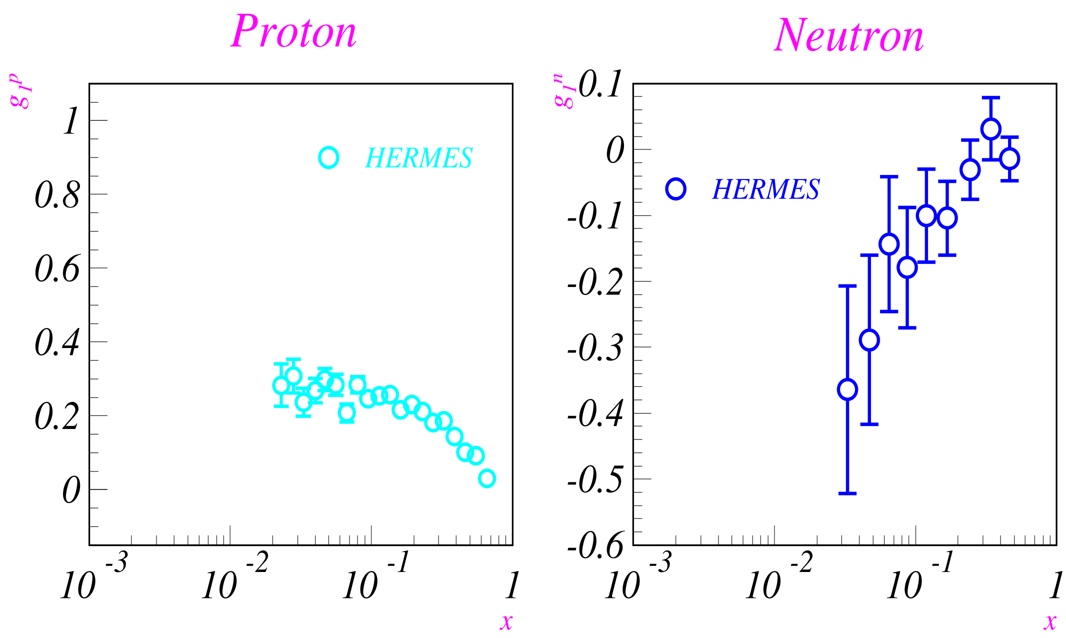
$$(\Gamma_1^d = 0.0291 \text{ with SMC pQCD fit.})$$

$$\Gamma_1^p = 0.118 \pm 0.004 \pm 0.007$$

Bjorken S.R.: $\Gamma_1^p - \Gamma_1^n = 0.176 \pm 0.003 \pm 0.007$

The HERMES Experiment at DESY

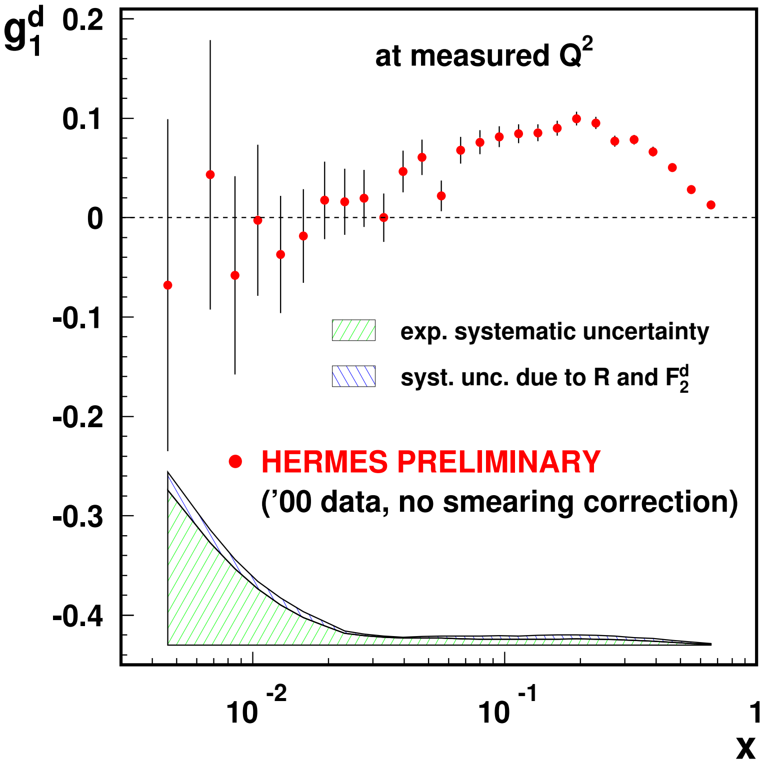
- Polarized 27.5 GeV electron beam
- $^3\mathrm{H}_e$ and H polarized internal gas (jet) targets
- Kinematic range:
  $0.023 \le x \le 0.6$
  $1.0\ \mathrm{GeV}^2 \le Q^2 \le 15\ \mathrm{GeV}^2$
  $< Q^2 > = 2.5\ \mathrm{GeV}^2$



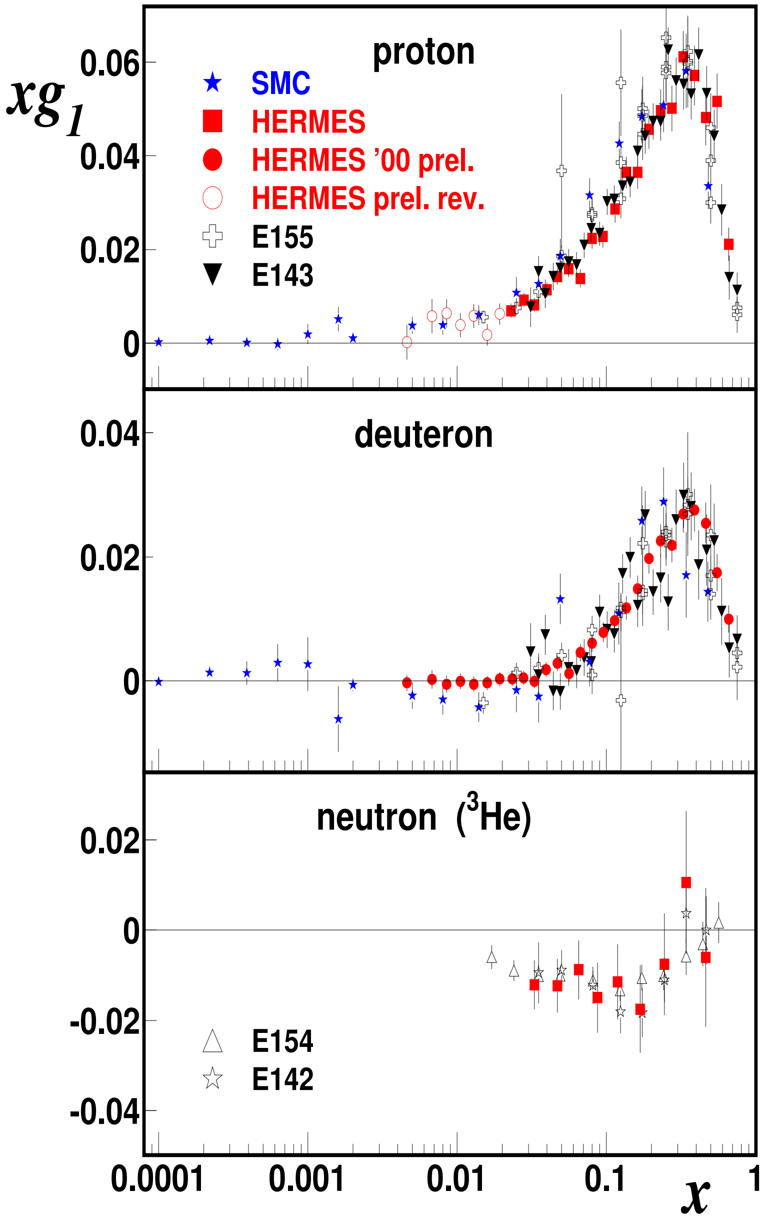
At $Q_0^2 = 2.5\ \mathrm{GeV}^2$ (assuming scaling):
Γ_1^n = -0.037 $\pm$ 0.013 $\pm$ 0.005 $\pm$ 0.006
(with Regge extrapolation for low x)

The HERMES Experiment at DESY (Cont.)

Preliminary deuteron data

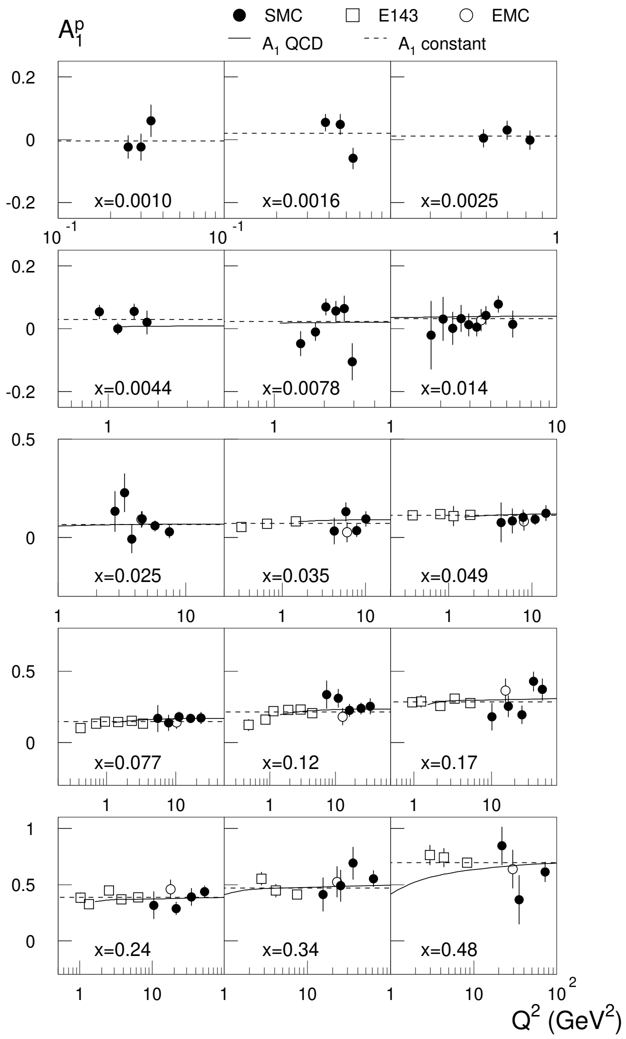


World g_1 data



Scaling of A_1^{p}

- No Q^2 dependence observed at large x
- Insufficient Q^2 range at small x
- Data is compatible with NO Q^2 dependence in A_1
- $g_1(x, Q^2) = \frac{A_1(x) F_2(x,Q^2)}{2x(1+R(x)}$



QCD Evolution - DGLAP Equations

In the parton model, g_1 is related to polarized quark and gluon distributions by an integral equation involving quark and gluon coefficient functions C_q^i and C_g through

$$
\begin{aligned}
g_1(x,t) &= \frac{1}{2}\sum_{k=1}^{n_f}\frac{e_k^2}{n_f}\int_x^1\frac{\mathrm{d}y}{y}\Big[C_q^{\mathrm{S}}(\tfrac{x}{y},\alpha_s(t))\Delta\Sigma(y,t) \\
&+ 2n_f C_g(\tfrac{x}{y},\alpha_s(t))\Delta g(y,t) \\
&+ C_q^{\mathrm{NS}}(\tfrac{x}{y},\alpha_s(t))\Delta q^{\mathrm{NS}}(y,t)\Big]
\end{aligned}
$$

where $t = \ln(Q^2/\Lambda^2)$ and Λ is a scale parameter.

$\Delta g(x,t)$ - Polarized gluon distribution.

$$
\Delta\Sigma(x,t) = \sum_{i=1}^{n_f}[\Delta q_i(x,t) + \Delta\bar{q}_i(x,t)],
$$

$$
\Delta q^{\mathrm{NS}}(x,t) =
$$

$$
\left(\sum_{k=1}^{n_f}\frac{e_k^2}{n_f}\right)^{-1}\sum_{i=1}^{n_f}\left(e_i^2 - \sum_{k=1}^{n_f}\frac{e_k^2}{n_f}\right)[\Delta q_i(x,t) + \Delta\bar{q}_i(x,t)]
$$

QCD Evolution - DGLAP Equations (Cont.)

The t dependence of the distributions follows the Altarelli-Parisi equations :

$$\frac{\mathrm{d}}{\mathrm{d}t}\Delta\Sigma(x,t) = \frac{\alpha_s(t)}{2\pi} \times$$
$$\int_x^1 \frac{\mathrm{d}y}{y}\left[P_{qq}^{\mathrm{S}}(\tfrac{x}{y},\alpha_s(t))\Delta\Sigma(y,t) + 2n_f P_{qg}(\tfrac{x}{y},\alpha_s(t))\Delta g(y,t)\right]$$
$$\frac{\mathrm{d}}{\mathrm{d}t}\Delta g(x,t) = \frac{\alpha_s(t)}{2\pi} \times$$
$$\int_x^1 \frac{\mathrm{d}y}{y}\left[P_{gq}(\tfrac{x}{y},\alpha_s(t))\Delta\Sigma(y,t) + P_{gg}(\tfrac{x}{y},\alpha_s(t))\Delta g(y,t)\right]$$

The non-singlet distribution evolves indepen-

dently of the singlet and gluon distributions:

$$\frac{\mathrm{d}}{\mathrm{d}t}\Delta q^{\mathrm{NS}}(x,t) = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{\mathrm{d}y}{y}\, P_{qq}^{\mathrm{NS}}(\tfrac{x}{y},\alpha_s(t))\Delta q^{\mathrm{NS}}(y,t)$$

The coefficient functions C_q^i and C_g and splitting functions $P_{i,j}$ can be expanded in powers of α_s. Use next to leading order (NLO) coefficient functions.

QCD Evolution

In the Adler-Bardeen scheme : $C_g^1 = \frac{\alpha_s}{4\pi}$
(Consistent with the U(1) anomaly)

$$\Gamma_1^{\mathrm{p}}(Q^2) = \frac{C^1_{\mathrm{NS}}(Q^2)}{12}\left[a_3 + \frac{1}{3}a_8\right] + \frac{C^1_{\mathrm{S}}(Q^2)}{9}a_0(Q^2)$$

$$\begin{aligned} a_0(Q^2) &= \Delta\Sigma - n_f\frac{\alpha_s(Q^2)}{2\pi}\Delta g(Q^2) \\ &= \sum_i^{n_f}\left[\Delta q_i - \frac{\alpha_s(Q^2)}{2\pi}\Delta g(Q^2)\right] \end{aligned}$$

In the $\bar{\mathrm{M}}$S scheme $C_g^1 = 0$. Then Δg does not contribute to Γ_1 and $\Delta\Sigma = a_0$.

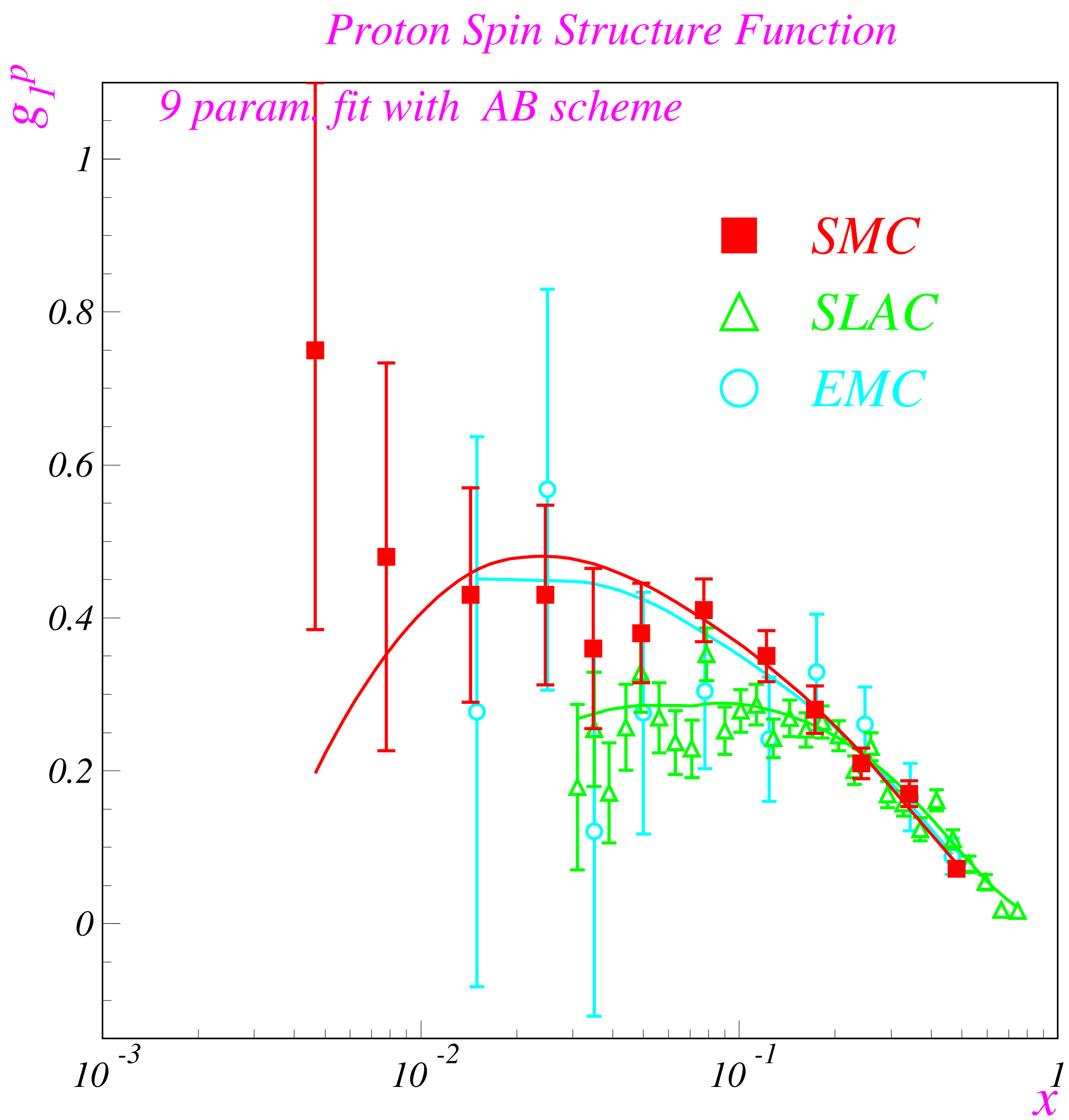
QCD Analysis in NLO

- R. Ball, S. Forte, G. Ridolfi Phys. Lett. B 378 (1996) 255
- Parton Distributions at $Q_0^2 = 1$ GeV^2:

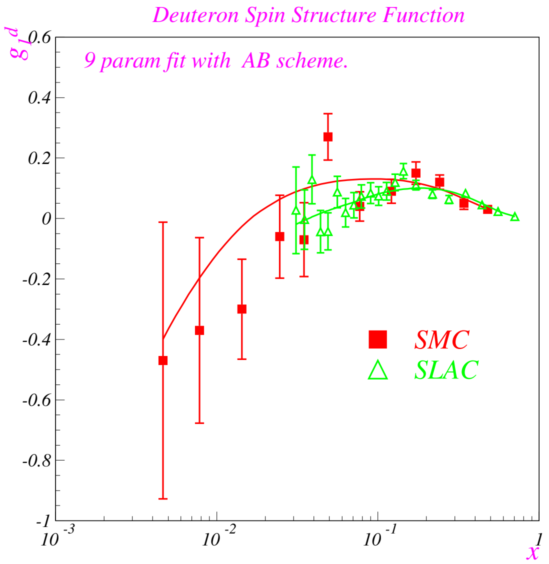
$$\Delta f = N(\alpha_f, \beta_f, a_f)\eta_f x^{\alpha_f}(1-x)^{\beta_f}(1+a_f x)$$

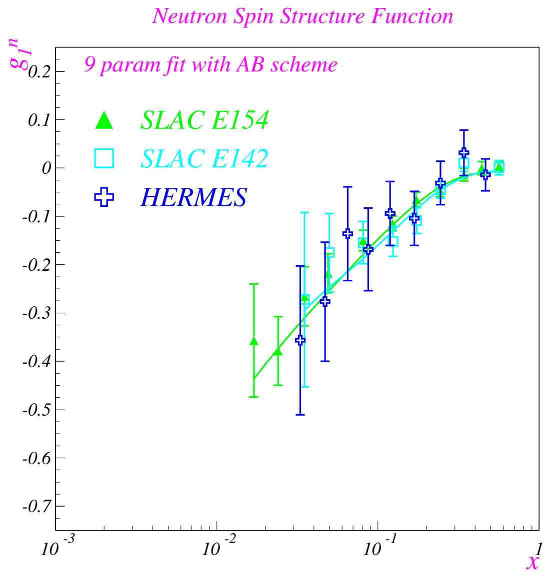
- Δf stands for:
  $\Delta\Sigma$: Singlet quark distribution
  $\Delta q_{NS}^{p,n}$: Non-singlet quark distribution
  Δg : Gluon distribution
- Normalization: $\int_0^1 N x^\alpha (1-x)^\beta (1+ax) = 1$
  - η_f are the first moments of parton distributions
- Obtain best fit parameters by evolving $g_1(x, Q^2)$ using DGLAP equations to fit the g_1 data (p,d,n) at the measured Q^2 and x.
- Poorly constrained parameters are fixed:
  $\beta_g = 4.0$, $a_g = a_{NS}^{p,n} = 0$
- Use Adler Bardeen scheme $C_g^1 = \frac{\alpha_s}{4\pi}$
  Compare also to $\overline{\rm MS}$ scheme.
- SMC, B. Adeva *et al;* Phys. Rev. **D 58** (1998) 112002
  NLO analysis of world data.

NLO Fit to World-Data



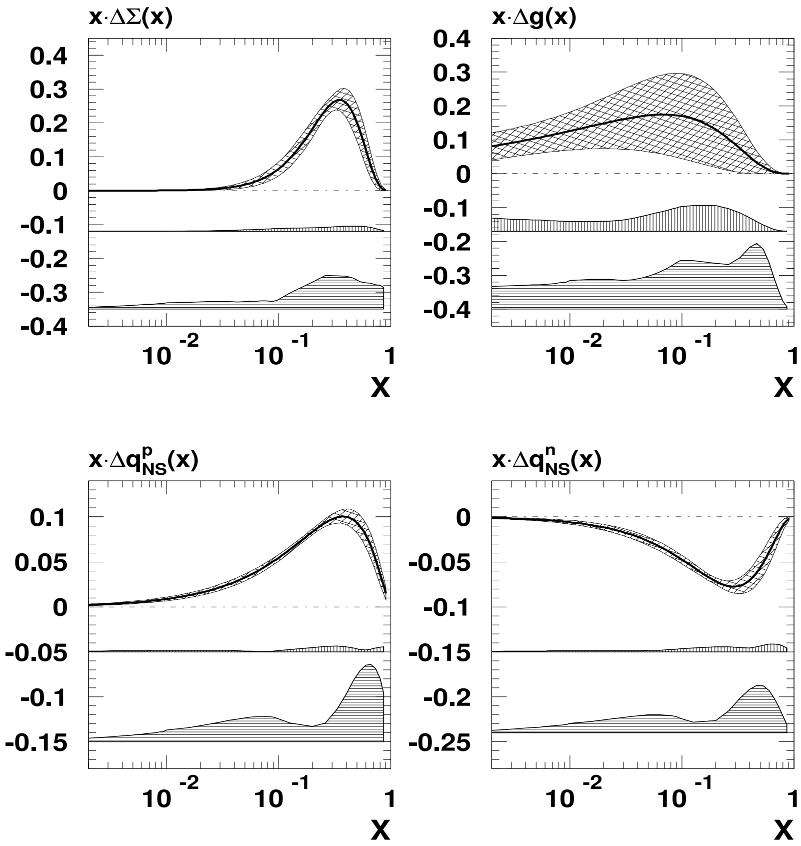
NLO Fit to World-Data (Cont.)





Parton Distributions (SMC)

AB scheme

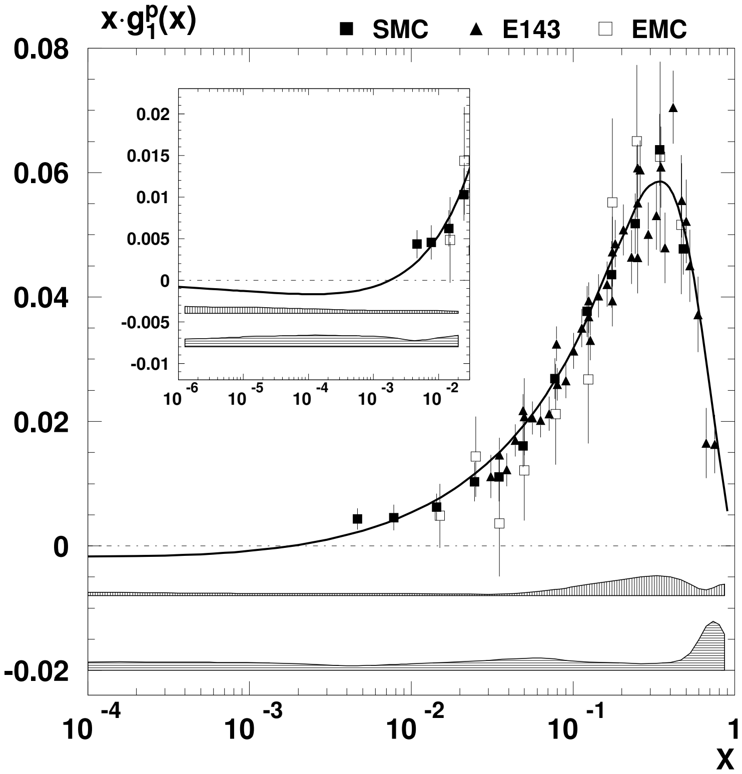


At 1 GeV^2

- SMC(p,d), SMC(p) E142(n), E143(p,d), E154(n) HERMES(n)
- $\Delta\Sigma = 0.38^{+0.03}_{-0.03}$
- $\Delta g = 0.99^{+1.17}_{-0.31}\ (\mathrm{stat})\ ^{+0.42}_{-0.22}\ (\mathrm{sys})\ ^{+1.43}_{-0.45}\ (\mathrm{th})$

Low x extrapolation of $g_1^{\rm p}$ and first moment

Proton world data evolved to $Q^2 = 5$ GeV^2



First moments:

SMC proton data (evaluated at 10 GeV^2):

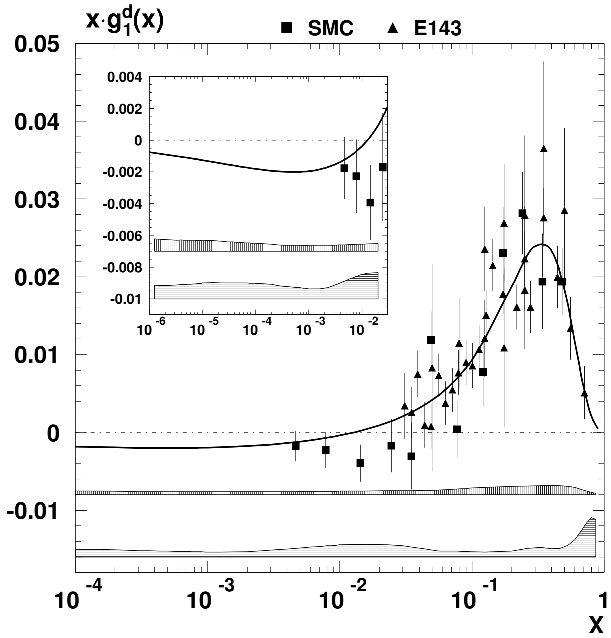
$$\int_0^1 g_1^{\rm p}(x){\rm d}x = 0.120 \pm 0.005 \pm 0.006 \pm 0.014$$

World proton data (evaluated at 5 GeV^2):

$$\int_0^1 g_1^{\rm p}(x){\rm d}x = 0.121 \pm 0.003 \pm 0.005 \pm 0.017$$

Low x extrapolation of g_1^{d} and first moment

Deuteron world data evolved to $Q^2 = 5$ GeV^2



First moments:

SMC deuteron data (evaluated at 10 GeV^2):

$$\int_0^1 g_1^{\mathrm{d}}(x)\mathrm{d}x = 0.019 \pm 0.006 \pm 0.003 \pm 0.013$$

SMC neutron (evaluated at 10 GeV^2):

$$\int_0^1 g_1^{\mathrm{n}}(x)\mathrm{d}x = -0.078 \pm 0.013 \pm 0.008 \pm 0.014$$

World deuteron data (evaluated at 5 GeV^2):

$$\int_0^1 g_1^{\mathrm{d}}(x)\mathrm{d}x = 0.021 \pm 0.004 \pm 0.003 \pm 0.016$$

World neutron data (evaluated at 5 GeV^2):

$$\int_0^1 g_1^{\mathrm{n}}(x)\mathrm{d}x = -0.075 \pm 0.007 \pm 0.005 \pm 0.019$$

New QCD analysis in NLO

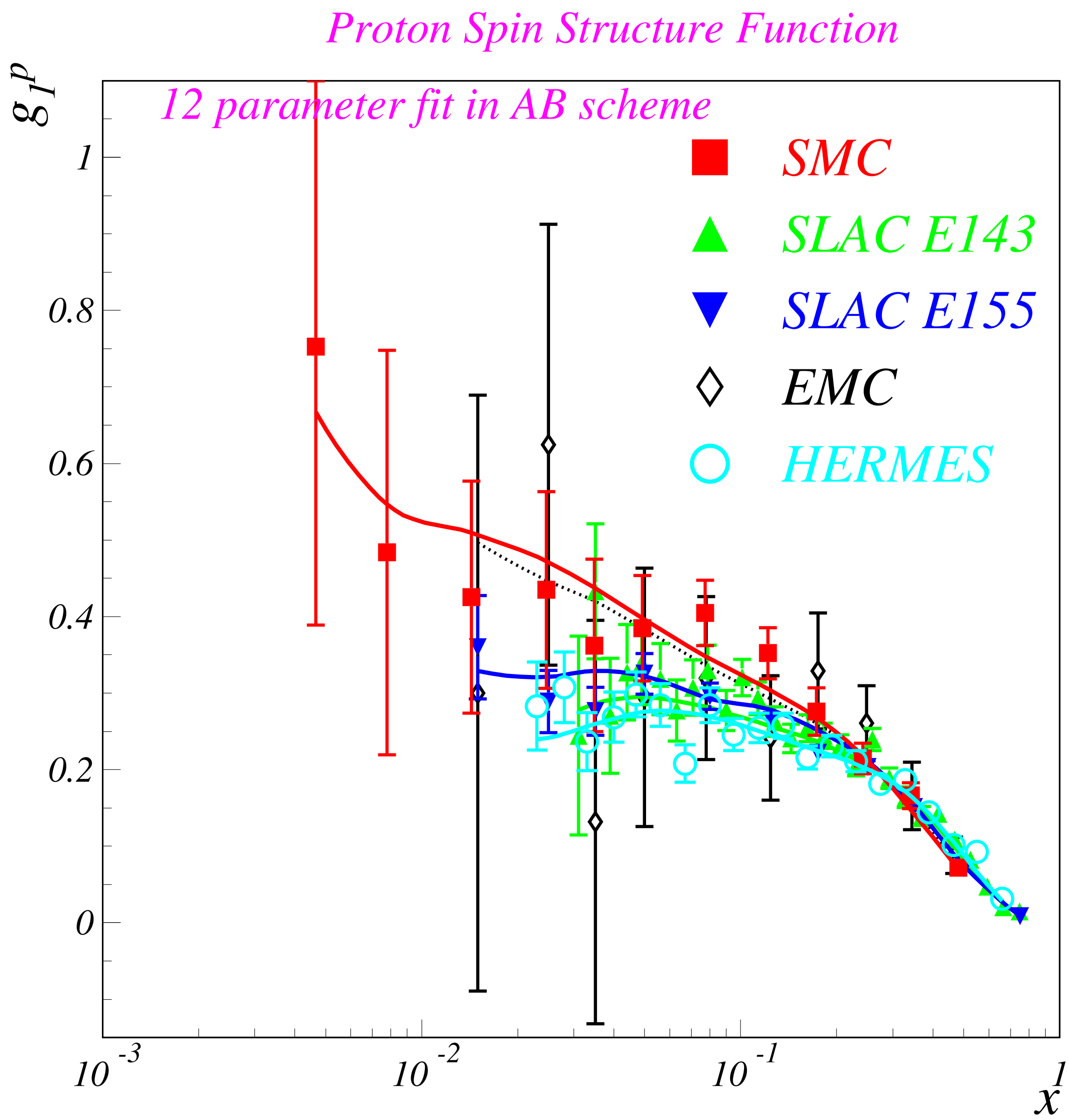
J. Lichtenstadt, Preliminary

- Include new and revised data (E143, E155, HERMES - p, ^3He).
- Fit 12 parameters.
- Parton Distributions at $Q_0^2 = 1$ GeV^2:

$$\Delta f = N(\alpha_f, \beta_f, a_f, \rho_f)\eta_f x^{\alpha_f}(1-x)^{\beta_f}(1+a_f x+\rho_f\sqrt{x})$$

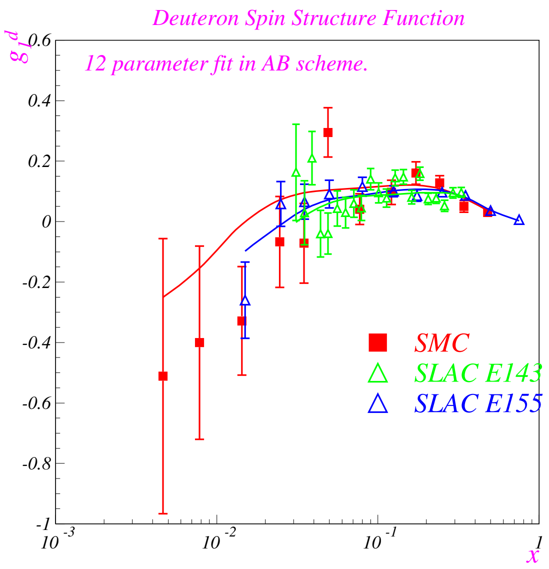
- Evaluate only statistical errors.
- Significant improvement in χ^2: 194.5/174 (Compared to 239.3/177 with 9 parameters).
- Systematic and theoretical are still significant (same).
- Analysis in AB scheme.

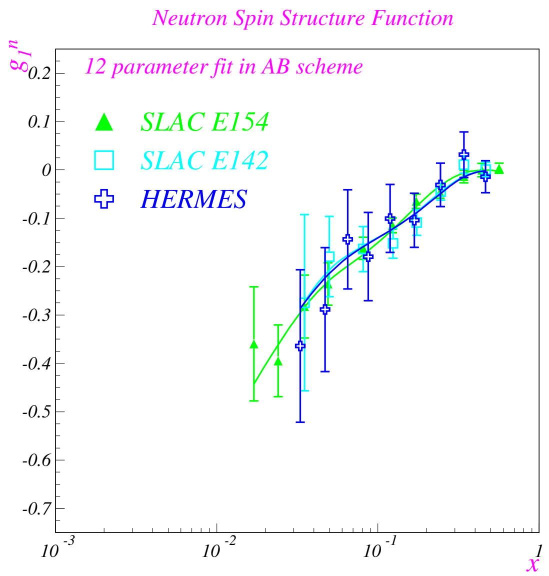
NLO Fit to World-Data
(Preliminary)



NLO Fit to World-Data (Cont.)

(Preliminary)

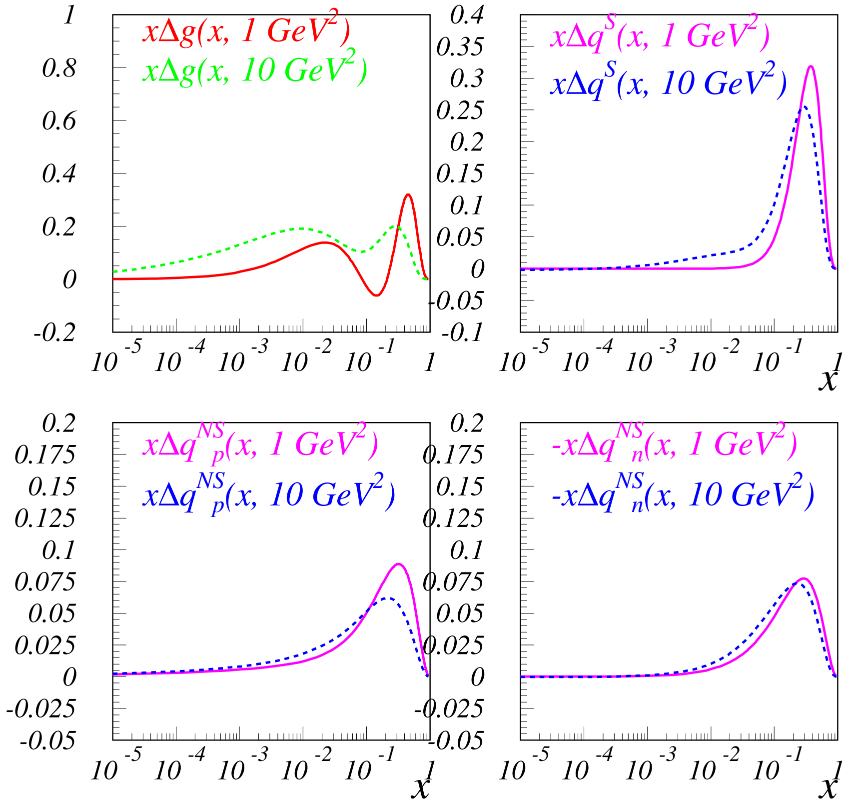




Parton Distributions (New Fit)

AB scheme

(12 parameter fit - PRELIMINARY)



At 1 GeV^2

- $\Delta\Sigma = 0.40^{+0.02}_{-0.02}$ (stat)
- $\Delta g = 0.63^{+0.20}_{-0.19}$ (stat)

The polarized gluon distribution Δg
and
The flavor singlet axial current a_0

From QCD analysis (in NLO and AB scheme):
At 1 GeV^2

$$\eta_g = \int_0^1 \Delta g(x)\mathrm{d}x = 0.63\ ^{+0.20}_{-0.19}\ (\mathrm{sta}).$$

In the $\bar{\mathrm{M}}$S scheme a_0 is identified with the first

moment of the singlet quark distribution $\int_0^1 \Delta\Sigma$

In the AB scheme the gluon contribution is subtracted:

$$a_0(Q^2) = \eta_{\mathrm{S}}^{\mathrm{AB}} - n_f \frac{\alpha_s(Q^2)}{2\pi}\eta_g(Q^2)$$

At 1 GeV^2 we obtain
$a_o = 0.30 \pm 0.04(\mathrm{sta}) \pm 0.19(\mathrm{sys})$

In the naive QPM $a_o = a_8 \simeq 0.58$

The Bjorken sum rule

A fundamental result in perturbative QCD

$$\Gamma_1^{\mathrm{p}} - \Gamma_1^{\mathrm{n}} = \frac{1}{6}\left|\frac{g_A}{g_V}\right| \cdot C_1^{\mathrm{NS}}(Q^2)$$

$C_1^{\mathrm{NS}}(Q^2$ has been calculate to 4th order in α_s

(In QCD analysis $\frac{g_A}{g_V}$ is fixed.)

Test the Bjorken sum rule by fitting $\frac{g_A}{g_V}$ in QCD analysis
At $Q_0^2 = 5$ GeV^2:

$$\left|\frac{g_A}{g_V}\right| = 1.15\ {}^{+0.03}_{-0.03}\ (\mathrm{sta})\ {}^{+0.07}_{-0.06}\ (\mathrm{sys})\ {}^{+0.14}_{-0.04}\ (\mathrm{th})$$

Obtain the Bjorken sum rule:

$$\begin{aligned}\Gamma_1^{\mathrm{p}} - \Gamma_1^{\mathrm{n}} &= 0.174\ {}^{+0.005}_{-0.005}\ (\mathrm{sta})\ {}^{+0.011}_{-0.009}\ (\mathrm{sys})\ {}^{+0.021}_{-0.006}\ (\mathrm{th}) \\ &= 0.174\ {}^{+0.024}_{-0.012}\end{aligned}$$

In good agreement with the theoretical value
$\Gamma_1^{\mathrm{p}} - \Gamma_1^{\mathrm{n}} = 0.181 \pm 0.003$

The Bjorken sum rule (Cont.)

Restrict QCD analysis to fit only Δq_{NS}

$$g_1^{\mathrm{p}}(x,Q^2) - g_1^{\mathrm{n}}(x,Q^2) =$$
$$\frac{1}{2}\langle e^2\rangle \int_x^1 \frac{\mathrm{d}y}{y}\left[C_{1,\mathrm{NS}}(\tfrac{x}{y},\alpha_s(t))\,\Delta q_{\mathrm{NS}}(y,t)\right]$$

with

$$\Delta q_{\mathrm{NS}}(x,Q^2) = \frac{3}{2}\left|\frac{g_A}{g_V}\right| \cdot N(\alpha,\beta)\cdot x^{\alpha}(1-x)^{\beta}$$

$$\left|\frac{g_A}{g_V}\right| = 1.20\ {}^{+0.08}_{-0.07}\ (\mathrm{sta})\ \ {}^{+0.12}_{-0.12}\ (\mathrm{sys})\ \ {}^{+0.10}_{-0.04}\ (\mathrm{th})$$

At $Q_0^2 = 5$ GeV^2 this value of g_A/g_V corresponds to the Bjorken sum:

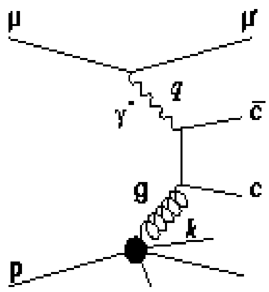
$$\begin{aligned}\Gamma_1^{\mathrm{p}} - \Gamma_1^{\mathrm{n}} &= 0.181\ {}^{+0.012}_{-0.011}\ (\mathrm{sta})\ \ {}^{+0.018}_{-0.018}\ (\mathrm{sys})\ \ {}^{+0.015}_{-0.006}\ (\mathrm{th})\\ &= 0.181\ {}^{+0.026}_{-0.021}\end{aligned}$$

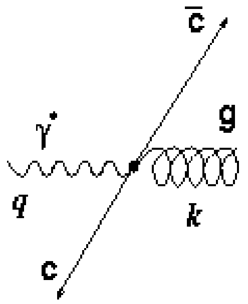
New experiments: COMPASS

Direct measurement of the polarized gluon distribution

Measure the asymmetry of processes in which
Δg contributes in leading order

Open charm production via photon gluon fusion





$$A_{\gamma \mathrm{N}}^{\bar{c}c}(\nu) = \frac{\Delta\sigma^{\gamma \mathrm{N} \to \bar{c}cX}}{\sigma^{\gamma \mathrm{N} \to \bar{c}cX}} = \frac{\int_{4m_c^2}^{2M_N\nu} \mathrm{d}\hat{s}\Delta\sigma(\hat{s})\Delta g(\eta,\hat{s})}{\int_{4m_c^2}^{2M_N\nu} \mathrm{d}\hat{s}\sigma(\hat{s})g(\eta,\hat{s})}$$

Will be measured at COMPASS and in RHIC-SPIN.

COMPASS will measure $\frac{\Delta g}{g}$ with an accuracy of:

$\delta A_{\gamma \mathrm{p}}^{\bar{c}c} = 0.06$ corresponding to $\delta\left(\frac{\Delta g}{g}\right) = 0.15$

Next Generation Experiments - Colliders

e-RHIC Machine Parameters

- Beam Energies:
  - $E_p = 250$ GeV
  - $E_e = 10$ GeV
- **Beam Polarizations:**
  - $P_p = 0.7$
  - $P_e = 0.7$
- **Integrated Luminosities** ($\mathcal{L}$:)
  - 85 pb^{-1}/day (4.2 fb^{-1} / year)

Kinematic and Detector Cuts:

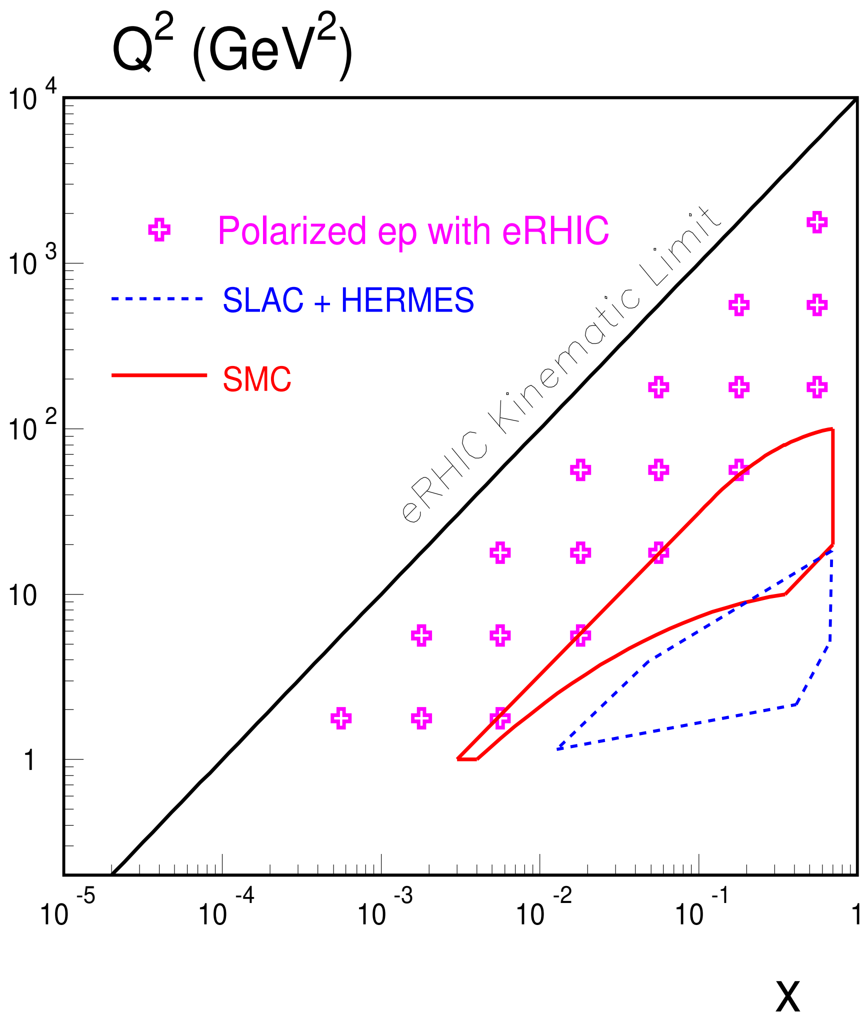
- $0.01 \; < \; y \; < \; 0.9$

Resultant Kinematic Range:

- $6 \times 10^{-4} \; < \; x \; < \; 0.6$
- $1.8 \; < \; Q^2 \; < \; 1.8 \times 10^3$ (GeV^2)

Measurement of $g_1(x, Q^2)$ at e-RHIC

Kinematic range:



- Beam energies $E_p = 250$ GeV; $E_e = 10$ GeV provide $\sqrt{s} \sim 100$ GeV
  A significant improvement compared to **fixed target** experiments.

What shall we learn from new collider polarized data?

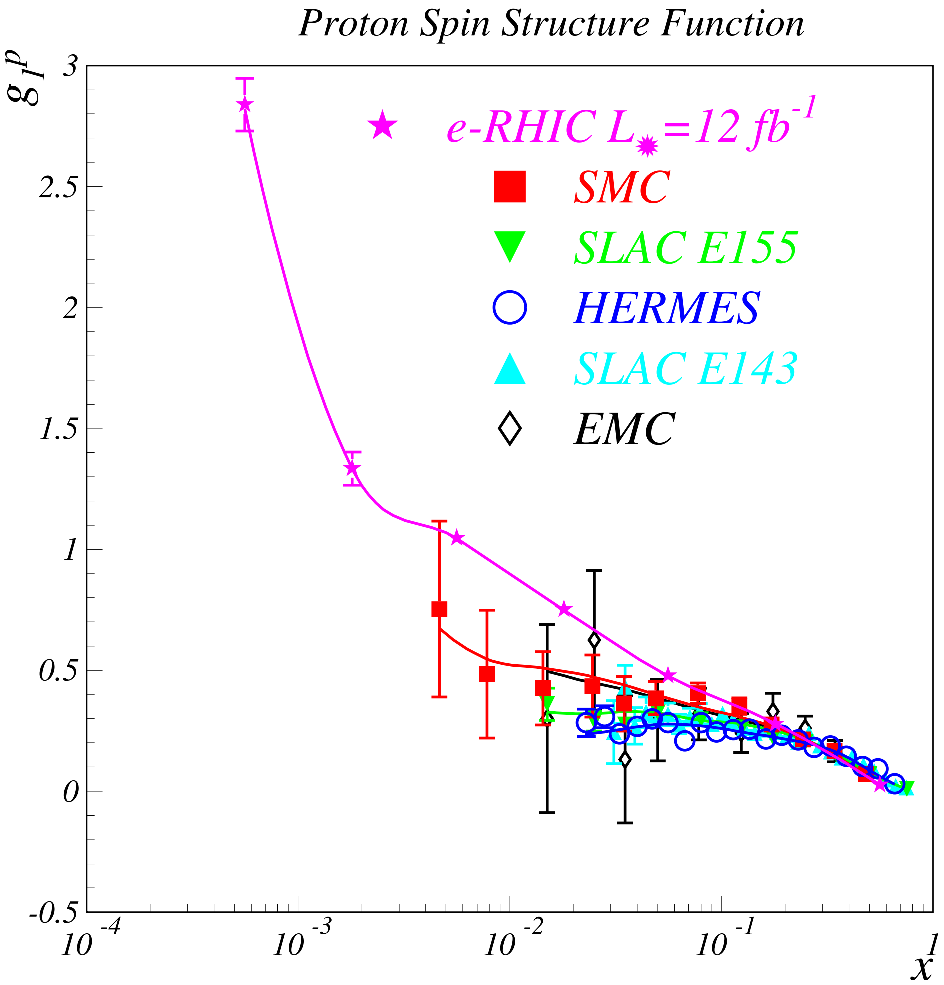
1. Projection of $g_1(x, Q^2)$ values at e-RHIC and QCD analysis

- **Statistical uncertainty on g_1^p at e-RHIC**
  - Use DIS cross section formula to estimate the DIS event rates at e-RHIC
  - **Detector acceptance**
    - Apply kinematic acceptance cuts on the projected data
- **g_1 prediction in e-RHIC $x - Q^2$ range**
  - QCD analysis of present data
  - Use best fit parameters and DGLAP equations to calculate $g_1^p(x, Q^2)$ for e-RHIC kinematics.
- **Randomize projected data around the exact value within the statistical error**

- **QCD analysis of present-day data with projected data to deduce Δg**

Fit to world data and e-RHIC projections

Three years - 12.6 fb^{-1}



From QCD analysis (in NLO) at 1 GeV^2:

$$\eta_g = \int_0^1 \Delta g(x)\mathrm{d}x = 0.7\,^{+0.08}_{-0.08}\;(\text{statistical})$$

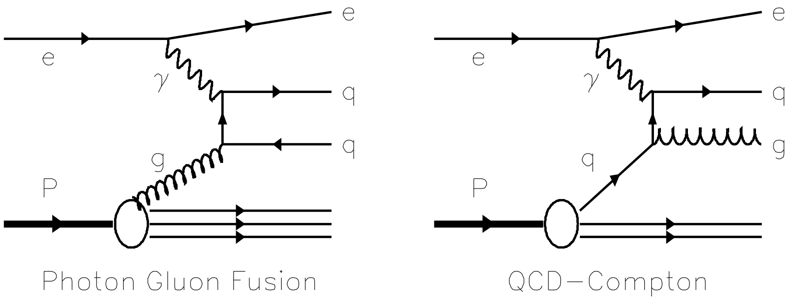
$$\eta_q = \Delta\Sigma = 0.41 \pm 0.015\;(\text{statistical})$$

What shall we learn from new collider (e-RHIC) polarized data?

2. $\Delta g(x)$ from (2+1) Jet Asymmetries

With G. Rädel and A. DeRoeck

- Process: Photon Gluon Fusion (PGF).



$$x_g = x_{\mathrm{Bj}}(1 + \frac{\hat{s}}{Q^2})$$

  - In leading order: $\sigma \sim \alpha_s \times G$
  - Process used at HERA to determine the gluon density G(x).

- For polarized DIS:

$$A = \frac{\sigma_{2-\mathrm{jet}}^{\uparrow\uparrow} - \sigma_{2-\mathrm{jet}}^{\uparrow\downarrow}}{\sigma_{2-\mathrm{jet}}^{\uparrow\uparrow} + \sigma_{2-\mathrm{jet}}^{\uparrow\downarrow}}$$

- Background from QCD Compton.

$$A \sim a_{\mathrm{PGF}} \cdot \frac{\Delta g}{G} \cdot \frac{\sigma_{\mathrm{PGF}}}{\sigma_{\mathrm{Total}}} + b_{\mathrm{QCD-C}} \cdot \frac{\Delta q}{q} \cdot \frac{\sigma_{\mathrm{QCD-C}}}{\sigma_{\mathrm{Total}}}$$

Combined analysis of g_1 and 2-jet data

A. Polarized gluon distribution Δg

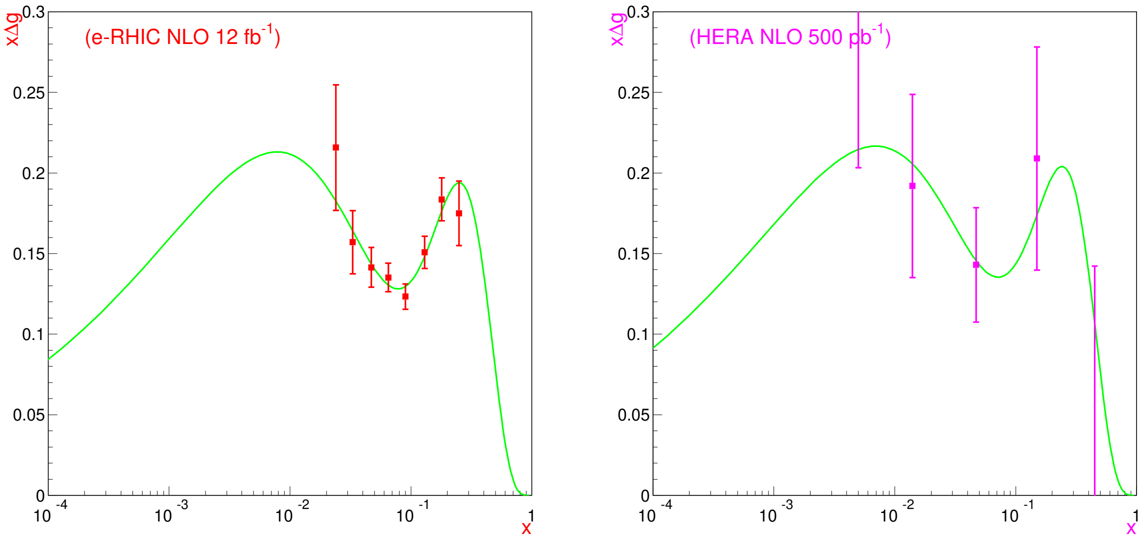
From QCD analysis (in NLO) at 1 GeV^2:

$$\eta_g = \int_0^1 \Delta g(x)\mathrm{d}x = 0.64 \pm 0.04(\text{statistical})$$

$$\eta_q = \Delta\Sigma = 0.40 \pm 0.02 \ (\text{statistical})$$

B. Sensitivity to the shape of Δg

Polarized gluon distributions
Fits compared to $\Delta g(x)$ from 2-jet asymmetries



CONCLUSIONS

- **We are at the end of the second generation of spin structure function measurements with much better data and a better theoretical understanding**
- **g_1 data from all experiments are consistent**
- **Use QCD analysis in NLO to evolve the data to a common Q_0^2**
- **QCD analysis provides a better estimate on the low-x extrapolation for the first moment**
- **The Bjorken sum rule is confirmed.**
- **The polarized gluon distribution is still not well determined but we have an estimate on it size from QCD analysis of data**
- **New experiments (COMPASS) will measure processes which are directly related to Δg (like photon-gluon fusion)**
- **Extension of the kinematic range will be possible in future experiments such as e-RHIC or at polarized HERA (if approved). Will explore the low x behavior of g_1.**

- **Experiments at e-RHIC or at polarized HERA which will include also measurements of di-jet asymmetries are expected to determine the polarized gluon distribution with about 10% accuracy**