Physics Results from Polarized DIS

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1. Introduction

2. Valence Model and BSR

3. Sea constraints

4. Gluon Models

5. Experimental Results

6. Phyiscal Implications

1 Objectives

Spin Study Goals:

- Understand chiral symmetry breaking and helicity non-conservation on the hadronic level.
- Determine nucleon structure and long range dynamics.
- Study nucleon spin structure
- Constituent spin interactions

First two: long-range (NPQCD)
Last two: short-interaction (PQCD)

Valence Quark Model

Define valence quark spin-dilution factor, $cos\Theta_d$:

$$\Delta u_v \equiv cos\Theta_d(u_v - \tfrac{2}{3}d_v)$$
$$\Delta d_v \equiv cos\Theta_d(-\tfrac{1}{3}d_v)$$
$$cos\Theta_d = [1 + R(Q^2)xG(x,Q^2)]^{-1}$$

Unpolarized distributions from deep-inelastic data ($Q^2 = 4.0$ Gev^2):

Gluck, Reya and Vogt:

Martin, Roberts and Sterling:

BSR used to determine R:

$$f_v = \langle \Delta u_v \rangle + \langle \Delta d_v \rangle = 1.00 - 0.26 = 0.74$$
$$\mu_p/\mu_n = \frac{2\langle \Delta u_v \rangle - \langle \Delta d_v \rangle}{2\langle \Delta d_v \rangle - \langle \Delta u_v \rangle} = -1.49 \pm 0.03$$

B. Conventions

1. Broken SU(3) Sea

$\Delta\bar{u} = \Delta u_s = \Delta\bar{d} = \Delta d_s = (1+\epsilon)\Delta\bar{s} = (1+\epsilon)\Delta s$

γ_5 anomaly: $\langle p \mid \bar{q}\gamma^\mu\gamma_5 q \mid p\rangle$

For each quark flavor:

$\Delta q_5 = \Delta q_c - \frac{\alpha_s}{2\pi}\hat{\gamma} \otimes \Delta G$

Refs: Efremov and Teryaev; Altarelli and Ross
Carlitz, Collins and Mueller; Berger and Qiu

$\hat{\gamma}$ is convention dependent

physical observables are related to Δq_5

Δq_c do not evolve with Q_2

$$\sum_i (\langle \Delta q_5^i \rangle - \langle \Delta q_c^i \rangle) = \frac{N_f \alpha_s(Q^2)}{2\pi} \langle \Delta G(Q^2) \rangle \equiv \Gamma$$

2. Gluon Models:

(a) $\Delta G(x,Q^2) = xG(x,Q^2)$

(b) $\Delta G(x,Q^2) = 0$

C. Sum Rule Constraints

BSR

$$A_3 = \int_0^1 dx \left[g_1^p(x) - g_1^n(x) \right] = \frac{g_A}{g_V} \left(1 - \alpha_s^{corr}\right)$$

$$A_3 = \langle [\Delta u_v - \Delta d_v] \rangle = 1.258 \pm 0.004$$

Hyperon data

$$A_8 = \langle [\Delta u + \Delta d - 2\Delta s] \rangle = f_v + 4\epsilon \langle \Delta s \rangle = 0.58 \pm 0.02$$

Anomaly Independent Relation:

$$A_0 = \langle [\Delta u + \Delta d + \Delta s] \rangle = 9(1 - \alpha_s^{corr})^{-1} \langle g_1^p \rangle - \frac{3}{4} A_3 - \frac{1}{4} A_8$$

A_3, A_8: Anomaly terms cancel

$A_0 = \langle \Delta q \rangle_{tot} - \Gamma = f_v + f_s - \Gamma$

where f_v (f_s) is the fraction of spin carried by the valence (sea) quarks and $\langle \Delta q \rangle_{tot}$ is the spin carried by all quarks.

$$ {}^{p(n)} = \frac{1}{2}(1-\alpha_s^{corr})\langle[\frac{4(1)}{9}\Delta u_v + \frac{1(4)}{9}\Delta d_v + \frac{4(1)}{9}(\Delta u_s + \Delta\bar{u}) + \frac{1(4)}{9}(\Delta d_s + \Delta\bar{d}) + \frac{1}{9}(\Delta s + \Delta\bar{s})]\rangle $$

$$ \alpha_s^{corr} \approx (\frac{\alpha_s}{\pi}) + 3.5833(\frac{\alpha_s}{\pi})^2 + 20.2153(\frac{\alpha_s}{\pi})^3 + 130(\frac{\alpha_s}{\pi})^4, $$

$$ \begin{aligned} I^p &\equiv \int_0^1 g_1^p(x)dx = \left[\frac{a^3}{12} + \frac{a^8}{36} + \frac{a^0}{9}\right]\left(1-\alpha_s^{corr}\right), \\ I^n &\equiv \int_0^1 g_1^n(x)dx = \left[-\frac{a^3}{12} + \frac{a^8}{36} + \frac{a^0}{9}\right]\left(1-\alpha_s^{corr}\right), \\ I^d &\equiv (1-\frac{3}{2}\omega_D)\int_0^1 g_1^d(x)dx = \left[\frac{a^8}{36} + \frac{a^0}{9}\right]\left(1-\alpha_s^{corr}\right)(1-\frac{3}{2}\omega_D), \end{aligned} $$

Key Elements:

1. Separate sea and valence
2. Include anomaly term in Δq
3. Separate strange sea (mass effect, ϵ)
4. Include higher order QCD corr.
5. Separate analysis for each exp.
6. Different Gluon Models
7. BSR is Basis
8. Results Compared

Phenomenological Approach

BSR: $I_1^p - I_1^n = \frac{A_3}{6}(1 - \alpha_s^{corr})$ --- I_1^p

$A_0 = 9(1 - \alpha_s^{corr})^{-1}\, I_1^p - \frac{A_8}{4} - \frac{3A_3}{4}$ --- A_0

$\langle \Delta q \rangle_{tot} = A_0 + \Gamma$ --- $\langle \Delta q \rangle_{tot}$

$A_0 - A_8 = 6\, \langle \Delta s \rangle - \Gamma$ --- $\langle \Delta s \rangle$

$\langle \Delta S \rangle = A_0 - \langle \Delta q \rangle_v + \Gamma$ --- $\langle \Delta S \rangle$

$\langle \Delta S \rangle = (6 + 4\epsilon)\, \langle \Delta s \rangle$ --- ϵ

$\langle \Delta S \rangle = 4\, \langle \Delta u \rangle_s + 2\, \langle \Delta s \rangle$ --- $\langle \Delta u \rangle_s$

$\frac{1}{2} = \frac{1}{2}\, \langle \Delta q \rangle_{tot} + \langle \Delta G \rangle + L_z$ --- L_z

Deuteron: $I_1^p - I_1^d/(1 - \frac{3}{2}\omega_D) = \frac{A_3}{12}(1 - \alpha_s^{corr})$ --- I_1^p

Experimental Parameters for the Integrated Structure Functions

Quantity	SMC (I^p)	SMC (I^d)	E142 (I^n)	E143 (I^d)	PRELIM E154 (I^n)
I^{exp}	.136	.034	−.022	.041	−.037
Stat. err.	±.011	±.009	±.007	±.003	±.004
Sys. err.	±.011	±.006	±.006	±.004	±.010
Avg. Q^2 (GeV^2)	10.0	10.0	2.0	3.0	5.0
$\alpha_s(Q^2)$	.27	.27	.385	.35	.33

HERMES (I^n)
−.033
±.013
±.005
3.0
.35

Integrated polarized distributions by flavor $\Delta G = xG$

HERMES	Quantity	$SMC(I^p)$	$SMC(I^d)$	$E143(I^d)$	E154 (I^n) PREL.
-.052	$< \Delta u >_{sea}$	$-.077$	$-.089$	$-.068$	-.063
-.012	$< \Delta s >$	$-.037$	$-.048$	$-.028$	-.020
0.90	$< \Delta u >_{tot}$	0.85	0.82	0.87	0.87
-.37	$< \Delta d >_{tot}$	$-.42$	$-.43$	$-.40$	-.39
-.02	$< \Delta s >_{tot}$	$-.07$	$-.10$	$-.06$	-.04
-1.6	$\eta_u = \eta_d$	-2.4	-2.8	-2.1	-1.9
-0.7	η_s	-2.0	-3.0	-1.6	-1.1
3.29	ϵ	1.09	0.84	1.41	2.10
0.08	Γ	0.06	0.06	0.08	0.08
0.134	I^p	0.136	0.129	0.131	0.134
0.51	$< \Delta q >_{tot}$	0.36	0.29	0.41	0.45
0.44	$< \Delta G >$	0.46	0.46	0.44	0.45
-.20	L_z	$-.14$	$-.11$	$-.15$	-.18

$$\Delta G = 0.$$

Quantity	$SMC(I^p)$	$SMC(I^d)$	$E143(I^d)$	VDM
$<\Delta u>_{sea}$	$-.087$	$-.099$	$-.082$	$-.045$
$<\Delta s>$	$-.047$	$-.058$	$-.042$	$-.005$
$<\Delta u_{tot}>$	.83	.80	.84	.91
$<\Delta d_{tot}>$	$-.44$	$-.45$	$-.43$	$-.35$
$<\Delta s_{tot}>$	$-.09$	$-.12$	$-.08$	$-.01$
$\eta_u = \eta_d$	-2.7	-3.2	-2.6	-1.4
η_s	-2.4	-3.7	-2.5	-0.3
ϵ	0.86	0.70	0.96	8.00
Γ	0.00	0.00	0.00	0.00
I^p	.136	.129	.131	.152
$<\Delta q>_{tot}$	0.30	0.23	0.33	0.55
L_z	0.35	0.39	0.35	0.23

Progress Since EMC:

1. Exp: Lower Error bars
   Probe small-x
   Γ^p, Γ^n, Γ^d

2. Th: HOC, New Pol. Models

3. Total Quark Contributions
   0 or 1: $\frac{1}{4}$ to $\frac{1}{2}$

4. Size of Gluon and Anomaly Term
   0 to 6: 0 to $\frac{1}{2}$ (0 to 0.1 anom)

5. Range of Strange Sea Size
   0 to -0.25: 0 to -0.12

6. Orbital component L_z
   0 to -6: +0.4 to -0.2

7. $\Delta q = xq$ $(\eta \neq \pm 1)$

8. BSR in tact (I_1^p)
   $I^p_{avg} = 0.133 \pm 0.004$

9. Differences in Exps.

Models of the Flavor Dependence of the Polarized Sea

Model	$\Delta u_{tot} = \Delta d_{tot}$	Δs_{tot}
$HJL(EMC)$	−0.27	+0.00
$VDM(Theory)$	−0.09	−0.01
$GR(I^n)$	−0.10	−0.02
$CR(I^n)$	−0.12	−0.03
$GR(E143\ I^d)$	−0.14	−0.06
$GR(I^p)$	−0.15	−0.07
$GR(SMC\ I^d)$	−0.18	−0.10
$EK(SMC/E142)$	−0.17	−0.10
$CR(I^d)$	−0.20	−0.11
$CR(I^p)$	−0.21	−0.12
$QRRS(EMC)$	−0.24	−0.15
$BEK(EMC)$	−0.26	−0.23

Physics Conclusions:

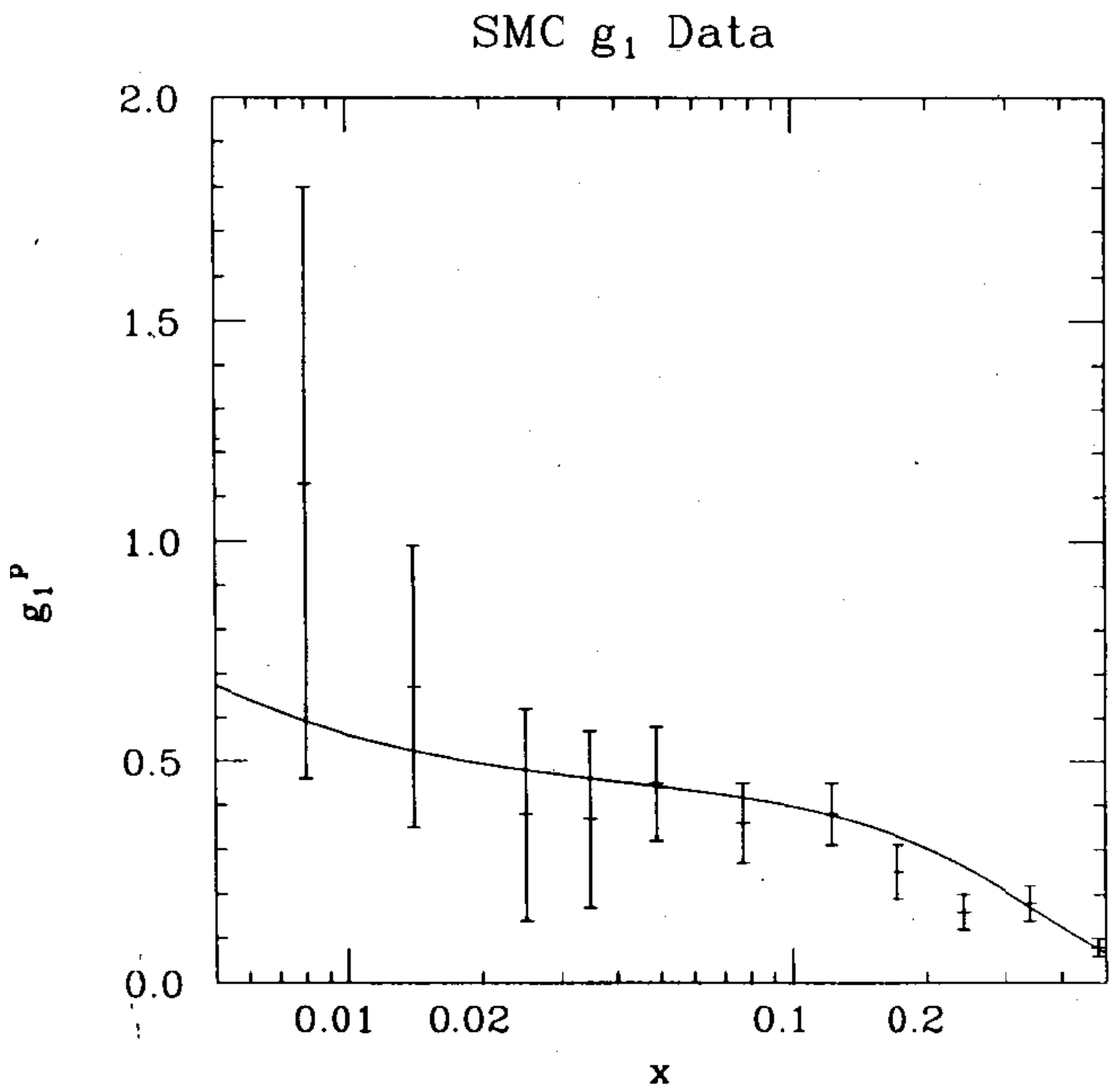
1. Total Quark Contributions
2. Significance of Anomaly Term
3. Different Strange Sea Models
4. Orbital component L_z
5. SU(3) Breaking of Sea
6. $\Delta q = xq$ Relation ($\eta \equiv \Delta q/q$)
7. BSR in tact (I_1^p)
8. Results Compared/Contrasted

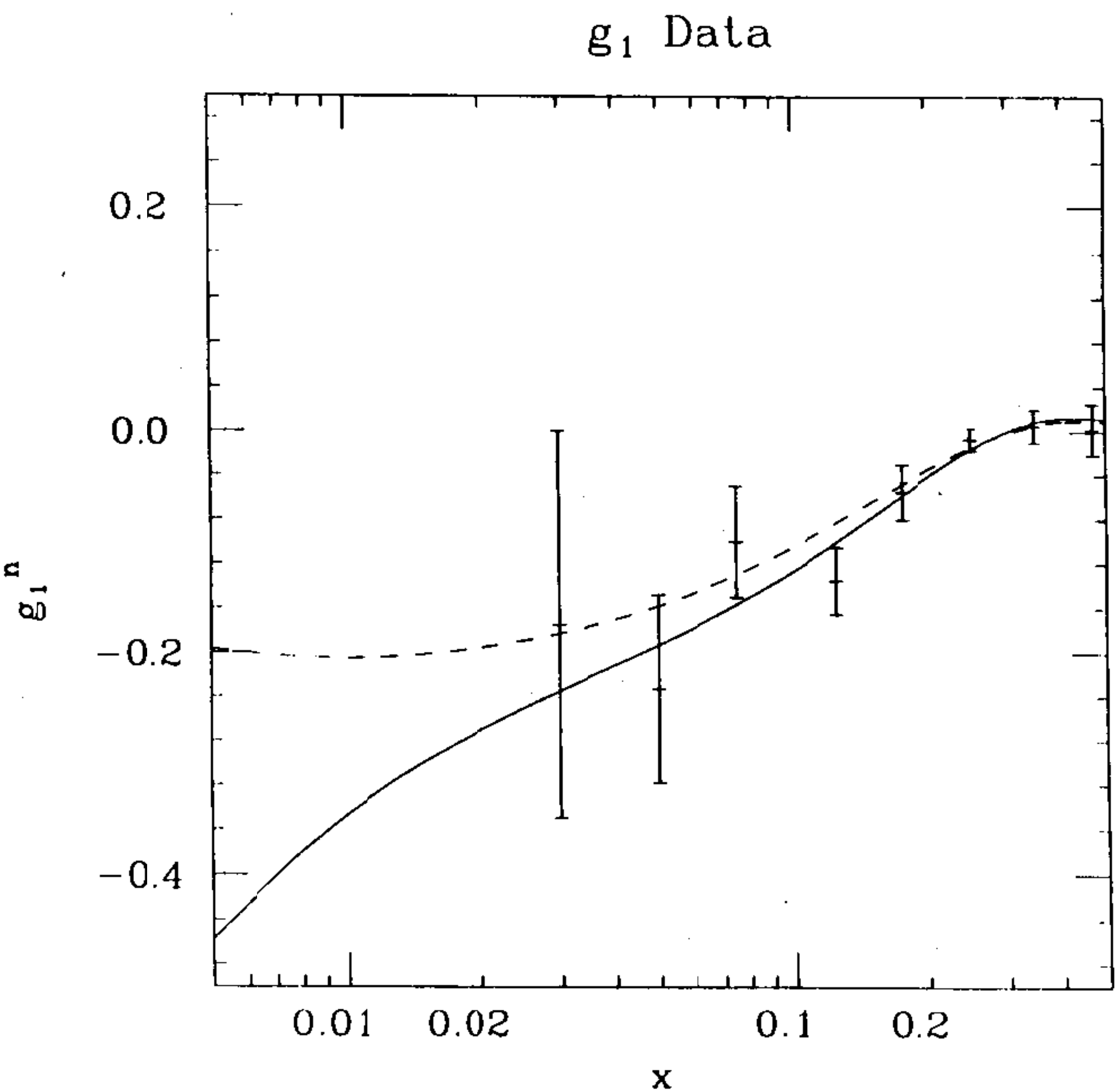
5 Deep Inelastic *ep* Scattering

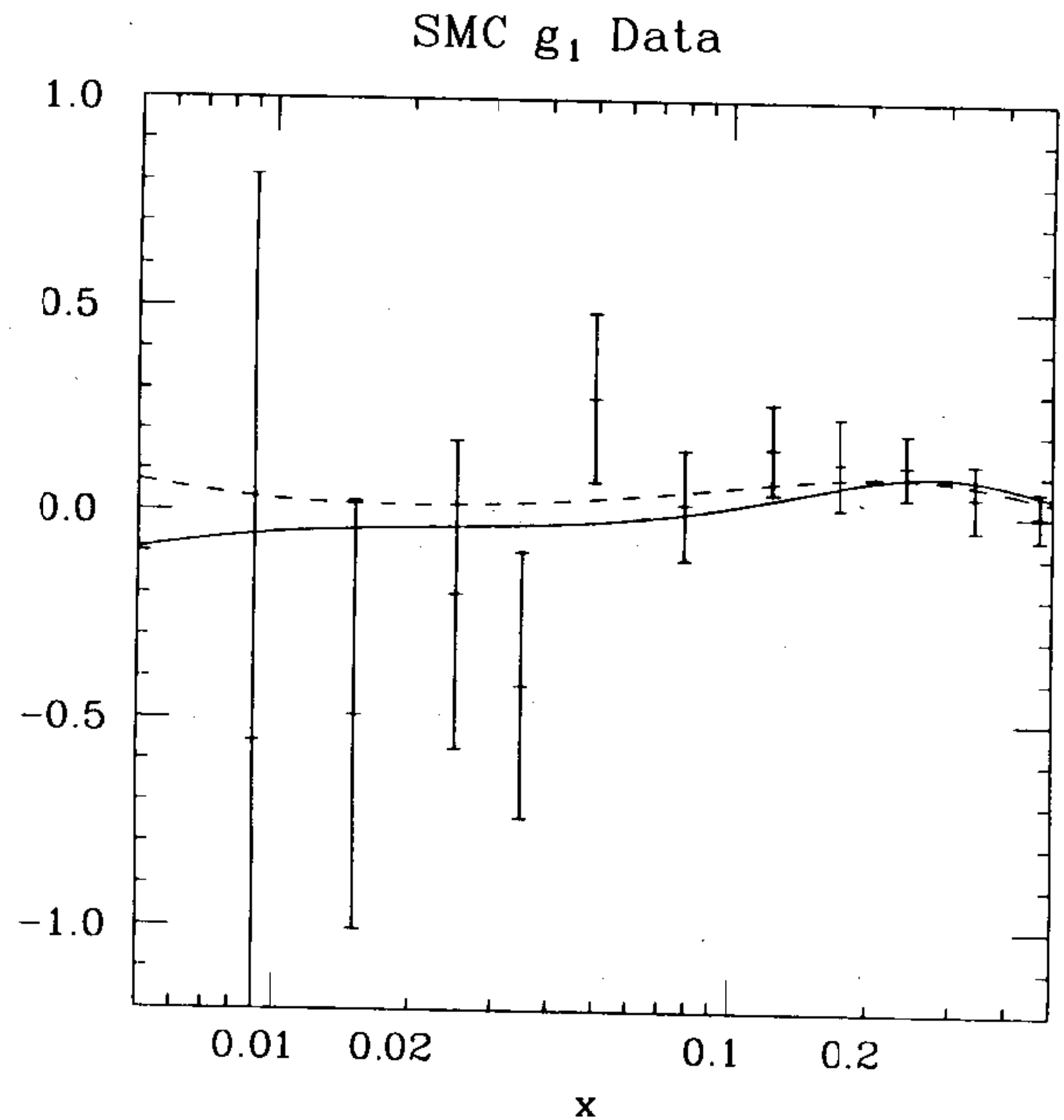
5.1 Leading Twist Observables

Nucleon Spin structure:
EMC (CERN)- naive quark model wrong
SLAC/CERN data- revised spin models
$Q^2 \simeq 2 \rightarrow 10$ GeV^2 and $x \simeq 0.003 \rightarrow 0.7$
Gives distributions $\Delta q_i(x, Q^2)$
Ref: hep-ph/9512250 - Phys. Rev. D55, 1244 (97)
Unanswered questions regarding:

(1) detailed spin structure of the nucleons,
(2) spin carried strange sea and gluons
(3) relations between polarized and unpolarized structure functions
(4) quark distribution factorization
(5) role of gluon anomaly


SMC g_1 Data
2.0
1.5
1.0
0.5
0.0
g_1^p
0.01
0.02
0.1
0.2
x


g_1 Data
g_1^n
0.2
0.0
−0.2
−0.4
0.01
0.02
0.1
0.2
x


SMC g1 Data
1.0
0.5
0.0
−0.5
−1.0
g1d
0.01
0.02
0.1
0.2
x

Extrapolation of $g_1(x)$ to $x \to 0$:

(1) small x provides insight into PQCD/NPQCD interface

(2) Regge model with intercept $\alpha_{a_1}(0) \simeq 0$

(3) data imply $g_1(x)$ may increase- small x

(4) PQCD evolution gives $g_1(x) \sim \exp\sqrt{\ln 1/x}$

(5) Regge w/ two-gluon Pomeron: $g_1 \sim \ln^2 x/x$

(6) extrapolation to $x = 0$ is important for proton structure at small x.

Measure g_1^p for $x \sim 10^{-4} - 10^{-5}$ at HERA

Experimental Program

1. Deep inelastic scattering to small-x:
   DESY, SLAC CERN

2. Polarized Drell-Yan: ΔS
   RHIC/PHENIX

3. pp hadronic jets: $\Delta\sigma_L^{jet}$, ΔG
   RHIC/STAR

4. Direct γ production at large p_T: ΔG
   RHIC/PHENIX

5. Inclusive π, K production: ΔG, L_z
   RHIC/PHENIX, DESY, UNK

6. Open Charm/heavy quark production: ΔG
   DESY, SLAC, RHIC, CERN

7. $W^{\pm}$ production: Δu_v, Δd_v
   SLAC, CERN

8. Elastic pp: NPQCD effects, p Wave function
   DESY, UNK

Conclusions

1. We can fit data well using many models

2. Important differences at small x

3. Disagreements on size of strange sea and gluons

4. Further experiments necessary:
   a. DIS at smaller x, and Q^2
   b. Jet, heavy Q, meson production
   c. Drell-Yan (lepton pair production)
   d. CC - $W^{\pm}$ production
5. Locations:
   a. CERN
   b. HERA
   c. RHIC
   d. SLAC