Nearly 10 Years of Spin Physics at Jefferson Lab

W. Korsch

Keh-Fei Liu's 60th Birthday Symposium

Apr. 21, 2007

UNIVERSITY OF KENTUCKY

Nucleon Spin Sum Rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + L_q(\mu) + J_g(\mu)$$

($\mu \rightarrow$ scheme dependence)

- $\Delta\Sigma = \int_0^1 \sum_i (\Delta q_i(x) + \Delta\bar{q}_i(x))$ $\rightarrow$ singlet axial charge
- L_q orbital angular momentum of the quarks
- J_q total angular momentum of the gluons

Results from Lattice QCD (Keh-Fei Liu et al.)

Results from Lattice QCD

- ✘ $\Delta u = 0.79(11)$
- ✘ $\Delta d = -0.42(11)$
- ✘ $\Delta s = -0.12(1)$

S.J. Dong, J.-F. Lagaë, and K. F. Liu, PRL 75, (1995)

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More Results from Lattice QCD

- ✘ $\Delta\Sigma = 0.30 \pm 0.07$
- ✘ $L_q = 0.17 \pm 0.06$
- ✘ $J_g = 0.20 \pm 0.07$

N. Mathur *et al.*, PRD 62 (2000)

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Recent Results from HERMES

$$\Delta u + \Delta\bar{u} = 0.842 \pm 0.004 \pm 0.008 \pm 0.009$$
$$\Delta d + \Delta\bar{d} = -0.427 \pm 0.004 \pm 0.008 \pm 0.009$$
$$\Delta s + \Delta\bar{s} = -0.085 \pm 0.013 \pm 0.008 \pm 0.009$$

$$\Delta\Sigma = 0.330 \pm 0.011 \pm 0.025 \pm 0.028$$

$Q^2 = 5GeV^2$, NLO ($\overline{MS}$), SU(3)$_f$ symmetry

A. Airapetian *et al.*, HERMES, PRD 75 (2007)

More Results from Lattice QCD

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- ✘ $L_q = 0.17 \pm 0.06$
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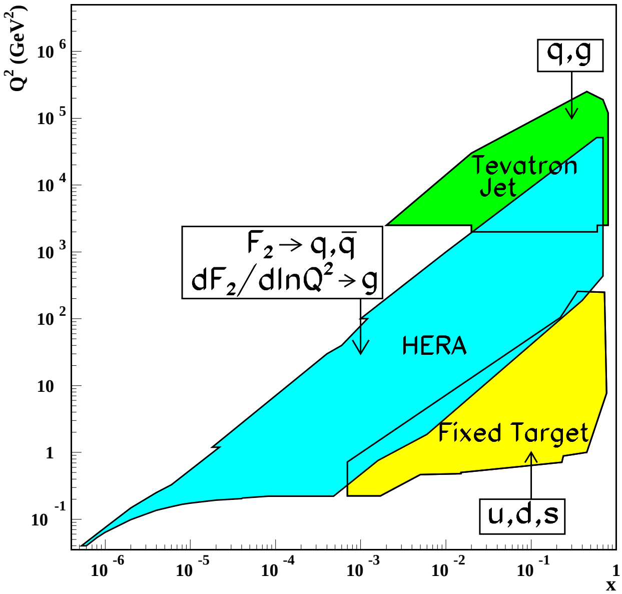
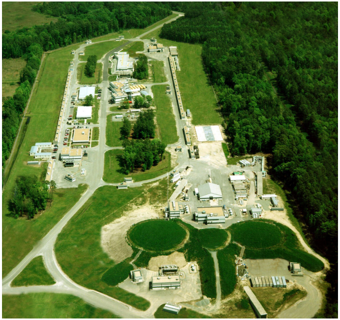
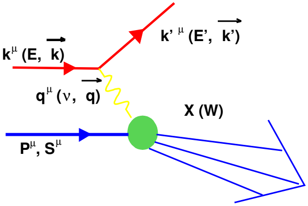


Q^2 (GeV^2)
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
q,g
Tevatron Jet
$F_2 \rightarrow q,\bar{q}$
$dF_2/d\ln Q^2 \rightarrow g$
HERA
Fixed Target
u,d,s
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

JLab Hall	Experimental Parameters				
	Target	density [cm^{-2}]	polarization	current	$\Delta\Omega$ [msr]
A	$^3\vec{He}$	10^{22}	0.5	10 μA	2$\times$6
B	$N\vec{H}_3$, $N\vec{D}_3$	$> 10^{23}$	0.7(p), $\sim$0.3(d)	2 nA	1500
C	$N\vec{H}_3$, $N\vec{D}_3$	$> 10^{23}$	0.7(p), $\sim$0.2(d)	100 nA	8

- ✘ beam energy < 6 GeV
- ✘ beam polarization $\sim$ 0.8
- ✘ polarized luminosities: $\mathcal{L} \approx (10^{35} - 10^{36})$/cm^2/s
- ✘ ideal for large-x physics and moments





Kinematic variables

$$W = \textit{invariant mass}$$
$$Q^2 = -q^2 = 4EE' \sin^2(\theta/2)$$
$$\nu = E - E' = \frac{P \cdot q}{M}$$
$$x = \frac{Q^2}{2M\nu} \quad \gamma = \frac{2Mx}{\sqrt{Q^2}}$$

Beam: longitudinally polarized

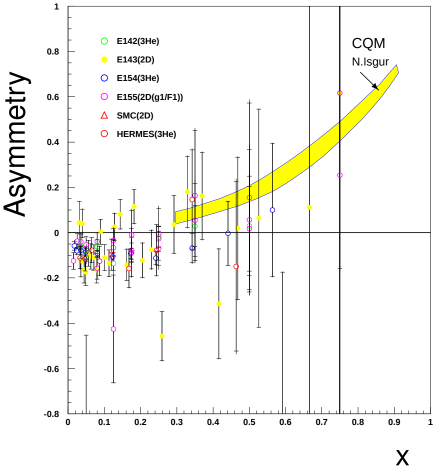
Target: longitudinally or transversely polarized

Measure scattering asymmetries ⇒ virtual photon asymmetries:

$$A_1(x, Q^2) = \frac{\sigma_{\frac{1}{2}} - \sigma_{\frac{3}{2}}}{\sigma_{\frac{1}{2}} + \sigma_{\frac{3}{2}}} = \frac{g_1(x, Q^2) - \gamma^2 g_2(x, Q^2)}{F_1(x, Q^2)}$$

$$A_2(x, Q^2) = \frac{2\sigma_{TL}}{\sigma_{\frac{1}{2}} + \sigma_{\frac{3}{2}}} = \frac{\gamma[g_1(x, Q^2) + g_2(x, Q^2)]}{F_1(x, Q^2)}$$

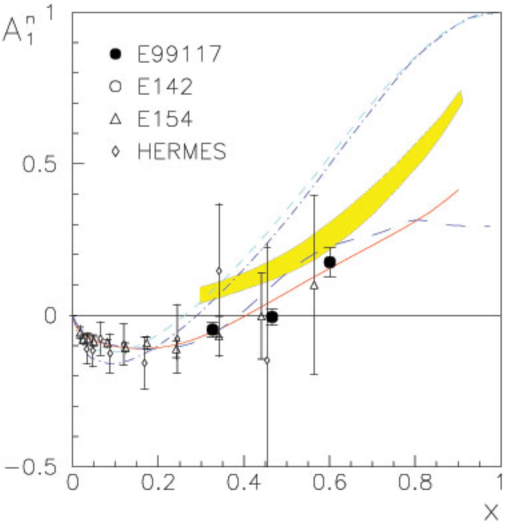
World data on A_1^n: (at measured Q^2)



☞ Large x data even consistent with SU(6) prediction: $A_1^n = 0$

Experiment E99-117 at JLab:

x	Q^2 [GeV^2/c^2]	W^2 [GeV^2]
0.33	2.72	6.38
0.48	3.55	4.80
0.61	4.86	4.00



dashed-dotted: S. Brodsky, M. Burkardt, I. Schmidt; Nucl. Phys. B441 (1995)
short dashed: E. Leader, A. Sidorov, D. Stamenov, Int. J. Mod. Phys. A13 (1998)
red solid: E. Leader, A. Sidorov, D. Stamenov; Eur.Phys. J C23 (2003)
long dashed: C. Bourrely, J. Soffer, F. Bucella; Eur.Phys. J C23 (2002)

Uncertainties:

- $\frac{\Delta E_b}{E_b} < 5 \cdot 10^{-4}$
- $\frac{\Delta p}{p} < 5 \cdot 10^{-4}$
- $\Delta \theta_e < 0.1^\circ$
- $\frac{\Delta P_b}{P_b} < 3\%$
- $\frac{\Delta P_t}{P_t} < 4\%$
- $\Delta \theta_t < 0.5^\circ$

Spin-Flavor Decomposition at Large x

Neglecting the sea quarks and combining neutron *and* proton data:

$$\frac{g_1^p}{F_1^p} = \frac{4\Delta u+\Delta d+4\Delta\bar{u}+\Delta\bar{d}}{4u+d+4\bar{u}+\bar{d}}$$

$$\frac{g_1^n}{F_1^n} = \frac{\Delta u+4\Delta d+\Delta\bar{u}+4\Delta\bar{d}}{u+4d+\bar{u}+4\bar{d}}$$

$$\frac{\Delta u+\Delta\bar{u}}{u+\bar{u}} = \frac{4}{15}\frac{g_1^p}{F_1^p}(4+R^{du}) - \frac{1}{15}\frac{g_1^n}{F_1^n}(1+4R^{du})$$

$$\frac{\Delta d+\Delta\bar{d}}{d+\bar{d}} = \frac{4}{15}\frac{g_1^n}{F_1^n}(4+\frac{1}{R^{du}}) - \frac{1}{15}\frac{g_1^p}{F_1^p}(1+\frac{4}{R^{du}})$$

with $R^{du} = \frac{d+\bar{d}}{u+\bar{u}}$.

Neglecting the sea quarks and combining neutron *and* proton data:

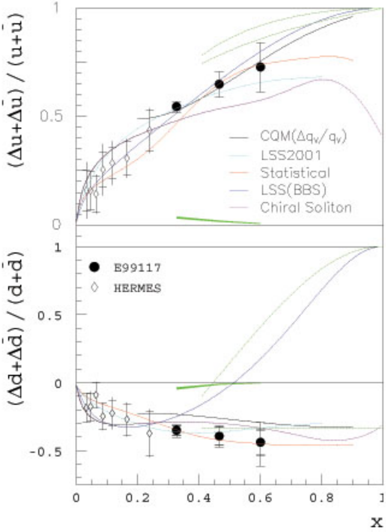
$$\frac{g_1^p}{F_1^p} = \frac{4\Delta u + \Delta d + 4\Delta\bar{u} + \Delta\bar{d}}{4u + d + 4\bar{u} + \bar{d}}$$

$$\frac{g_1^n}{F_1^n} = \frac{\Delta u + 4\Delta d + \Delta\bar{u} + 4\Delta\bar{d}}{u + 4d + \bar{u} + 4\bar{d}}$$

$$\frac{\Delta u + \Delta\bar{u}}{u + \bar{u}} = \frac{4}{15}\frac{g_1^p}{F_1^p}(4 + R^{du}) - \frac{1}{15}\frac{g_1^n}{F_1^n}(1 + 4R^{du})$$

$$\frac{\Delta d + \Delta\bar{d}}{d + \bar{d}} = \frac{4}{15}\frac{g_1^n}{F_1^n}\left(4 + \frac{1}{R^{du}}\right) - \frac{1}{15}\frac{g_1^p}{F_1^p}\left(1 + \frac{4}{R^{du}}\right)$$

with $R^{du} = \frac{d+\bar{d}}{u+\bar{u}}$.



From ^{3}He to the Neutron

In general: $g_{1,2}^{^3He}(x,Q^2) = P_n g_{1,2}^n(x,Q^2) + 2P_p g_{1,2}^p(x,Q^2)$

- spin depolarization → S′ -, D - states → $P_n = 0.86^{+0.036}_{-0.020}$, $P_p = -0.028^{+0.094}_{-0.004}$
- nuclear binding, Fermi motion ⟶ Δ isobar, pions, vector mesons, off-shell effects
- small-x-effects (nuclear shadowing, nuclear anti-shadowing: $0.05 \lesssim x \lesssim 0.2$)

In resonance region: nuclear binding and Fermi motion significant:
$g_{1,2}^n \Rightarrow$ (20-30)% uncertainty, but effects on integrals smaller ($\lesssim$10%)

$$\Gamma^n(Q^2) = \frac{1}{P_n}\Gamma^{^3He}(Q^2) - 2\frac{P_p}{P_n}\Gamma^p(Q^2)$$

Proton: MAID or CLAS (Hall B)

J.L. Friar et al., PRC42, 2310 (1990)
C. Ciofi degli Atti et al., PRC48, R968 (1993)
F. Bissey et al., PRC65, 064317 (2002)

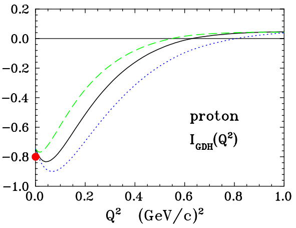
The Generalized Drell-Hearn-Gerasimov Sum Rule

$$\mathrm{I}(\mathrm{Q}^2 = 0) = \int_{\nu_{\mathrm{thresh}}}^{\infty} \frac{d\nu}{\nu}(\sigma_{\uparrow\downarrow}(\nu) - \sigma_{\uparrow\uparrow}(\nu)) = -\frac{2\pi^2\alpha}{\mathrm{M_N}}\kappa_{\mathrm{N}}^2 \Rightarrow \mathrm{I}(\mathrm{Q}^2) \quad ✔$$

$$\mathrm{I^n}(\mathrm{Q}^2) = \frac{1}{\mathrm{P_n}}\widetilde{\mathrm{I}}^{^3\mathrm{He}}(\mathrm{Q}^2) - 2\frac{\mathrm{P_p}}{\mathrm{P_n}}\mathrm{I^p}(\mathrm{Q}^2)$$

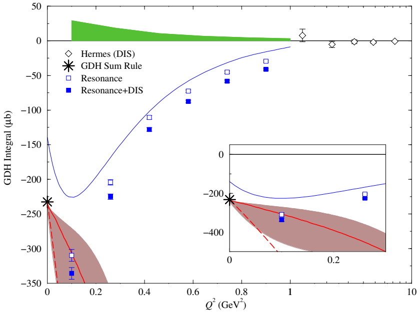
S.B. Gerasimov, *Sov. J. Nucl. Phys.* 2, 430, 1966
S.D. Drell and A.C. Hearn, *Phys. Rev. Lett.* 16, 908, 1966

C. Ciofi degli Atti, S. Scopetta; PLB 404, 223 (1997)
X. Ji and J. Osborne, J. Phys. G: Nucl. Part. Phys 27 (2001

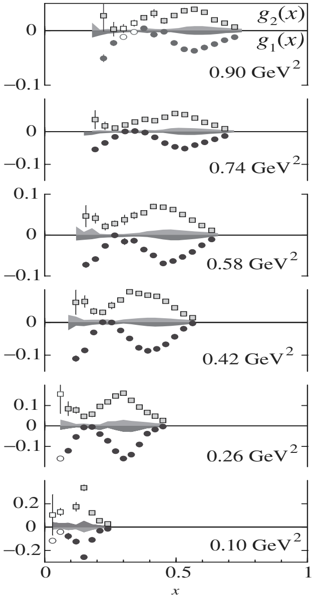


D. Drechsel *et al.*, *Phys. Rev.* **D63**,114010, 2001

→ also data from Hall B



$g_{1,2}^{3He}$ at low Q^2 and low W



Hall A: g_1^{3He} and g_2^{3He}

- pronounced Δ resonance
- $g_2 \approx -g_1 \Rightarrow g_2$ is not small !!
  note: $\sigma_{LT} \propto (g_1 + g_2)$, Δ is M1 transition

Extension of pQCD to Resonance Regime

Relation between 1st Cornwall-Norton moment of (spin-dependent) scaling function (N =p,n) and the OPE:

$$\Gamma_1^N(Q^2) \equiv \int_0^1 dx\, g_1^N(x, Q^2) = \sum_{\tau=2,4,...} \frac{\mu_\tau^N(Q^2)}{Q^{\tau-2}} = \mu_2^N(Q^2) + \frac{\mu_4^N(Q^2)}{Q^2} + \frac{\mu_6^N(Q^2)}{Q^4} + $$

- μ_τ contain nucleon matrix elements
  - μ_2 ➛ incoherent scattering of partons (+ perturbative QCD corrections) ➛ large Q^2
  - $\mu_{\tau>2}$ ➛ coherent scattering of several (few) partons (+ pertubative QCD corrections), measure of quark-gluon and quark-quark correlations
  - measure of "Initial(Final) State Interactions" ➛ should become more important at lower Q^2
- related to quark-hadron duality

Look at μ_2:

$$\mu_2(Q^2 \to \infty) = \int_0^1 dx\, g_1(x) = \pm a_3 + a_8 + a_0$$

- Axial charges:
  $a_3 \to g_A|_{np} = 1.2670(35)$ ✔
  $a_8 \to$ hyperon weak decay (0.579(25))✔
  $a_0 \to \Delta\Sigma = \sum_{u,d,s}(\Delta q + \Delta\bar{q})$, from fit to high Q^2 data ✔

  ($SU(3)_f$ symmetry assumed)
- finite Q^2: use Q^2 dependence of coefficient functions
- Accessing higher twist terms:

$$\Rightarrow \Delta\Gamma_1(Q^2) \equiv \Gamma_1(Q^2) - \mu_2(Q^2)$$

twist-2 (target mass correction): $a_2 = 2\int_0^1 dx\, x^2 g_1(x)$ ✔

$$\mu_4 = \frac{M^2}{9}(a_2 + 4d_2 + 4f_2)$$

twist-4: f_2 → **extract from fit**

twist-3: $d_2 = \int_0^1 dx\, x^2(2g_1(x) + 3g_2(x)) = 3\int_0^1 dx\, x^2 g_2^{\tau=3}(x)$

X. Ji and P. Unrau, Phys. Lett. B333 (1994)
E. Stein et al., Phys. Lett. B353 (1995)
X. Ji and W. Melnitchouk, Phys. Rev. D56 (1997)

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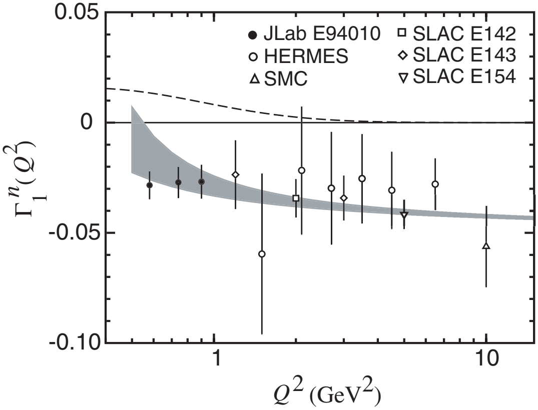
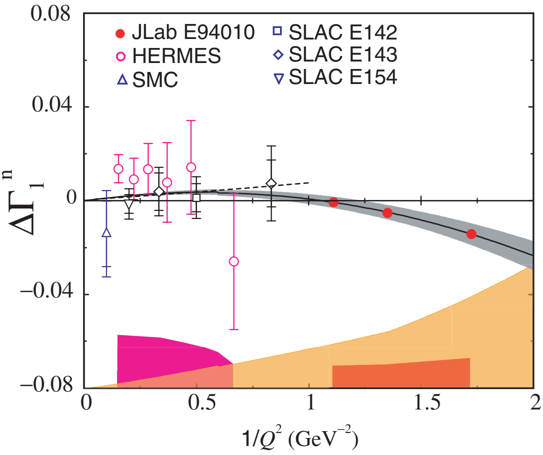
pol. ^{3}He from Hall A



Elast. contribution included

$$\Gamma_1(Q^2) = \int_0^1 dx\, g_1(x, Q^2)$$

Z.-E. Meziani et al., Phys. Lett. B 613 (2005)
M. Osipenko et al., Phys.Lett. B 609 (2005)



Fitted range:
$0.5\ \mathrm{GeV}^2 < Q^2 < 10\ \mathrm{GeV}^2$

$f_2^n = 0.034 \pm 0.043$ (tot. uncert.)
$\mu_6^n/M^4 = -0.019 \pm 0.017$

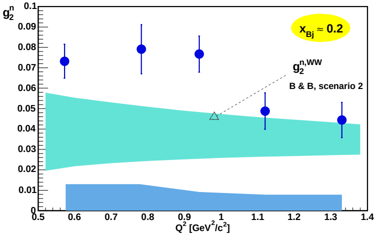
(Values for $Q^2 = 1\ \mathrm{GeV}^2$)

$a_2^n = -0.0031(20)$
$d_2^n = 0.0079(48)$ (E155x)

Z.-E. Meziani et al., Phys. Lett. B 613 (2005)

The Spin Structure Function g_2^n

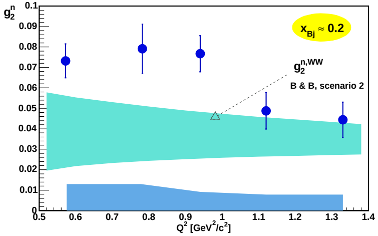
E97-103: 1.92 GeV $<$ W $<$ 2.48 GeV



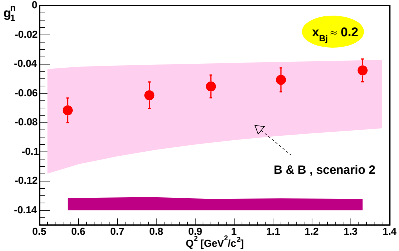
➯ higher twist (twist-3?) increase for $Q^2 \lesssim 1$ GeV^2, but not huge (h.t. > 0)

K. Kramer et al., Phys. Rev. Lett. 95 (2005)

E97-103: 1.92 GeV $<$ W $<$ 2.48 GeV



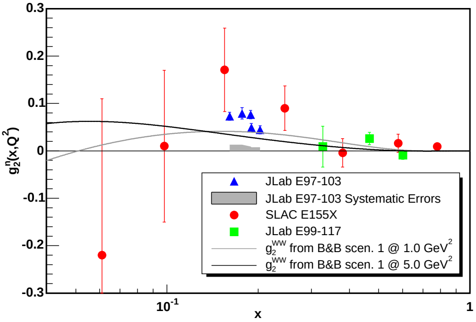
Evolve Blümlein and Böttcher pol. parton distribution functions down to low Q^2: twist-2 evolution



⇨ higher twist (twist-3?) increase for $Q^2 \lesssim 1$ GeV^2, but not huge (h.t. > 0)

K. Kramer et al., Phys. Rev. Lett. 95 (2005)

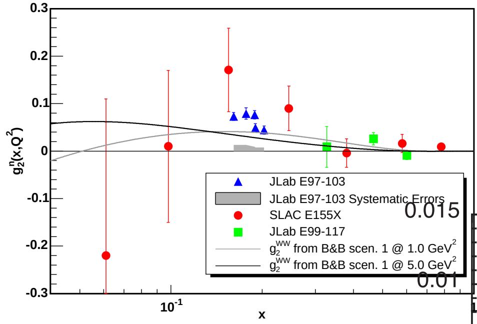
⇨ higher twist contributions appear to be small (or cancel) down to $Q^2 \approx 0.54$ GeV^2

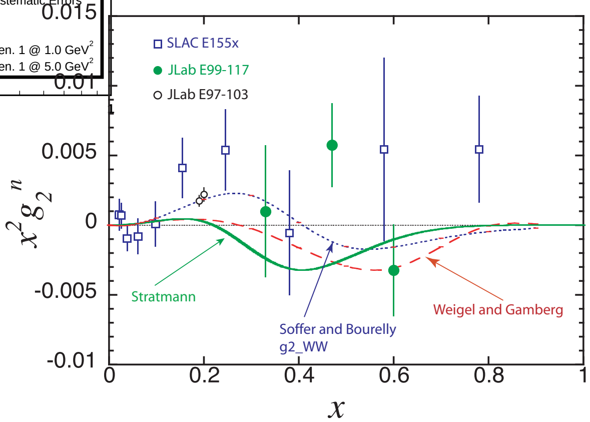


$$d_n^2 = 0.0062 \pm 0.0028$$

$$\overline{Q^2} \approx 5 \text{ GeV}^2$$

X. Zheng et al., Phys.Rev.C 70 (2004)
P.L. Anthony et al., Phys. Lett. B553 (2003)





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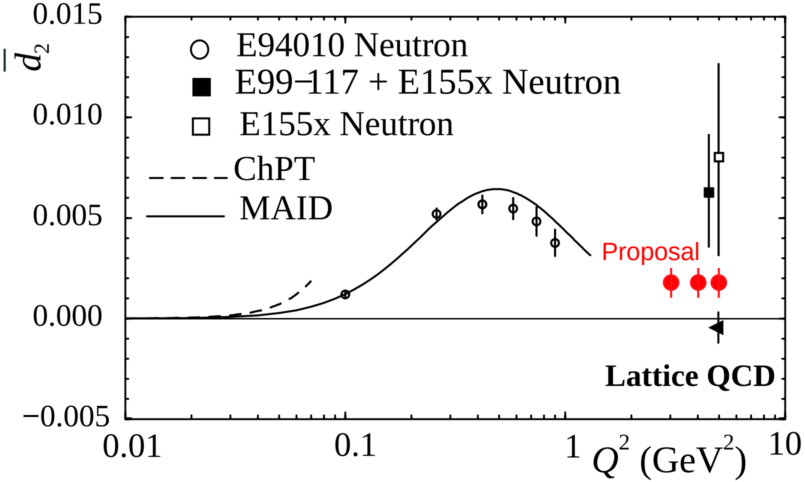
X. Zheng et al., Phys.Rev.C 70 (2004)
P.L. Anthony et al., Phys. Lett. B553 (2003)

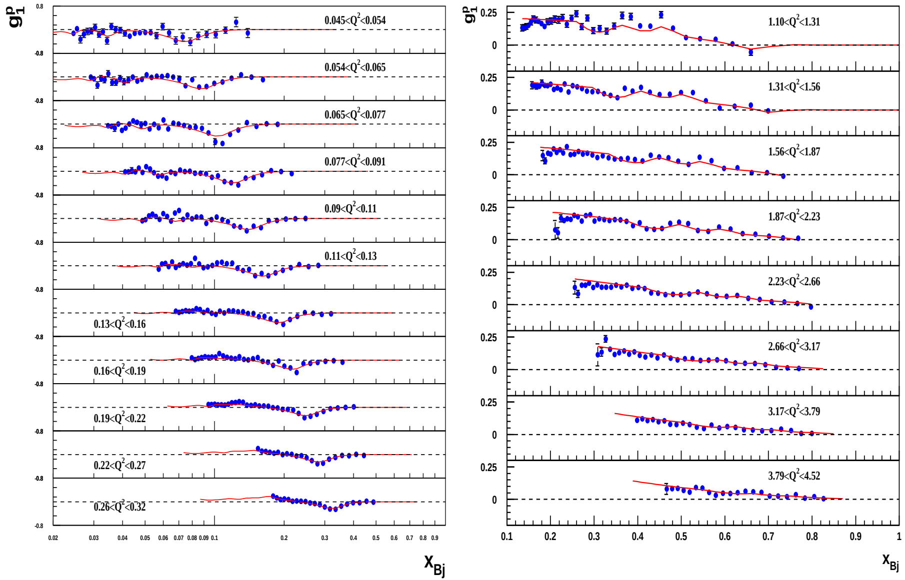
Status and Future of d_2^n



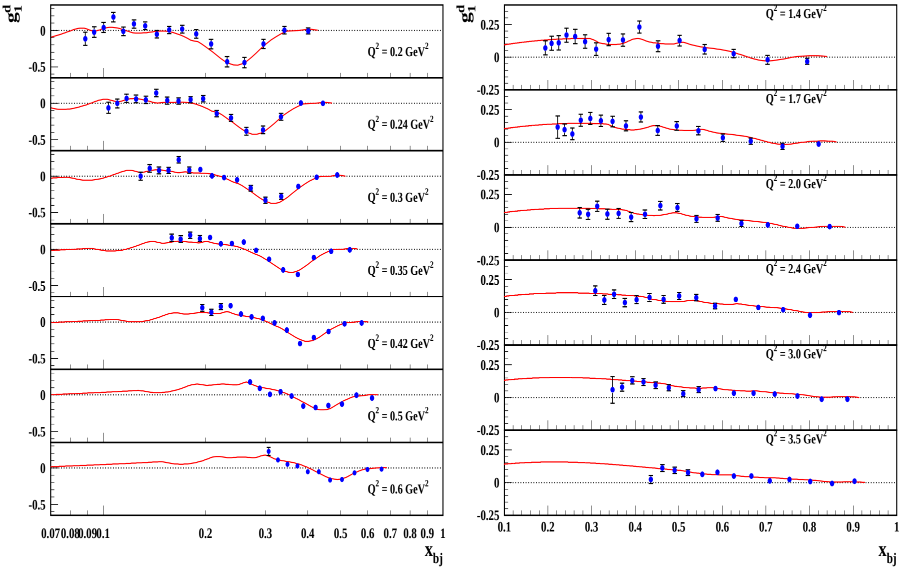
2008: $\mathrm{d}_2(\langle Q^2\rangle = 3GeV^2)$
JLab at 12 GeV: $\mathrm{d}_2(\langle Q^2\rangle = 3, 4, 5GeV^2)$

M. Göckeler *et al.*, Phys. Rev. D 63 (2001)

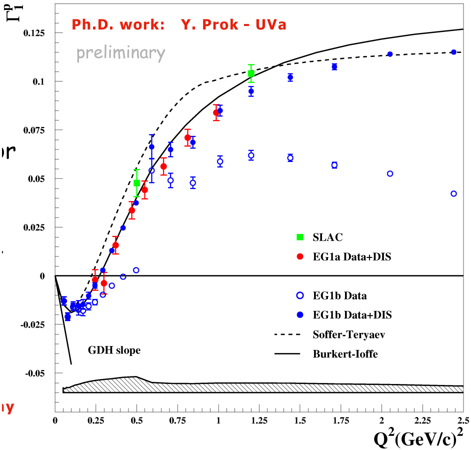
Results on g_1^p from Hall B

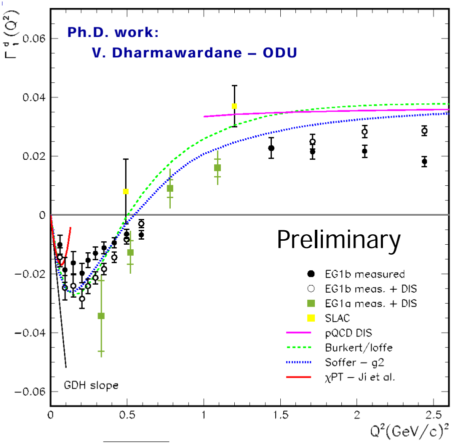


Results on g_1^d from Hall B



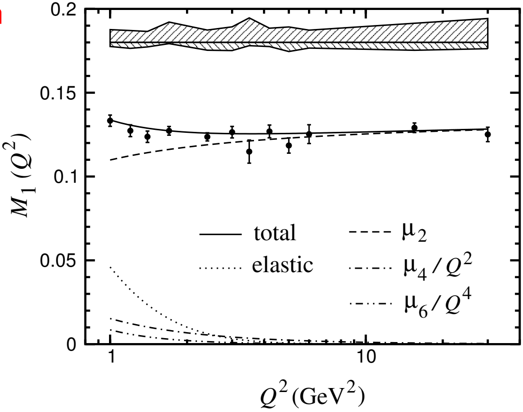
$\Gamma_1^p(Q^2)$ and $\Gamma_1^d(Q^2)$ from Hall B





Higher Twist Contributions to $\Gamma_1^p(Q^2)$

EG1a Collaboration



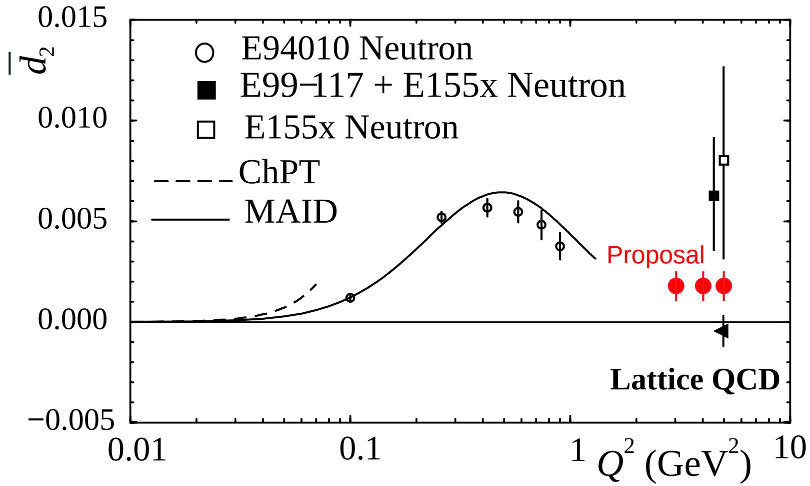
$f_2^p = 0.039 \pm 0.022(\text{stat.}) \pm {}^{0.000}_{0.018}(\text{sys.}) \pm 0.030(\text{low x}) \pm {}^{0.007}_{0.011}(\alpha_s)$

$\mu_6^p = 0.011 \pm 0.013(\text{stat.}) \pm {}^{0.010}_{0.000}(\text{sys.}) \pm 0.011(\text{low x}) \pm 0.000(\alpha_s)$

Values at Q^2 = 1 GeV^2

M. Osipenko et al., Phys.Lett. B 609 (2005)

Future Higher Twist Studies in Hall A



2008: $d_2(\langle Q^2\rangle = 3GeV^2)$
JLab at 12 GeV: $d_2(\langle Q^2\rangle = 3, 4, 5GeV^2)$

- at infinite Q^2:
  Bjorken integral: Hall A and Hall B data combined

$$\Gamma_1^{p-n} \equiv \Gamma_1^p - \Gamma_1^n \equiv \int_0^1 dx\,(g_1^p(x) - g_1^n(x)) = \frac{g_A}{6}$$

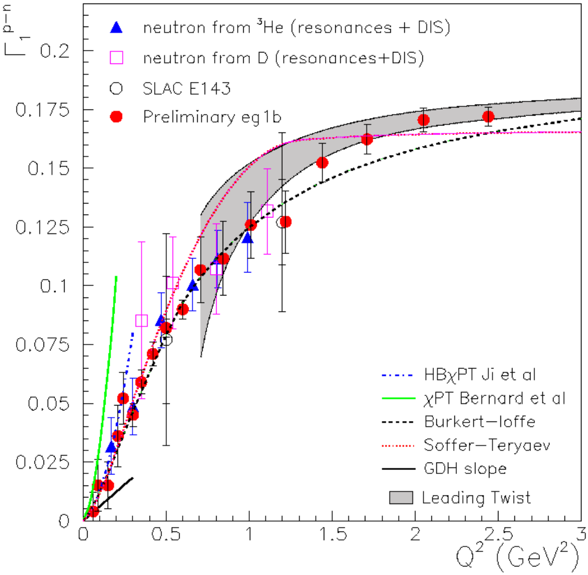
- at finite (large) values of Q^2 and leading twist (= twist-2), $\overline{\text{MS}}$ scheme:

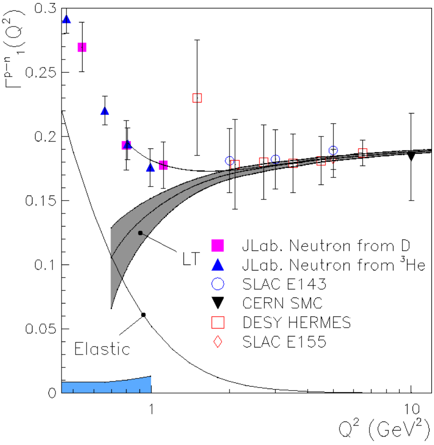
$$\Gamma_1^{p-n}(Q^2) = \frac{g_A}{6}\left[1 - \frac{\alpha_s}{\pi} - 3.58\left(\frac{\alpha_s}{\pi}\right)^2 - 20.21\left(\frac{\alpha_s}{\pi}\right)^3 + \ldots\right] = \mu_2^{p-n}(Q^2)$$

- at finite (small) values of Q^2 and power corrections (OPE):

$$\Gamma_1^{p-n}(Q^2) = \sum_{i=1}^{\infty} \frac{\mu_{2i}^{p-n}(Q^2)}{Q^{2i-2}} = \mu_2^{p-n}(Q^2) + \frac{\mu_4^{p-n}(Q^2)}{Q^2} + \frac{\mu_6^{p-n}(Q^2)}{Q^4} + \ldots$$

The Bjorken Integral in the Transition Regime





Fitted range:
$0.8\ \mathrm{GeV}^2 < Q^2 < 10\ \mathrm{GeV}^2$

$f_2^{p-n} = -0.11 \pm 0.15(\mathrm{uncor})^{+0.04}_{-0.03}(\mathrm{cor})$
$\mu_6^{p-n}/M^4 = 0.08 \pm 0.06(\mathrm{uncor}) \pm 0.01\ (\mathrm{cor})$

Fitted range:
$0.66\ \mathrm{GeV}^2 < Q^2 < 10\ \mathrm{GeV}^2$

$f_2^{p-n} = -0.17 \pm 0.05(\mathrm{uncor})^{+0.04}_{-0.05}(\mathrm{cor})$
$\mu_6^{p-n}/M^4 = 0.12 \pm 0.02(\mathrm{uncor}) \pm 0.01\ (\mathrm{cor})$

(Values for Q^2 = 1 GeV^2)

Low x extrapolation consistently done $\rightarrow$ Bianchi & Thomas (2 GeV $< W <$ 32 GeV) + Regge parameterization for $W >$ 32 GeV (Note: Bj integral is flavor non-singlet)

A. Deur et al., Phys. Rev. Lett. 93 (2004)

- ✗ Nucleon spin physics program at JLab has been successful for $\approx$10 years.
- ✗ High luminosity $\Rightarrow$ Q^2 evolution of moments can be measured.
- ✗ Interesting results in the large x region $\rightarrow$ $\Delta d/d$ negtive
- ✗ Higher twist effects in spin structure g_1 and g_2 functions appear to be small for the proton and the neutron down to $Q^2 < 1$ GeV^2.

Outlook

$^3\vec{He}$ Program

- Bloom-Gilman Duality
- $gDGH: \; Q^2 < 0.5 \; GeV^2$
- $^3\vec{He}(\vec{e}, e'n) \Rightarrow G_E^n : Q^2 \leq 3.4 \; GeV^2$
- SSAs: $^3\vec{He}(\vec{e}, e'\pi^{\mp})X$
- $^3\vec{He}(\vec{e}, e'd(n)) \Rightarrow {}^3He$ w.f., G_E^n
- $d_2 \; @ \; Q^2 = 3 \; GeV^2, \; A_y$
- JLab @ 11 GeV

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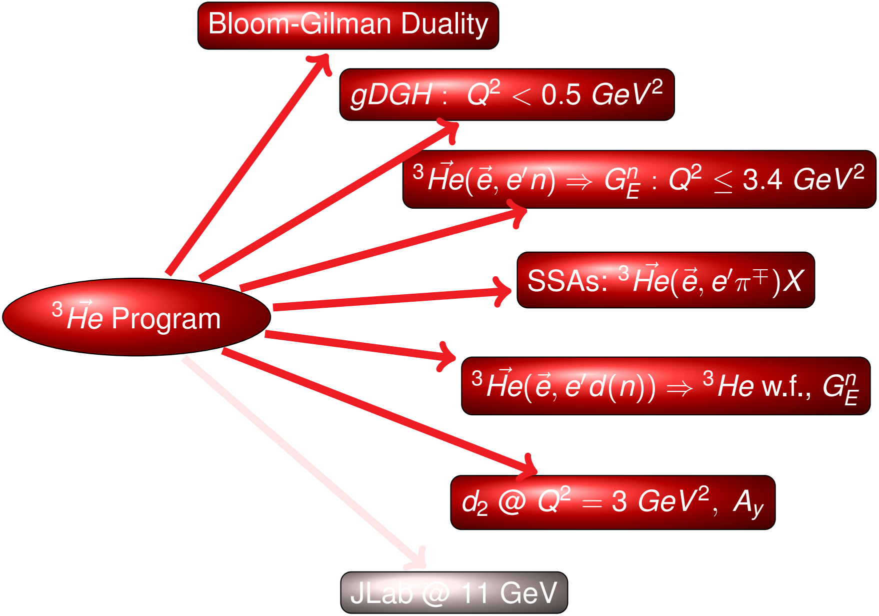

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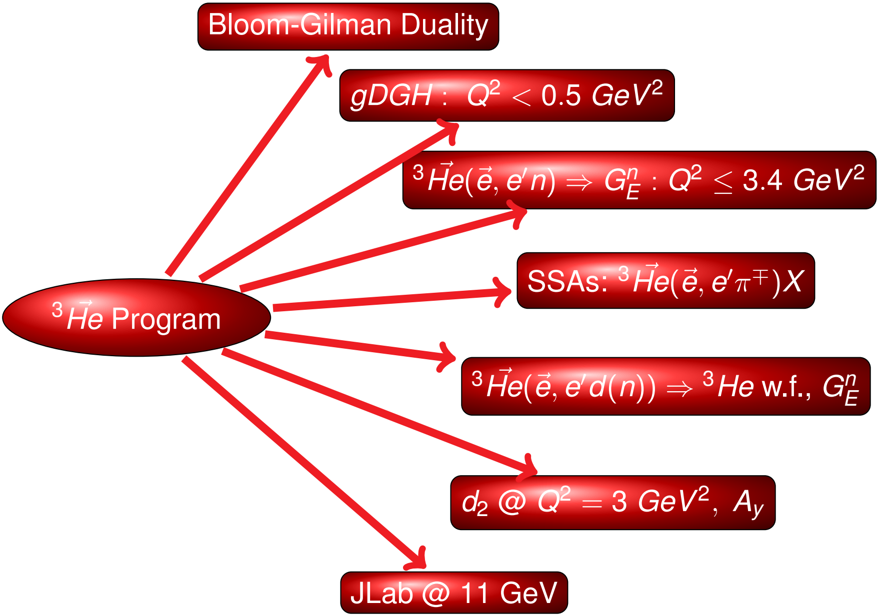
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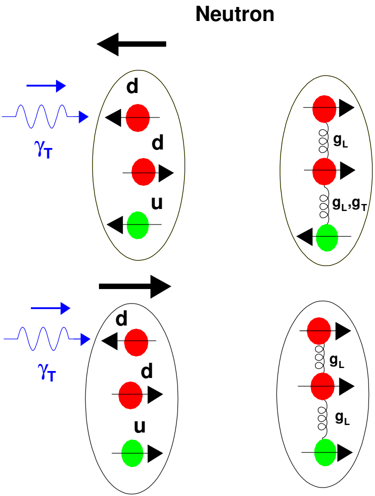
Additional Slides

Also: $\frac{\acute{d}}{d} \to 1$ as $x \to 1$



Coupling of a large-$k^2[\approx m^2/(1-x)]$ longitudinal gluon to small-p^2 quarks is suppressed by $(p^2/k^2)^{1/2} \sim (1-x)^{1/2}$ relative to the transverse coupling.

G.R. Farrar and D.R. Jackson, *Phys. Rev. Lett.* **35**, 1416 (1975)