# Spin Physics with Polarized $^3$He

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"Testing QCD through Spin Observables in Nuclear Targets"
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- ✗ $^3\overrightarrow{\mathrm{He}}$ in Nuclear Physics
- ✗ From $^3$He to the neutron
- ✗ Sum rules (GDH) , Spin-Structure Functions: $g_1^n,\ g_2^n$
- ✗ Summary and Outlook

# A Short Summary of $^3\overrightarrow{\text{He}}$ Targets in Nuclear Physics

Development of polarized $^3\overrightarrow{\text{He}}$ target technology:

| Lab/Exp | year | beam | I[$\mu$A] | $\rho$[cm$^{-2}$] | $\mathcal{L}$[s$^{-1}$cm$^{-2}$] | P | Physics |
|---|---|---|---|---|---|---|---|
| MIT/Bates (I) | 90 | $e^-$ | 6 | $7.5 \cdot 10^{20}$ | $2.8 \cdot 10^{34}$ | 0.19 | $G_E^n$, $^3$He struct. |
| MIT/Bates (IIa) | 90 | $e^-$ | 11 | $1.1 \cdot 10^{19}$ | $7.6 \cdot 10^{32}$ | 0.30 | $G_E^n$, $^3$He struct. |
| TRIUMF | 91 | p | $3.5 \cdot 10^{-3}$ | $2.0 \cdot 10^{21}$ | $4.4 \cdot 10^{31}$ | 0.60 | $^3$He struct. |
| SLAC (E142) | 92 | $e^-$ | 1.5 | $7 \cdot 10^{21}$ | $6.6 \cdot 10^{34}$ | 0.35 | $g_{1,2}^n$, $\Gamma_1^n$ |
| MIT/Bates (IIb) | 93 | $e^-$ | 25 | $3.3 \cdot 10^{18}$ | $5.1 \cdot 10^{32}$ | 0.38 | $G_M^n$, $^3$He struct. |
| IUCF | 93 | p | 70 | $1.5 \cdot 10^{14}$ | $6.6 \cdot 10^{28}$ | 0.46 | $^3$He struct. |
| HERMES | 95 | $e^+$ | $20 \cdot 10^3$ | $3.3 \cdot 10^{14}$ | $4.1 \cdot 10^{31}$ | 0.46 | $g_1^n$, $\Gamma_1^n$, GDH |
| NIKHEF | 96 | $e^-$ | $80 \cdot 10^3$ | $7 \cdot 10^{14}$ | $3.5 \cdot 10^{32}$ | 0.50 | $G_E^n$, $^3$He struct. |
| SLAC (E154) | 95 | $e^-$ | 1.5 | $8 \cdot 10^{21}$ | $7.5 \cdot 10^{34}$ | 0.38 | $g_{1,2}^n$, $\Gamma_1^n$ |
| MAMI | 97 | $e^-$ | 7 | $5 \cdot 10^{20}$ | $2.2 \cdot 10^{32}$ | 0.50 | $G_E^n$, $^3$He struct. |
| JLab | 98-?? | $e^-$ | (10-15) | $(8 - 10) \cdot 10^{21}$ | $6.7 \cdot 10^{35}$ | (0.35-0.45) | $g_{1,2}^n$, $A_1^n$, GDH, $G_{E,M}^n$ |
| BLAST | 03(?) | $e^-$ | $(80 \cdot 10^3)$ | $(7 \cdot 10^{14})$ | $(3.5 \cdot 10^{32})$ | (0.5) | $G_{E,M}^n$, $^3$He struct. |

$\Rightarrow$ polarized $^3\overrightarrow{\text{He}}$ targets + high intensity and highly polarized beams

$\Rightarrow$ precision experiments on $^3$He and neutron possible

# How to Extract Neutron Properties from $^3\overrightarrow{\mathrm{He}}$?

Perform inclusive or semi-inclusive asymmetry measurements:

- scattering asymmetries (↔ virtual photon asymmetries):

$$A_\parallel = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = D(A_1 + \eta A_2) \qquad A_\perp = \frac{\sigma^{\downarrow\rightarrow} - \sigma^{\uparrow\rightarrow}}{\sigma^{\downarrow\rightarrow} + \sigma^{\uparrow\rightarrow}} = d(A_2 - \xi A_1)$$

Target spin alignment: (anti-)parallel or perpendicular to $\overrightarrow{k_i}$ (DIS), or $\overrightarrow{q}$ (elastic, q.e.).

<u>*Inclusive* DIS</u>:

$$A_\parallel^{^3He} = D' \cdot \{(E + E' cos(\vartheta)) g_1^{^3He}(x, Q^2) - \frac{Q^2}{\nu} g_2^{^3He}(x, Q^2)\}$$

$$A_\perp^{^3He} = D' \cdot E' sin(\vartheta) \{ g_1^{^3He}(x, Q^2) + \frac{2E}{\nu} g_2^{^3He}(x, Q^2)\}$$

$$D' = \frac{1}{F_1(x, Q^2)} \cdot \frac{1}{\nu} \cdot \frac{1 - \epsilon}{1 + \epsilon R(x, Q^2)}$$

**From $^3$He to neutron:** So far

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

- ☞ spin depolarization ⟶ S′ -, D - states

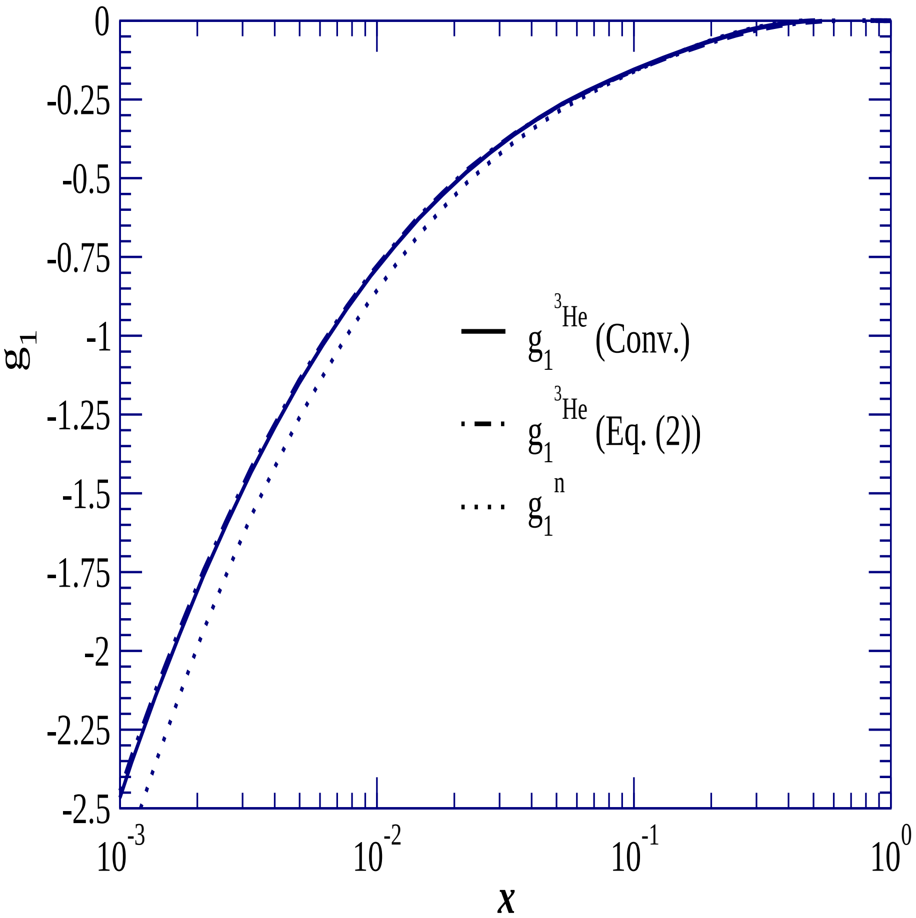
but there are also:

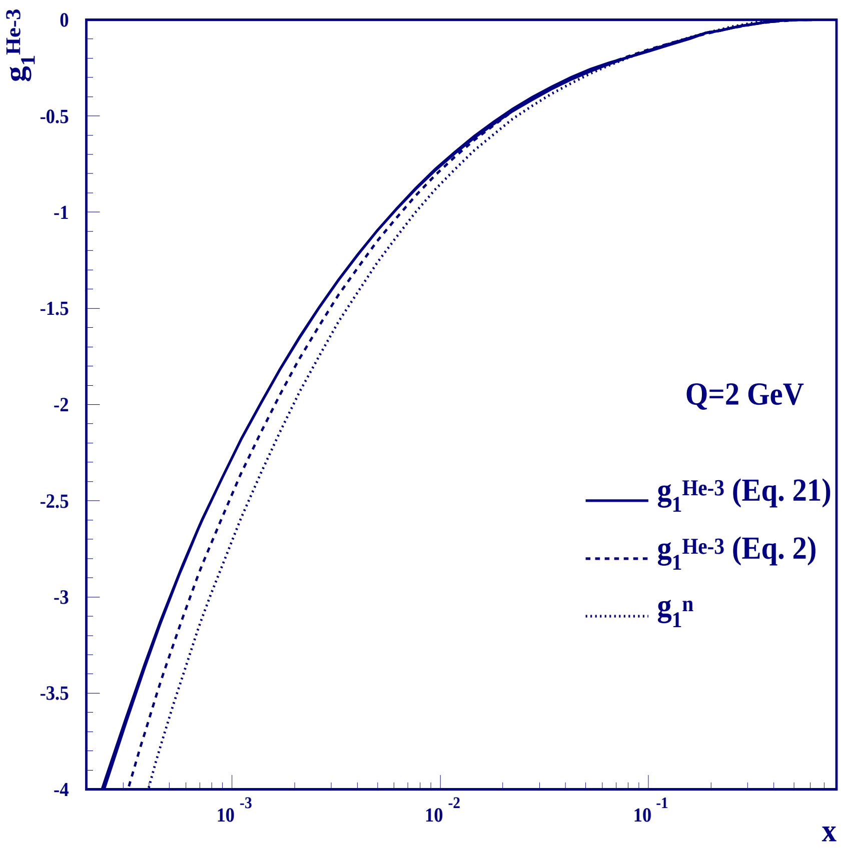
- ☞ nuclear binding, Fermi motion ⟶ Δ isobar, pions, vector mesons, off-shell effects
- ☞ small-x-effects (nuclear shadowing, nuclear anti-shadowing: $0.05 \lesssim x \lesssim 0.2$

F. Bissey *et al.* hep-ph/0109069

⇒ talk by F. Bissey

Bottom line: nuclear effects in DIS regime $(10^{-4} < x < 0.8)$ have been studied in great detail and have to be taken into account.



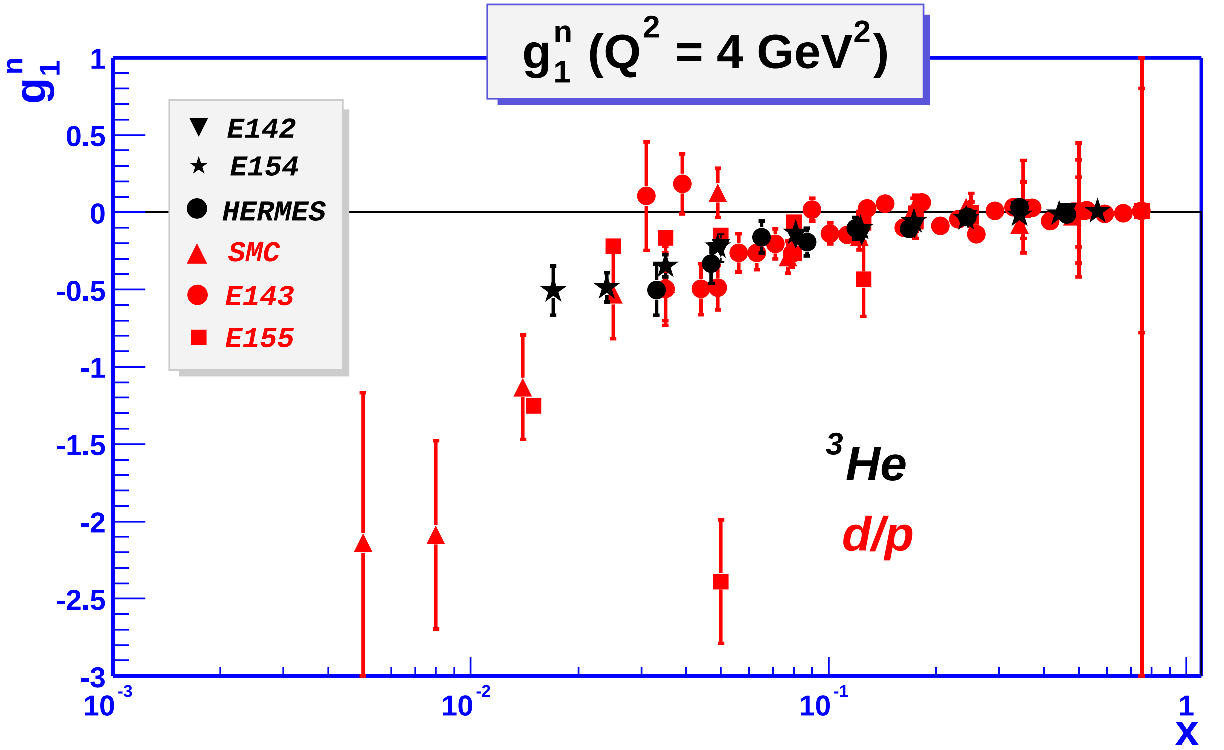


Standard analysis: $g_1^n(x,Q^2) = \frac{1}{P_n}(g_1^{3He}(x,Q^2) - 2P_p g_1^p(x,Q^2))$

$P_n = 0.86 \pm 0.02$, $P_p = -0.028 \pm 0.004$

⇒ Effects on spin-structure functions can be sizable, effect on sum rules should be smaller.

# Comparison of $g_1^n(x, Q^2)$ extractions (old analysis):



$\Rightarrow$ Bjorken Sum Rule: NLO QCD corrections up to $\alpha_s^3$

$$\Gamma_1^p - \Gamma_1^n(Q^2 = 5GeV^2) = 0.176 \pm 0.003 \pm 0.007(exp) \quad (0.181 \pm 0.005(theo))$$

Agreement between experiment - theory : $\lesssim$ 5%

# $\chi PT$ meets $pQCD$: Gerasimov-Drell-Hearn (GDH) Sum Rule

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

$\Longrightarrow$ relate spin-dependent forward Compton scattering amplitude for *real photons* to spin-dependent cross-sections:
$\Rightarrow$ causality, unsubtracted dispersion relation, optical theorem (unitarity)
$\Rightarrow$ low-energy theorem:

$$\mathcal{R}e\ g(\nu, Q^2 = 0) = \frac{2}{\pi} P \int_{\nu_{thresh}}^{\infty} \frac{\nu' d\nu'}{\nu'^2 - \nu^2} (\sigma_{\uparrow\downarrow}(\nu') - \sigma_{\uparrow\uparrow}(\nu'))$$

$$g(0, Q^2 = 0) = -\frac{1}{2} (\frac{\alpha}{M_N^2}) \kappa_N^2 .$$

F.E Low, Phys. Rev. 96, 1428 (1954)
M. Gell-Mann and M.L. Goldberger, Phys. Rev. 96, 1433 (1954)

$g(\nu, Q^2 = 0) =$ spin-flip amplitude in Compton scattering, $\kappa_N^2$ is anomalous magnetic moment of the nucleon.

Combining the above equations gives: $(\nu \to 0)$

$$\boxed{I(Q^2 = 0) = \int_{\nu_{thresh}}^{\infty} \frac{d\nu}{\nu} (\sigma_{\uparrow\downarrow}(\nu) - \sigma_{\uparrow\uparrow}(\nu)) = -\frac{2\pi^2 \alpha}{M_N} \kappa_N^2}$$

$\Leftarrow$ GDH Sumrule

# Generalized GDH Sum: $\gamma \longrightarrow \gamma^\star$

Transverse part of spin-dependent cross section:

$$I(Q^2) = \int_{\nu_{thresh}}^{\infty} \frac{d\nu}{\nu}(\sigma^T_{\uparrow\downarrow}(\nu, Q^2) - \sigma^T_{\uparrow\uparrow}(\nu, Q^2)) = \int_{\nu_{thresh}}^{\infty} \frac{d\nu}{\nu}\sigma_{TT'}(\nu, Q^2)$$

D. Drechsel, Prog. Part. Nucl. Phys. 34, 181, 1995
D. Drechsel *et al.*, Phys. Rev. D63,114010, 2001

In DIS: $\sigma^T_{\uparrow\downarrow} - \sigma^T_{\uparrow\uparrow} \propto F_1 \cdot A_1$, in resoncance region $F_1$ poorly known → need to measure cross sections directly.

For $Q^2 \to \infty$:

$$I(Q^2) = \frac{16\pi^2\alpha}{Q^2}\int_0^1 dx g_1^N(x, Q^2) = \frac{16\pi^2\alpha}{Q^2}\Gamma_1^N(Q^2)$$

M. Anselmino *et al.*, Sov. J. Nucl. Phys. 49, 136, 1989

X. Ji and J. Osborne, J. Phys. G: Nucl. Part. Phys. 27, 127, 2001

For the Neutron:

$$I(Q^2 \to \infty) \approx \frac{-18.5\mu b}{Q^2}$$

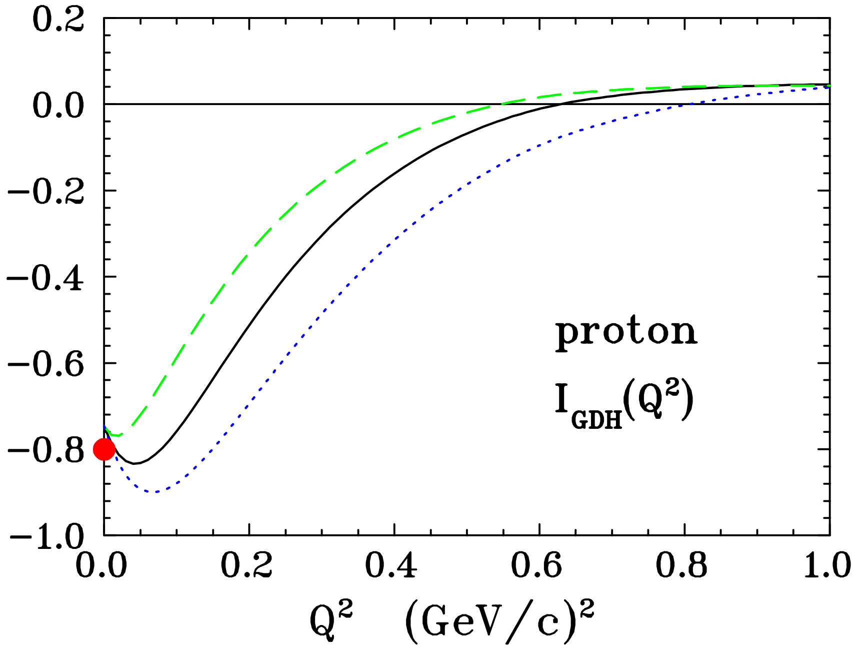
# Extraction of $I^n(Q^2)$ from $I^{^3He}(Q^2)$

Follow procedure suggested by C. Ciofi degli Atti and S. Scopetta:

C. Ciofi degli Atti, S. Scopetta; PLB 404, 223 (1997)

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

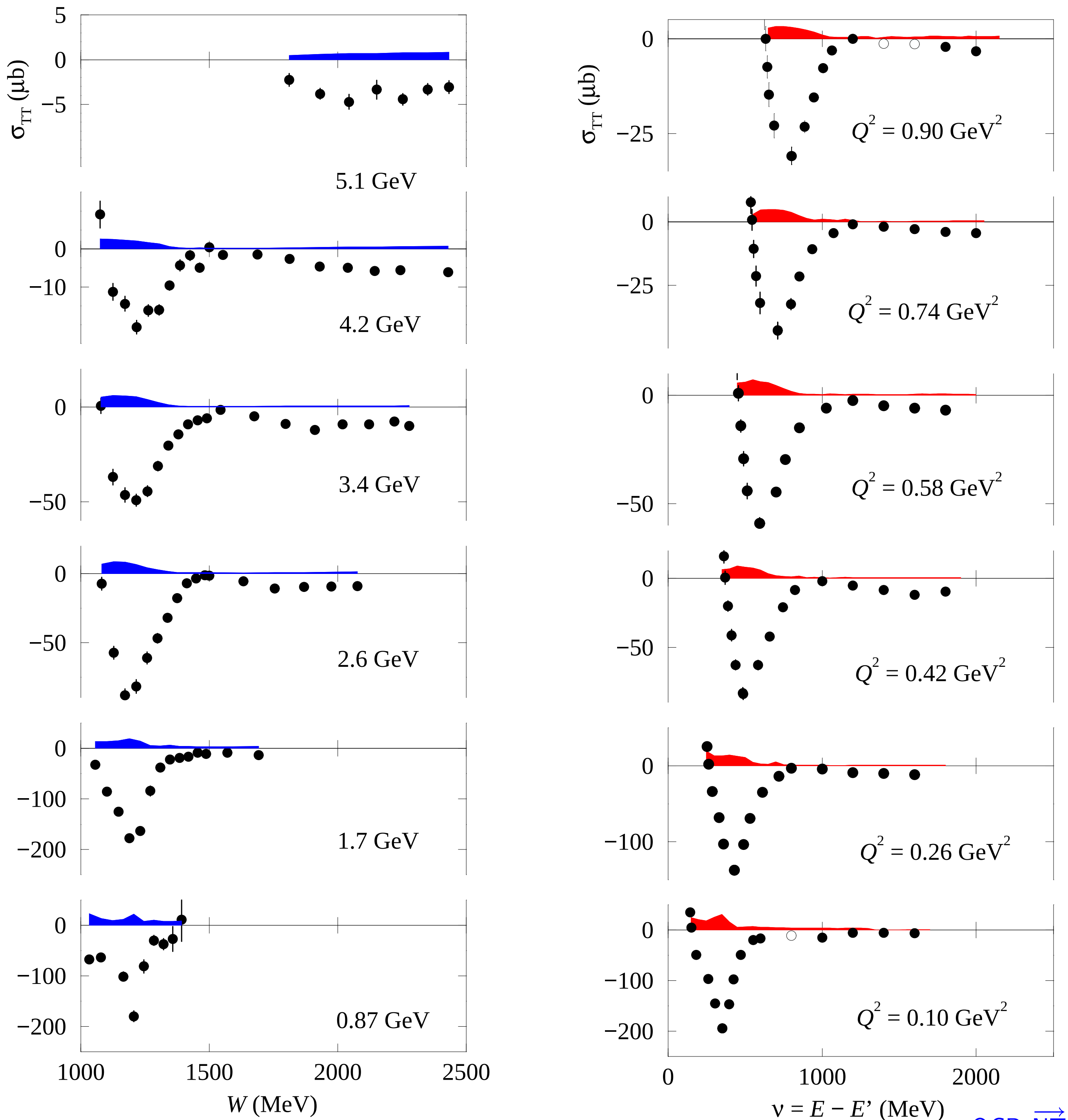
$P_p = -0.028 \pm 0.004,\ P_n = 0.86 \pm 0.02$; dilution factors omitted



⇒ LETs, GDH-MAMI, MAID, Bianchi *et al.*

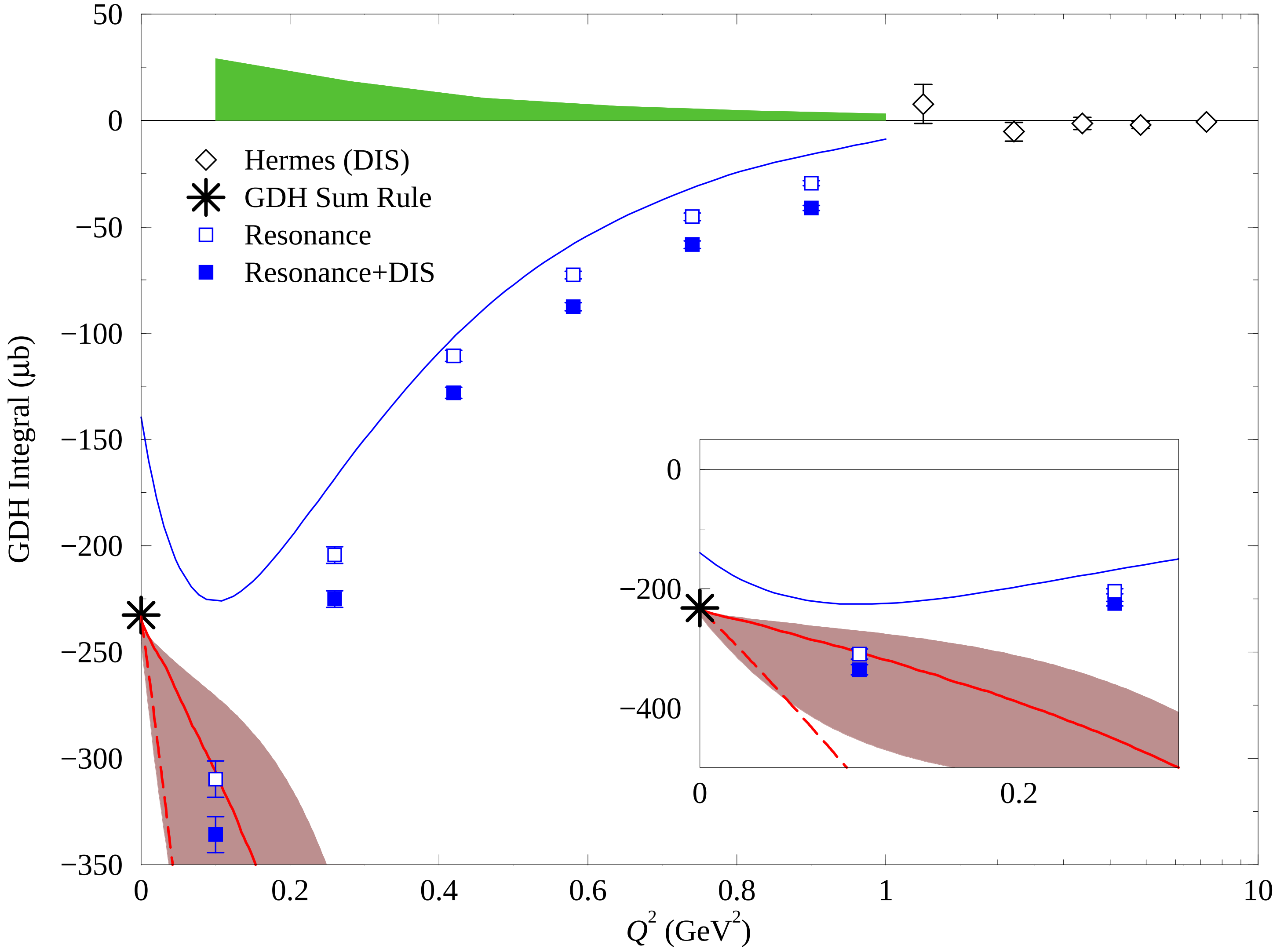
D. Drechsel *et al.*, Phys. Rev. D63,114010, 2001

# Cross-sections obtained by E94-010 (JLab, Hall A):



# GDH Integral on the Neutron

Jefferson Lab E94010



red solid line, shaded area: Lorentz-invariant CHPT (“infrared regularization”).

V. Bernard *et al.*, hep-ph/0203167

red dashed line: HBCHPT

X. Ji and J. Osborne, J. Phys. G: Nucl. Part. Phys. 27, 127, 2001

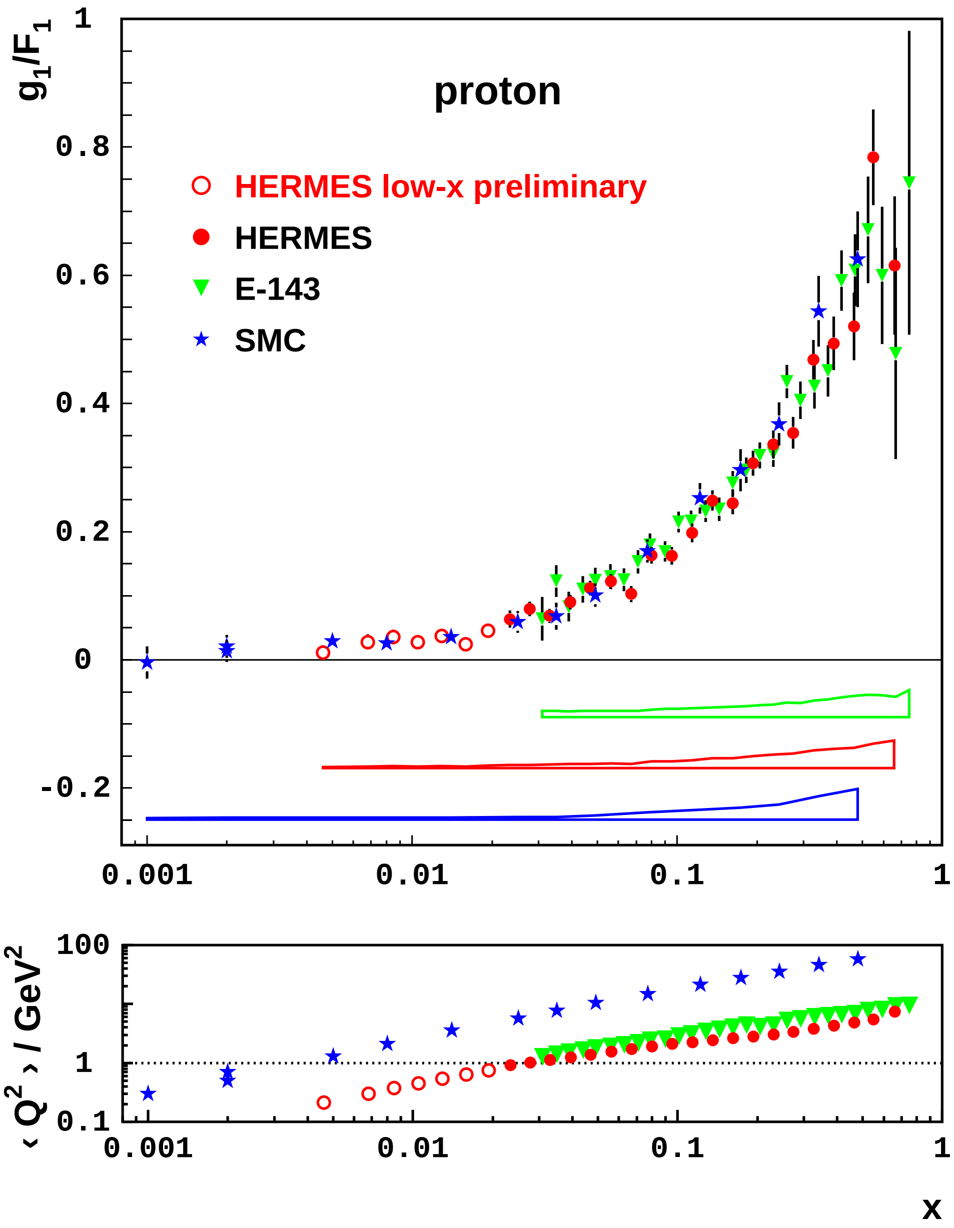
# More on the $(x, Q^2)$ Dependence of the Neutron Spin Structure Functions

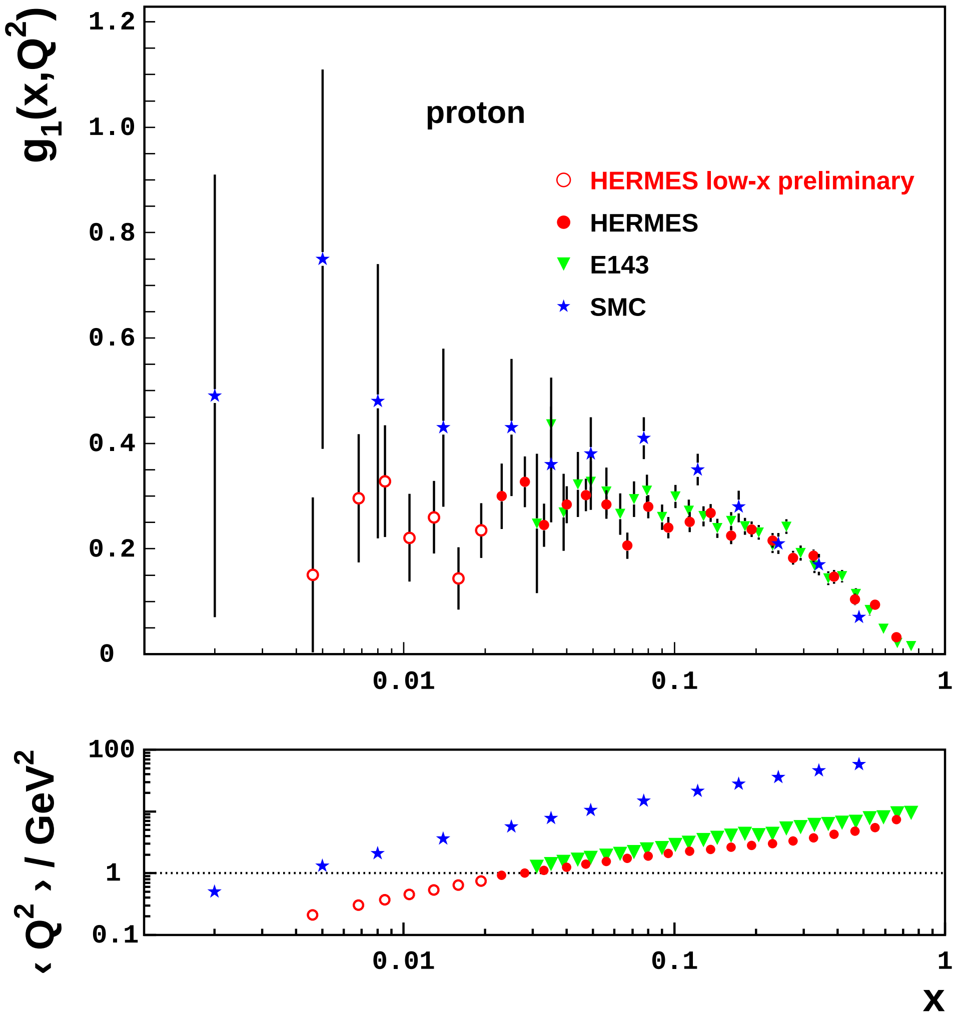
Experimentally accessible ranges in $(x, Q^2)$: W $\gtrsim$ 1.8 GeV

| Lab | Exp. | $x$ | $Q^2$ [GeV$^2$] |
|---|---|---|---|
| SLAC | E142 | 0.03 — 0.6 | 1.1 — 5.5 |
| | E143 | 0.03 — 0.6 | 0.3 — 10 |
| | E154 | 0.01 — 0.7 | 1 — 17 |
| | E155 | 0.02 — 0.8 | 1 — 40 |
| | E155x | 0.02 — 0.8 | 0.7 — 17 |
| CERN | EMC | 0.01 — 0.7 | 4.2 — 41.1 |
| | SMC | 0.003 — 0.7 | 1 — 90 |
| | COMPASS | 0.005 — 0.6 | 1 — 90 |
| DESY | HERMES | 0.02 — 0.6 | 1.2 — 12.1 |
| JLab | E99-117<br>E97-103 | 0.33 — 0.61<br>0.17 — 0.21 | 2.7 — 4.9<br>0.6 — 1.4 |

Low $Q^2$ measurements: $\Rightarrow$ sensitivity to higher twist effects.

# Low $Q^2$ measurements at HERMES: W $>$ 1.8 GeV





H. Böttcher, Proc. 14th Rencontres Valle D'Aoste, La Thuile (2000)
W.D. Nowak, Proc. DIS 2000 (2000)

# Uniqueness of $g_2$

To understand $g_2(x, Q^2)$ lets look at the moments of the spin structure functions using the OPE:

$$\int_0^1 x^n g_1(x, Q^2) dx = \frac{1}{4} \bar{\mathcal{O}}_n^{\{2\}} = \frac{1}{4} a_n \quad n = 0, 2, 4, \ldots$$

$$\int_0^1 x^n g_2(x, Q^2) dx = \frac{1}{4} \frac{n}{n+1} (\bar{\mathcal{O}}_n^{\{3\}} - \bar{\mathcal{O}}_n^{\{2\}}) = \frac{1}{4} \frac{n}{n+1} (d_n - a_n) \quad n = 2, 4, 6, \ldots$$

If the $\bar{\mathcal{O}}_n^{\{3\}} = 0$ :

$$g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_{x'}^1 \frac{dx'}{x'} g_1(x', Q^2)$$

S. Wandzura and F. Wilczek, Phys. Lett. B 72 (1977)

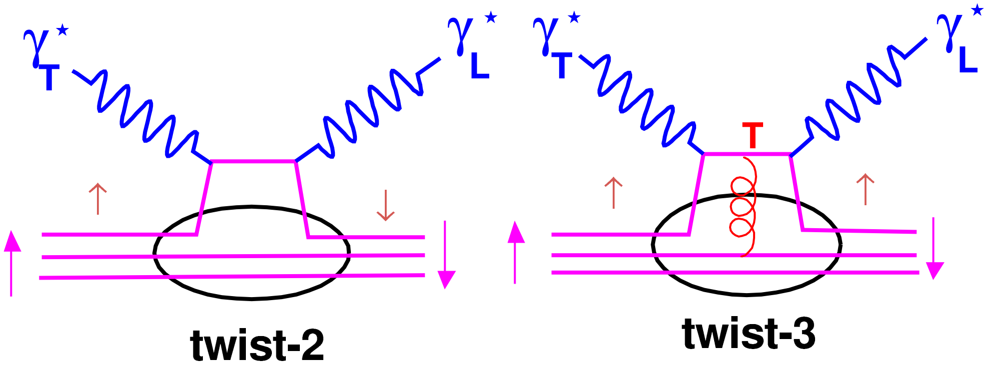
➜ leading twist part of $g_2(x, Q^2)$ is completely determined by twist-2 part of $g_1(x, Q^2)$:

$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) + g_2^{H.T.}(x, Q^2)$$

- higher twist (twist-3 and higher) contributions can be directly separated. → $g_2(x, Q^2)$ is a unique s.f.!!!

- higher twist contributions are larger at lower $Q^2$ $(\propto \frac{1}{Q^{\{\tau\}}})$

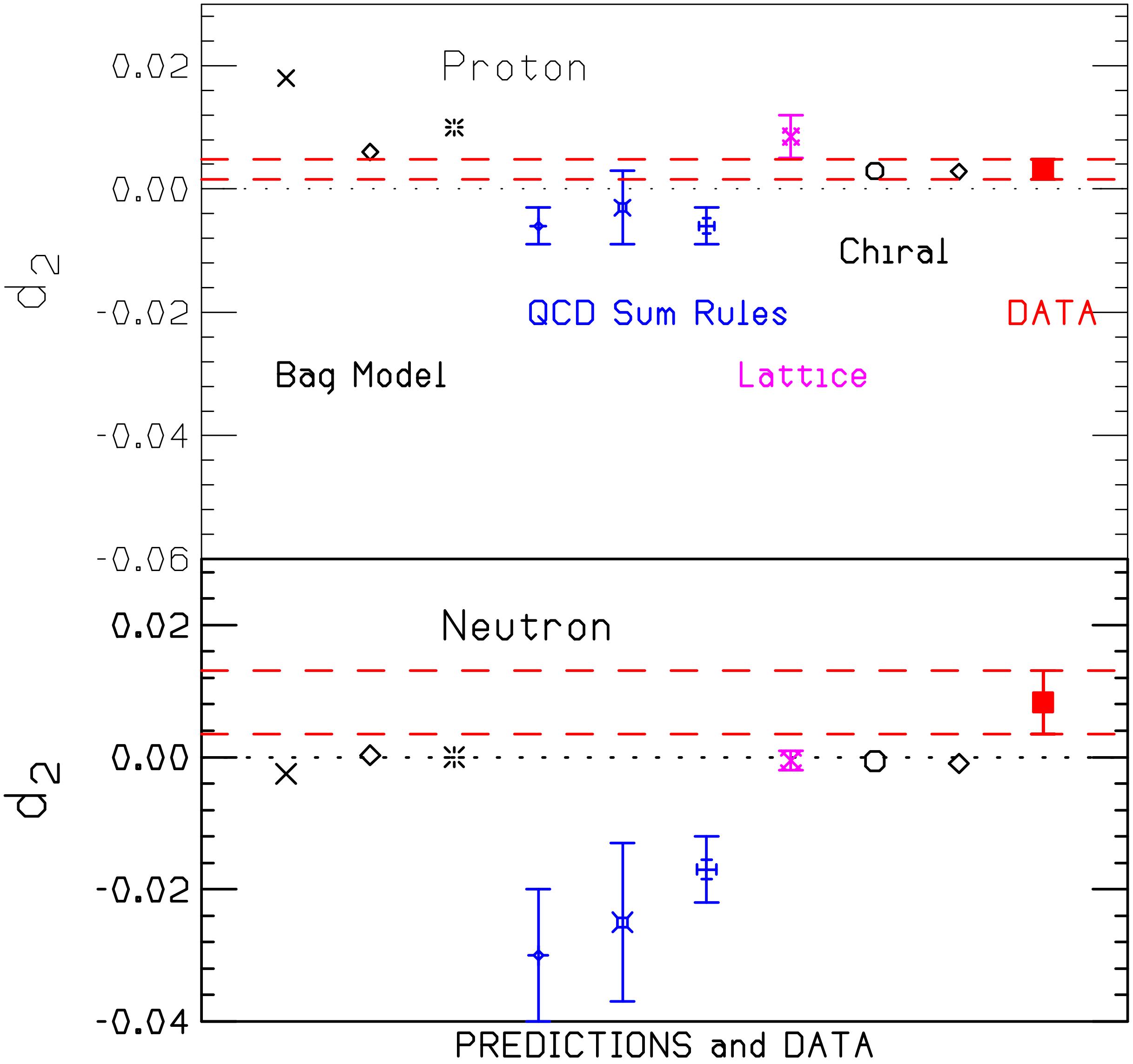
$\Rightarrow$ sensitive to quark-gluon correlations.



# THE TWIST-3 $d_2$ MATRIX ELEMENT

$$d_2 = 3\int_0^1 x^2[g_2(x,Q^2) - g_2^{WW}(x,Q^2)]dx$$

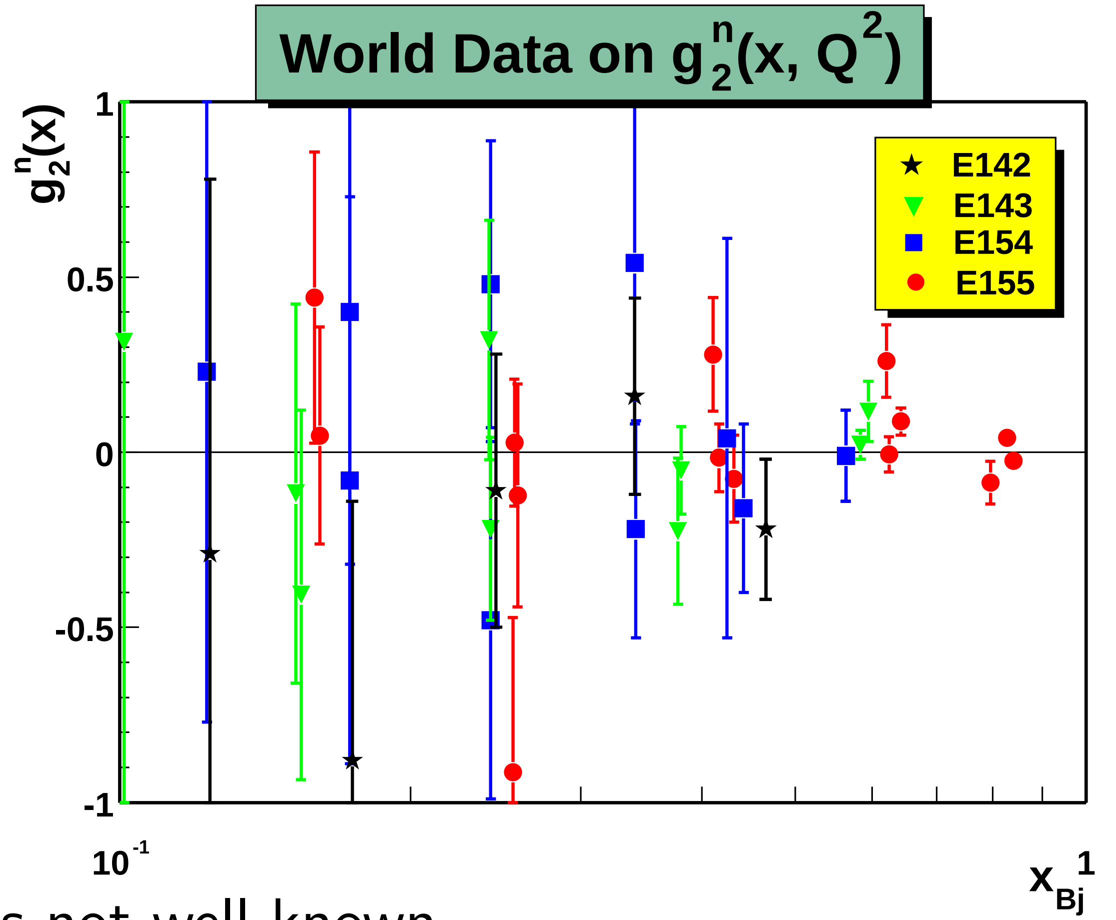
$0.0032 \pm .0016(p)$ $0.0083 \pm .0048(n)$



E155x, $\langle Q^2 \rangle = 3$ GeV$^2$

S. Rock, talk given at Zeuthen-DESY, SPIN01 (2001)

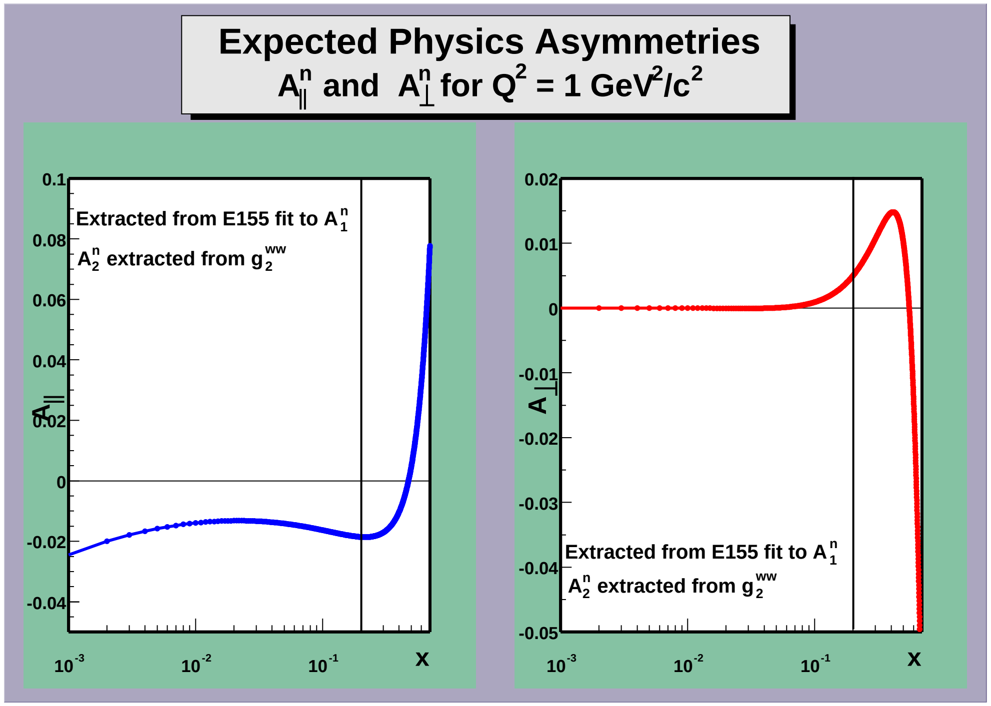
# World data on $g_2^n$ for $x > 0.1$: (E155x not included (sorry!!))



- $g_2^n(x, Q^2)$ is not well known
- difficult to measure $Q^2$ dependence of moments
- E97-103 decided to measure $g_2^n$ at different values of $Q^2$ and nearly constant $x$

# Experiment E97-103 at JLab:

| $Q^2$ [$GeV^2/c^2$] | x | $W^2$ [$GeV^2$] |
|---|---|---|
| 0.58 | 0.17 | 3.82 |
| 0.80 | 0.18 | 4.43 |
| 0.96 | 0.20 | 4.83 |
| 1.14 | 0.20 | 5.57 |
| 1.36 | 0.21 | 6.03 |



⇒ expected asymmetries are small:

$$\Rightarrow \quad A_{meas} = f \cdot P_t \cdot P_b \ \lesssim 0.2\%(\parallel),$$
$$500ppm(\perp)$$

Details ⇒ talk by K. Kramer

# Summary and Outlook

✗ Improved theory and experiment: (Spin-)Structure of the neutron can be extracted with high precision using $^3\overrightarrow{\text{He}}$ (in DIS):

- $Q^2$ dependence of Sum Rules seems feasible (→ GDH Sum at JLab).
- Need more data in low-x and large-x region.
- Low $Q^2$ should give us detailed information on scaling violations and higher twist effects.

✗ Hall A program at Jefferson Lab (→ high luminosity) can focus on kinematical regions which are difficult to access at other labs.

- GDH at medium $Q^2$
- GDH at low $Q^2$
- $A_1^n$ at large x $\Rightarrow$ E99-117, talk by X. Zheng
- higher twist in $g_2^n$ $\Rightarrow$ E97-103, talk by K. Kramer
- Duality in $g_1^n$ at large x $\Rightarrow$ E01-012
- $G_E^n$ at large $Q^2$ $\Rightarrow$ E02-013, talk by K. McCormick
- $d_2^n$ matrix element at $Q^2 = 2$ GeV$^2$ $\Rightarrow$ E01-111 ,talk By X. Jiang
- JLab 12 GeV $\Rightarrow$, talk by N. Liyanage
- ........