Study of the Spin Structure Functions of the Neutron at Low Q^2 with Polarized ^{3}He

presented by

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For JLab E94010 Collaboration

LowQ 03

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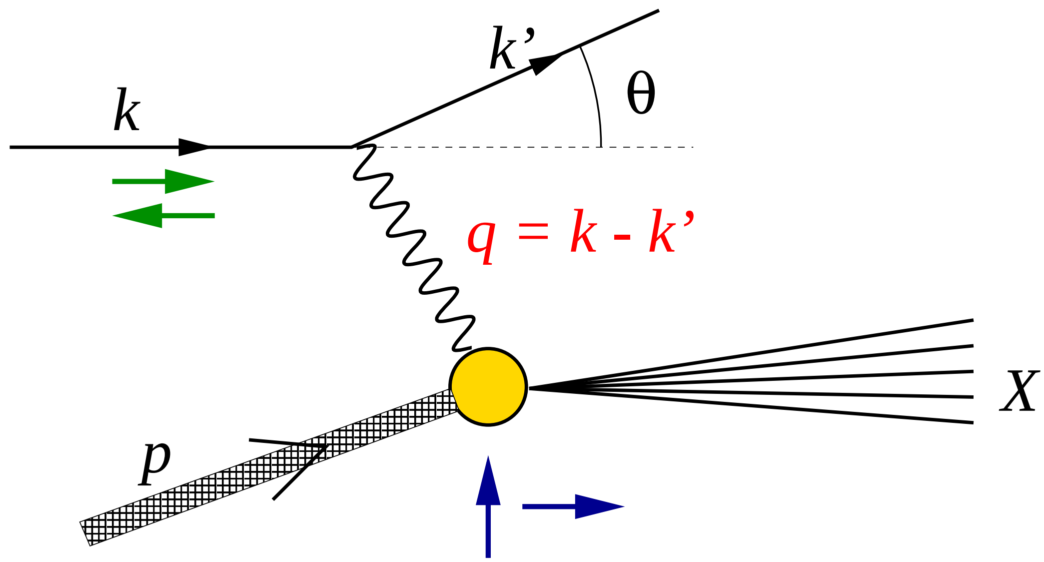
Inclusive Electron Scattering



- Four-momentum transfer

$$Q^2 = -q^2 = 4EE' \sin^2 \frac{\theta}{2}$$

- Energy transfer to the hadron

$$\nu = E - E'$$

- Mass of the hadronic residual (or invariant mass)

$$W = \sqrt{(p+q)^2} = \sqrt{M_N^2 + 2M_N\nu - Q^2}$$

- Bjorken scaling variable

$$x = \frac{Q^2}{2M_N\nu}$$

Structure Functions

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left[\frac{F_2}{\nu} + 2\frac{F_1}{M}\tan^2\frac{\theta}{2}\right]$$

$$\frac{d^2\sigma}{dE' d\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1 - \frac{Q^2}{\nu}g_2\right]$$

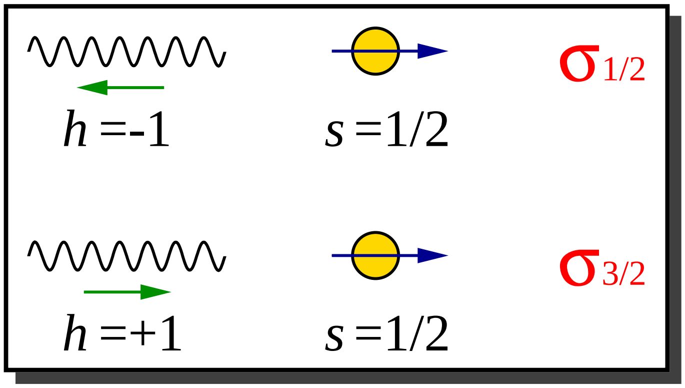
$$\frac{d^2\sigma}{dE' d\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2 \sin\theta}{MQ^2}\frac{E'^2}{E}\frac{1}{\nu^2}(\nu g_1 + 2E g_2)$$

$$\left.\begin{aligned} F_1(x) &= \tfrac{1}{2}\textstyle\sum_i e_i^2[q_i(x) + \bar{q}_i(x)] \\ F_2(x) &= \textstyle\sum_i e_i^2 x[q_i(x) + \bar{q}_i(x)] \end{aligned}\right\} F_2(x) = 2xF_1(x)\text{(Callan-Gross)}$$

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

$$\Delta q_i(x) = q_i^+(x) + \overline{q}_i^+(x) - q_i^-(x) - \overline{q}_i^-(x)$$

Gerasimov-Drell-Hearn Sum Rule



$$I_{\text{GDH}} = \int_{\nu_{\text{th}}}^{\infty} (\sigma_{1/2} - \sigma_{3/2}) \frac{d\nu}{\nu} = -\frac{2\pi^2 \alpha}{M^2} \kappa^2$$

κ : the nucleon anomalous magnetic moment

$$I_{\text{GDH}}^{\text{proton}} = -204.8 \mu b \qquad I_{\text{GDH}}^{\text{neutron}} = -233.2 \mu b$$

- Derived from very general principles applied to the forward Compton amplitude on the nucleon
- Valid for real photon ($Q^2 = 0$) absorption

GDH Integral at $Q^2 > 0$

$$I_{\rm GDH} \equiv \int (1-x)(\sigma_{1/2} - \sigma_{3/2}) \frac{d\nu}{\nu}$$
$$= \int \frac{8\pi^2\alpha}{M\nu}\left(g_1 - \frac{Q^2}{\nu^2} g_2\right)\frac{d\nu}{\nu}$$

Chiral perturbation theory calculation at small Q^2 gives*

$$S_1(0, Q^2) = 4\int G_1(\nu, Q^2)\frac{d\nu}{\nu}$$
$$= \int \frac{4}{M\nu} g_1 \frac{d\nu}{\nu}$$
$$\lim_{\nu\to 0} \frac{S_2(\nu, Q^2)}{\nu} = 4\int G_2(\nu, Q^2)\frac{d\nu}{\nu^2}$$
$$= \int \frac{4}{M\nu}\frac{g_2}{\nu^2}\frac{d\nu}{\nu}$$

As a result,

$$I_{\rm GDH} = 2\pi^2\alpha \left[S_1(0, Q^2) - Q^2 \left. \frac{S_2(\nu, Q^2)}{\nu} \right|_{\nu\to 0} \right]$$

* Xiangdong Ji and Jonathan Osborne, J. Phys. **G27** 127 (2001).

Integrals of Structure Functions

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

Bjorken Sum Rule

$$\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \frac{g_A}{6} \quad \text{as } Q^2 \to \infty$$

$$\Gamma_2(Q^2) = \int_0^1 g_2(x, Q^2)\, dx$$

Burkhardt-Cottingham Sum Rule

$$\Gamma_2(Q^2) = 0 \quad \text{at every } Q^2$$

$$\begin{aligned} d_2 &= 3\int_0^1 x^2 (g_2(x, Q^2) - g_2^{WW}(x, Q^2))\, dx \\ &= \int_0^1 x^2 (2g_1(x, Q^2) + 3g_2(x, Q^2))\, dx \\ g_2^{WW}(x, Q^2) &= -g_1(x, Q^2) + \int_x^1 \frac{g_1(y)}{y}\, dy \end{aligned}$$

$d_2(Q^2)$ measures twist 3 and higher contributions to g_2

Cont.

Spin Polarizabilities

$$\gamma_0(Q^2) = \frac{16M^2\alpha_{\rm em}}{Q^6}\int_0^{x_0} dx x^2 \left\{ g1(x,Q^2) - \frac{4M^2}{Q^2} g_2(x,Q^2) \right\}$$

$$\delta_{LT}(Q^2) = \frac{16M^2\alpha_{\rm em}}{Q^6}\int_0^{x_0} dx x^2 \left\{ g1(x,Q^2) + g_2(x,Q^2) \right\}$$

$$\delta_{LT}(Q^2) \to \frac{1}{3}\gamma_0(Q^2), \quad Q^2 \to \infty$$

$I_3(Q^2)$

$$I_3(Q^2) = \frac{2M^2}{Q^2}\int_0^{x_0} dx \left\{ g_1(x,Q^2) + g_2(x,Q^2) \right\}$$

$$I_3(0) = \frac{e\kappa}{4} \quad \text{if BC sum rule holds}$$

Spin Duality

Summary of the Experiment

$$\vec{e} + {}^3\vec{\mathrm{He}} \rightarrow e' + X$$

- **Beam** : Polarized electron beam at Jefferson Lab.

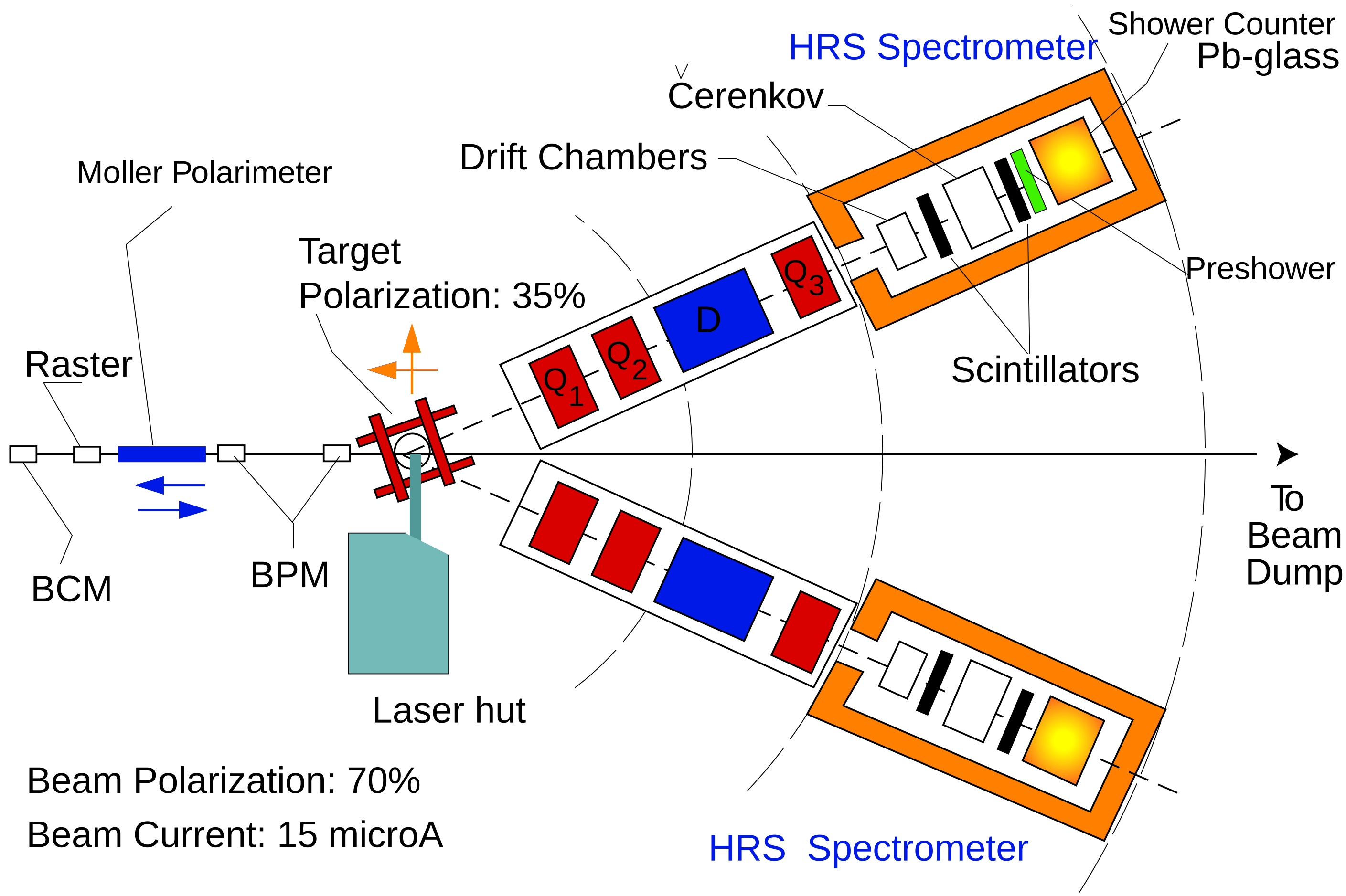
Energy	:	6 beam energies from 0.86 GeV to 5.1 GeV
Current	:	5 to 15 μA
Polarization	:	$>$ 70% (GaAs crystal)

- **Target** : Polarized ^{3}He target (Optical pumping)

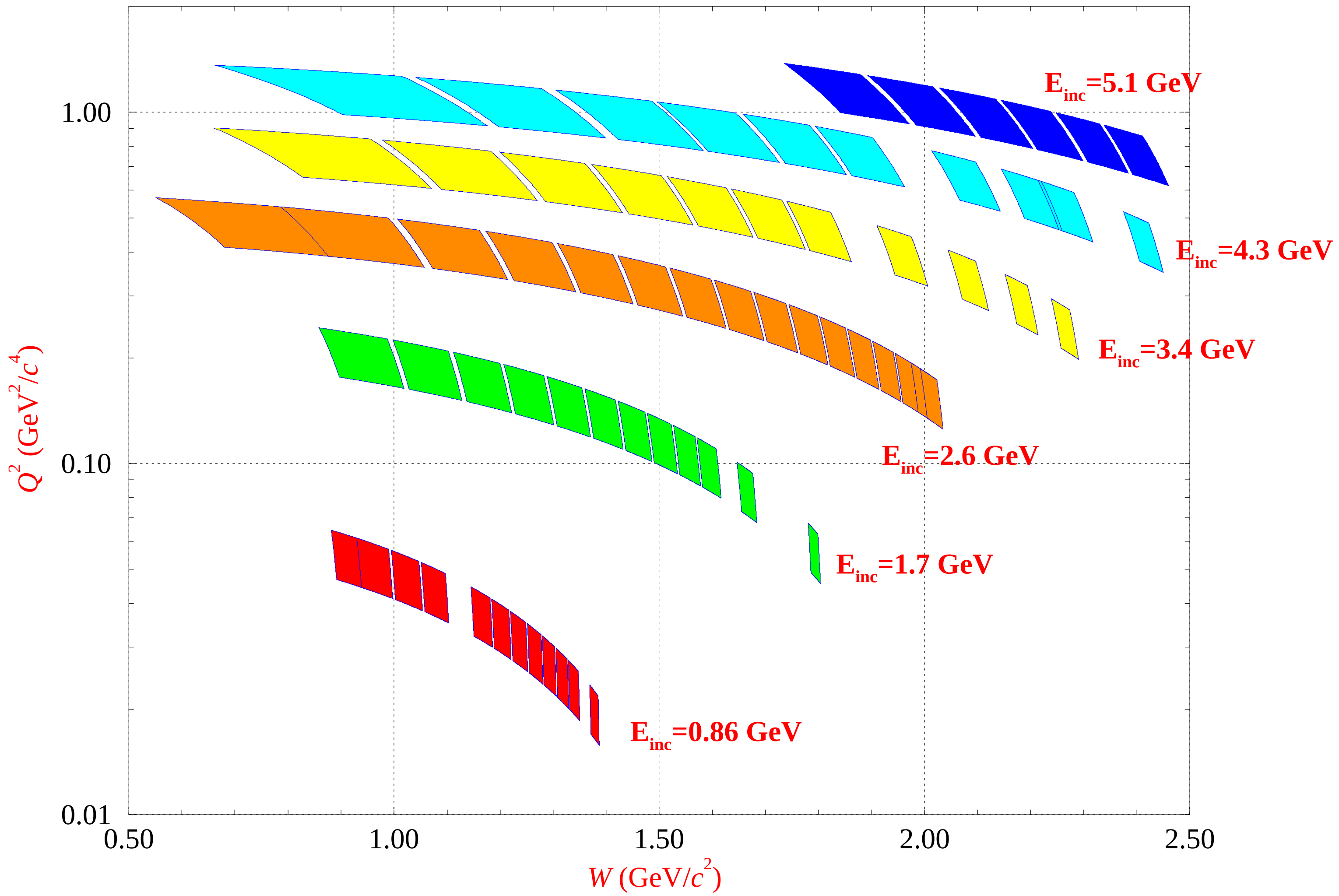
Polarization	:	average 35%
Density	:	$\sim$ 10 atm
Length	:	40 cm with window thickness of 0.1 mm

- **Scattering angle** : 15.5°
- **Detectors** : JLab Hall-A Spectrometers

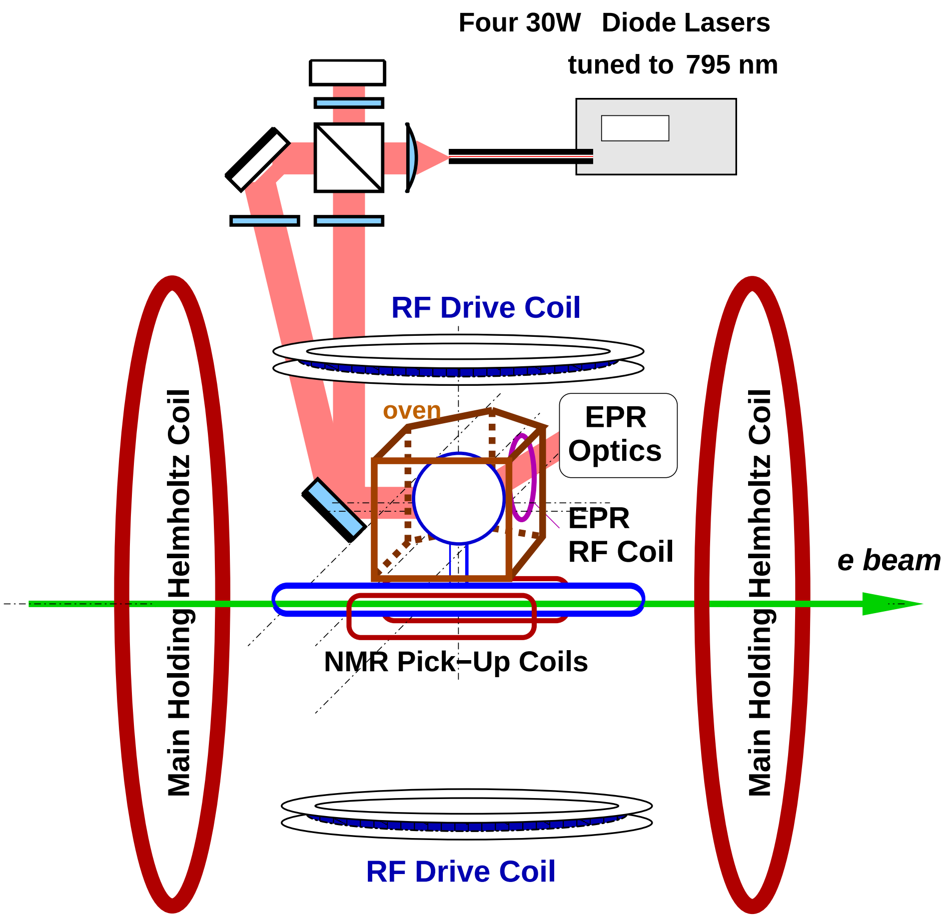
JLab E94010 Floor Configuration



JLab E94010 Kinematic Coverage



Polarized ^{3}He Target Setup



Caltech
JLab
U. of Kentucky
MIT
Princeton U.
Temple U.

- NMR and EPR techniques for polarization monitoring.
- Elastic asymmetry measurement for current induced depolarization.
- Target used successfully for several polarized ^{3}He experiments.
- Target length 40 cm, window thickness 0.1 mm.

Analysis Schematics

$$\vec{e} + {}^3\vec{\mathrm{He}} \longrightarrow e' + X$$

$\sigma_{\downarrow\Uparrow}$ $\sigma_{\uparrow\Uparrow}$ $\sigma_{\downarrow\Rightarrow}$ $\sigma_{\uparrow\Rightarrow}$

$$\Delta\sigma_{\parallel} = \frac{1}{P_b P_t}(\sigma_{\downarrow\Uparrow} - \sigma_{\uparrow\Uparrow})$$

$$\Delta\sigma_{\perp} = \frac{1}{P_b P_t}(\sigma_{\downarrow\Rightarrow} - \sigma_{\uparrow\Rightarrow})$$

$$g_1,\ g_2,\ \sigma_{1/2} - \sigma_{3/2}$$

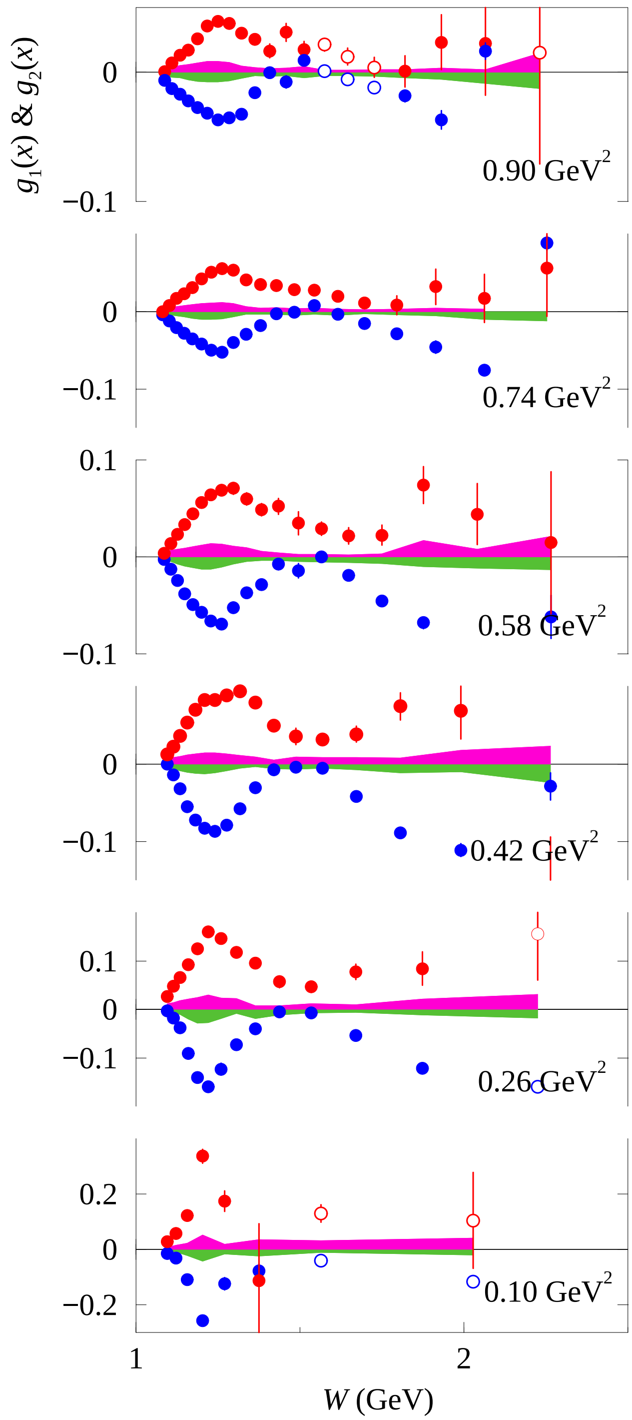
$$\Downarrow$$

$$I_{\mathrm{GDH}} = \int_{\nu_{\mathrm{th}}}^{\infty} (1-x)(\sigma_{1/2} - \sigma_{3/2}) \frac{d\nu}{\nu}$$

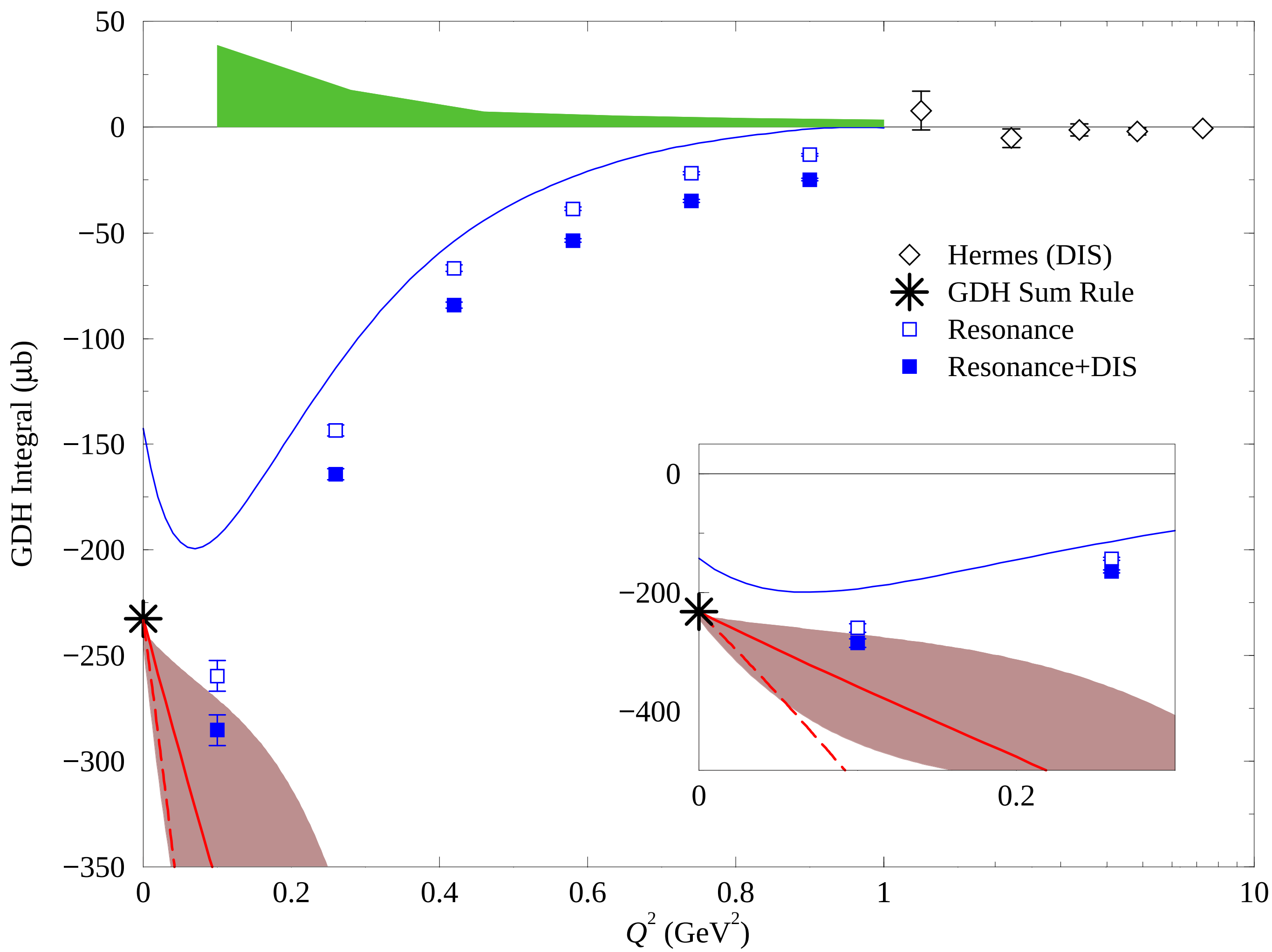
$$\Gamma_1 = \int_0^1 g_1(x, Q^2)\, dx$$

$$\Gamma_2 = \int_0^1 g_2(x, Q^2)\, dx$$

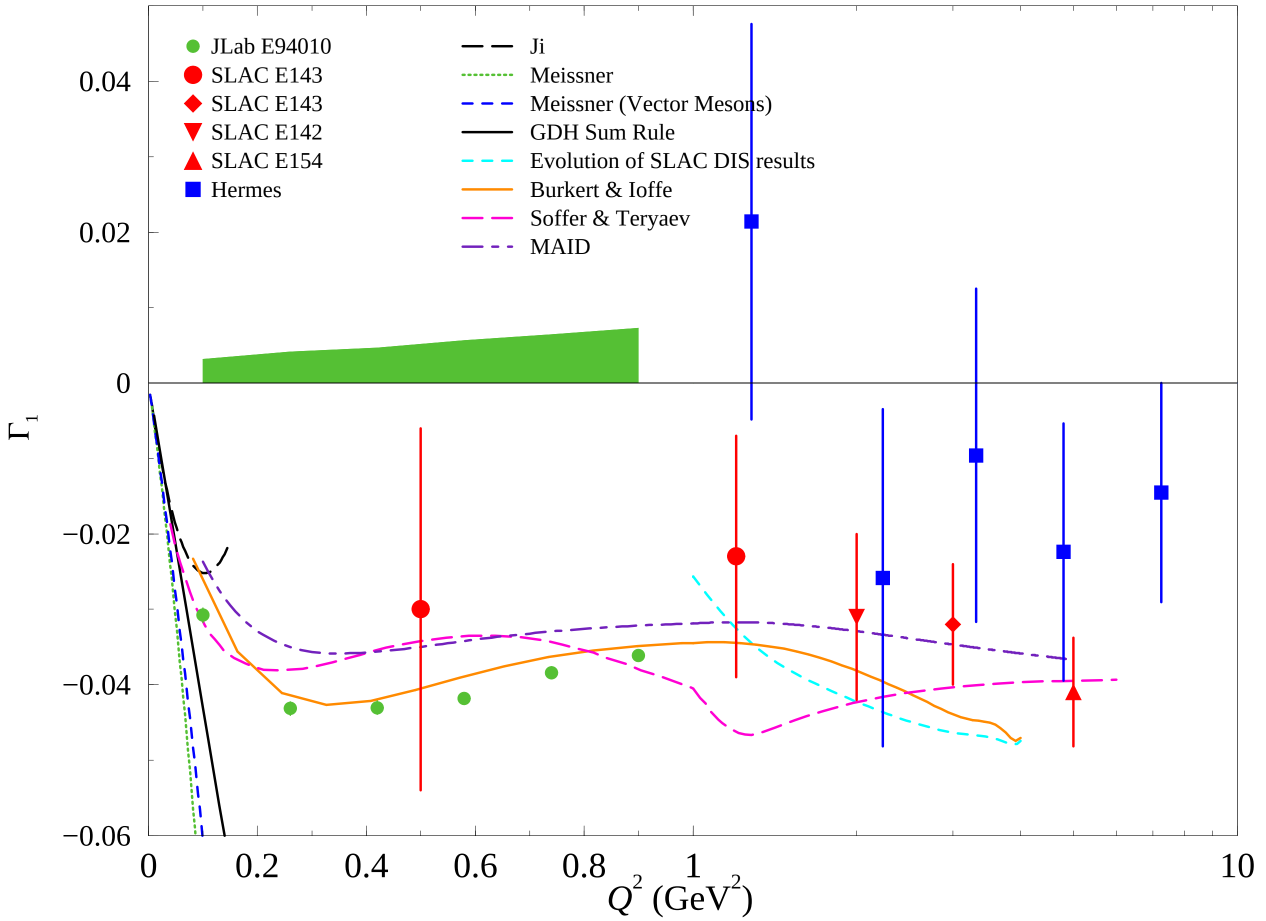
$g_1(x)$ and $g_2(x)$ at Constant Q^2



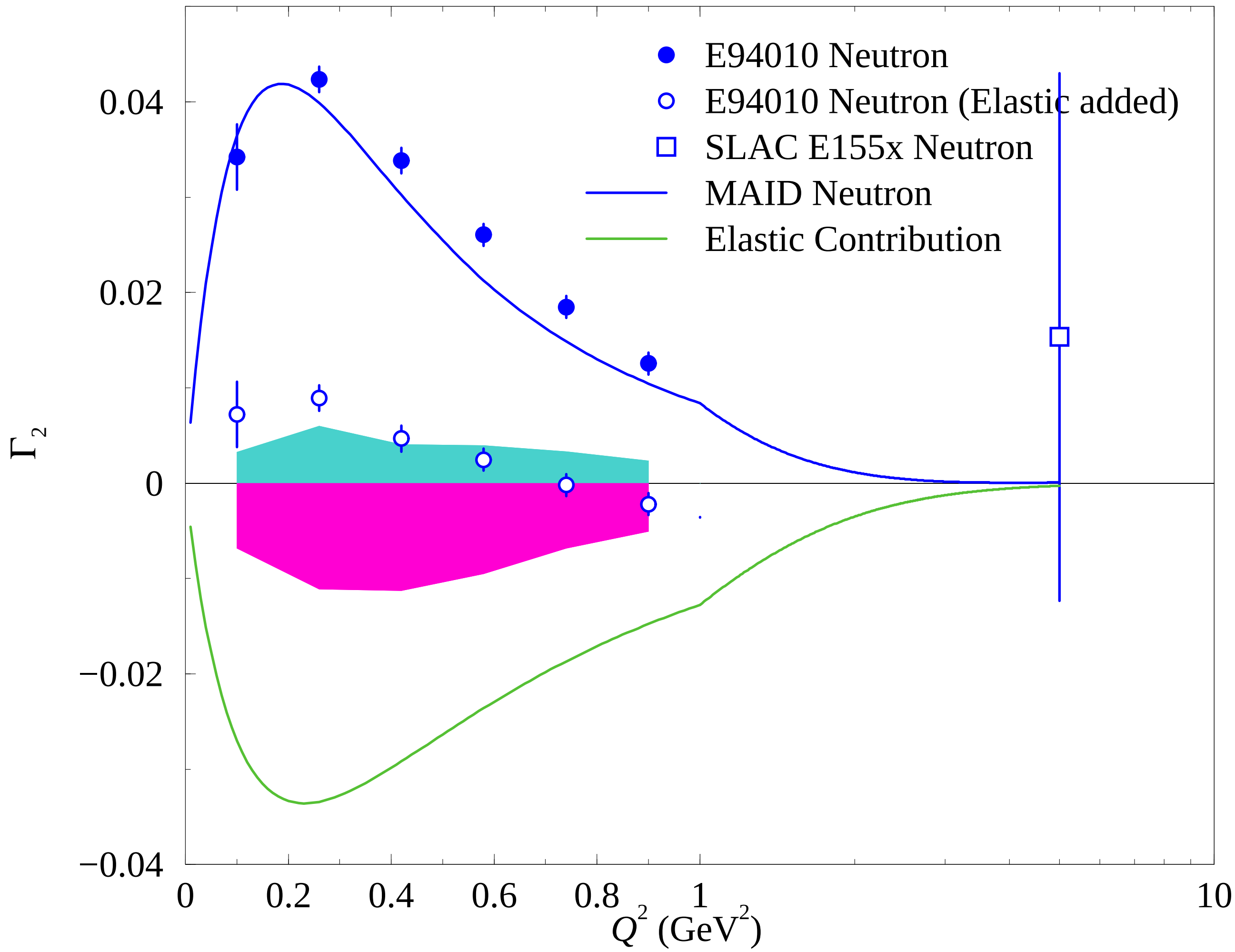
GDH Integral

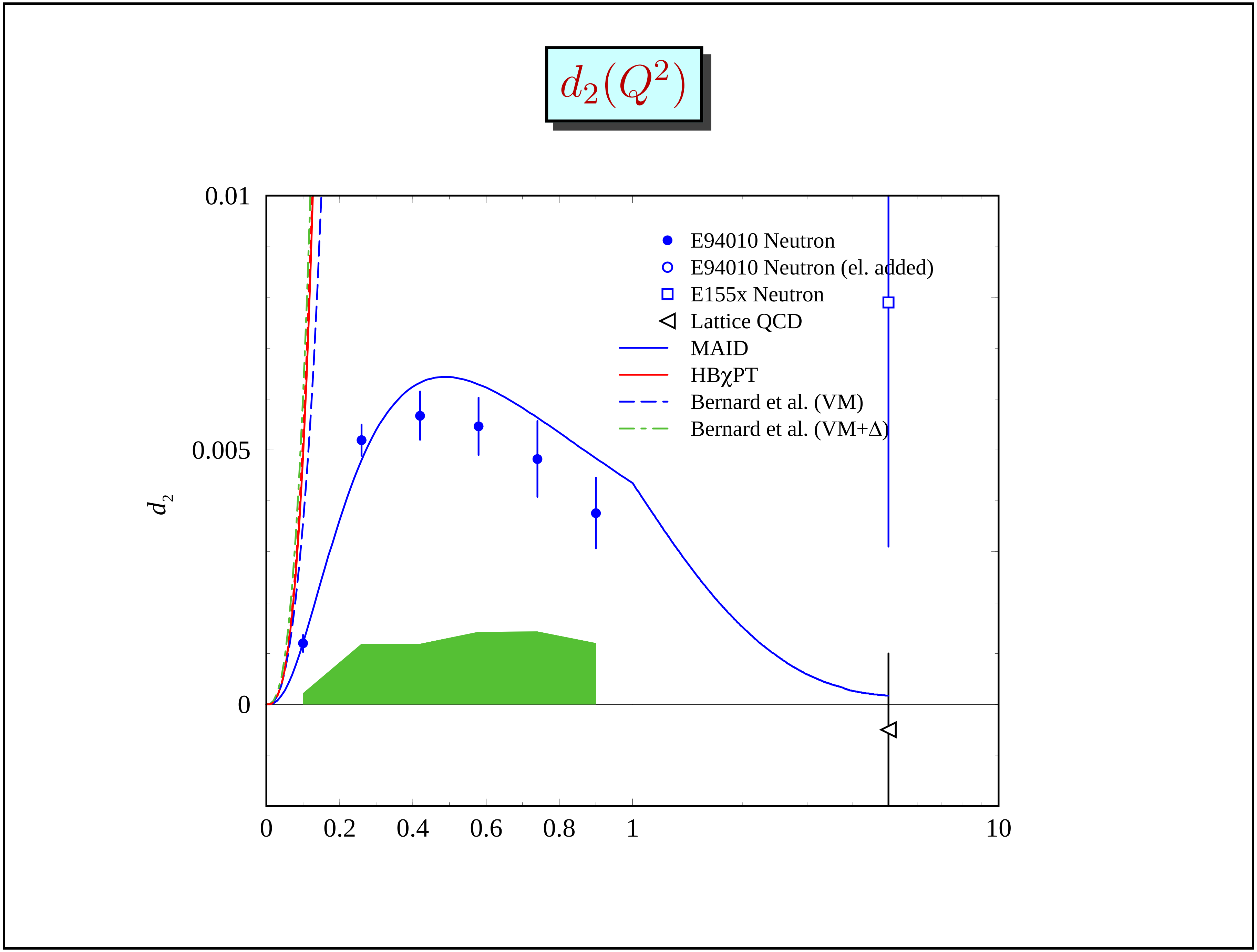


Integral of $g_1(x, Q^2)$



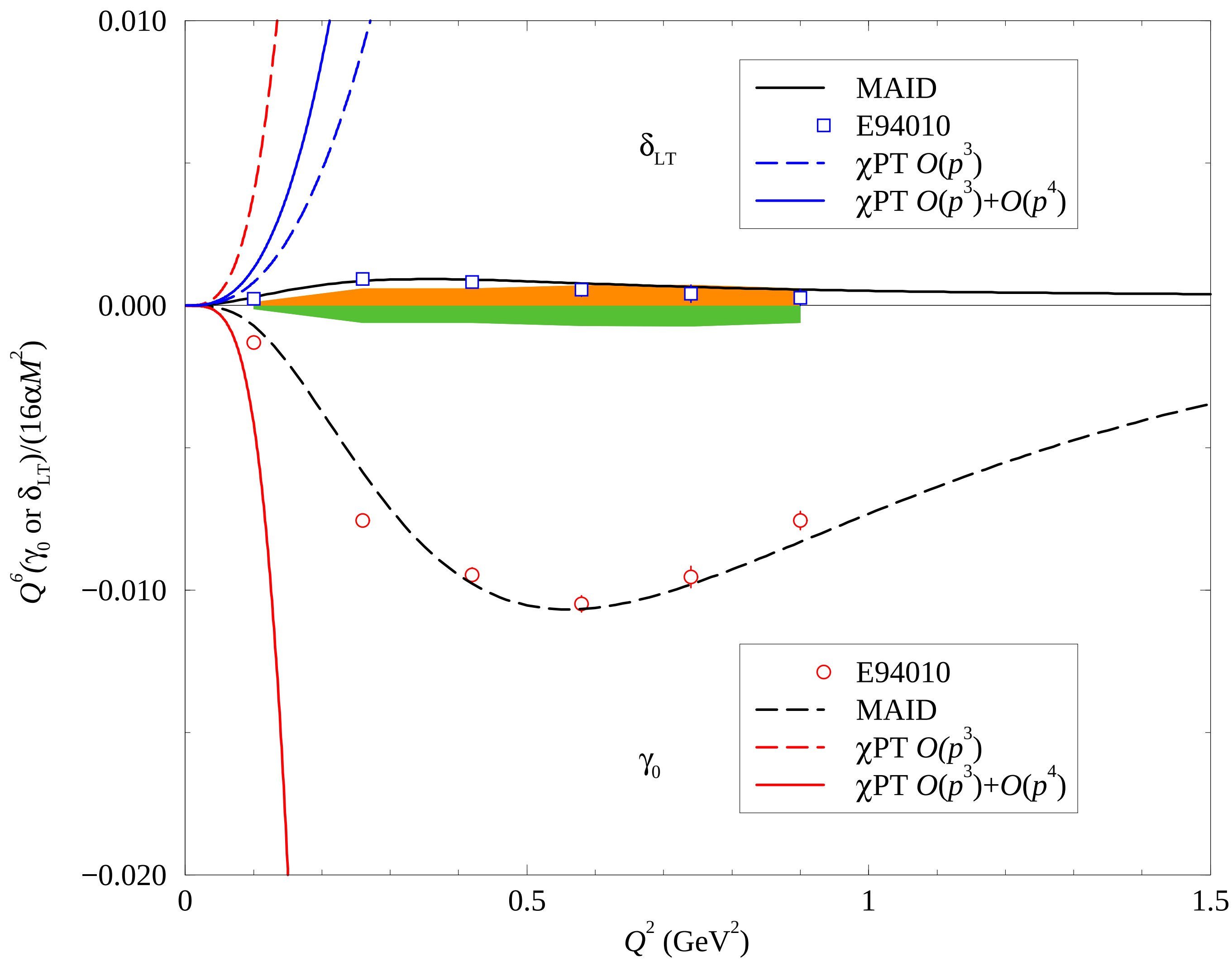
Integral of $g_2(x, Q^2)$

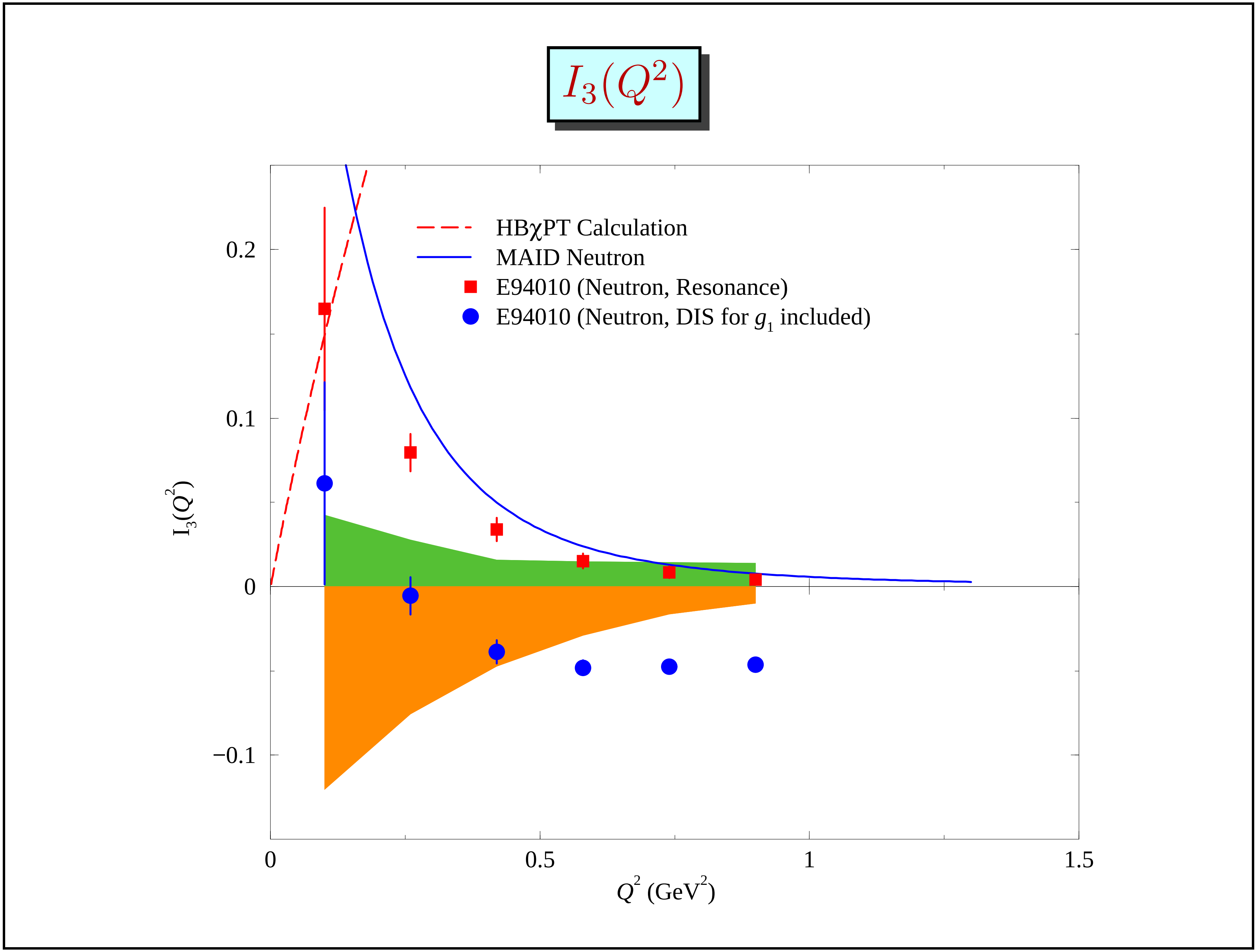




$d_2(Q^2)$
0.01
0.005
0
d_2
0
0.2
0.4
0.6
0.8
1
10
E94010 Neutron
E94010 Neutron (el. added)
E155x Neutron
Lattice QCD
MAID
HBχPT
Bernard et al. (VM)
Bernard et al. (VM+Δ)

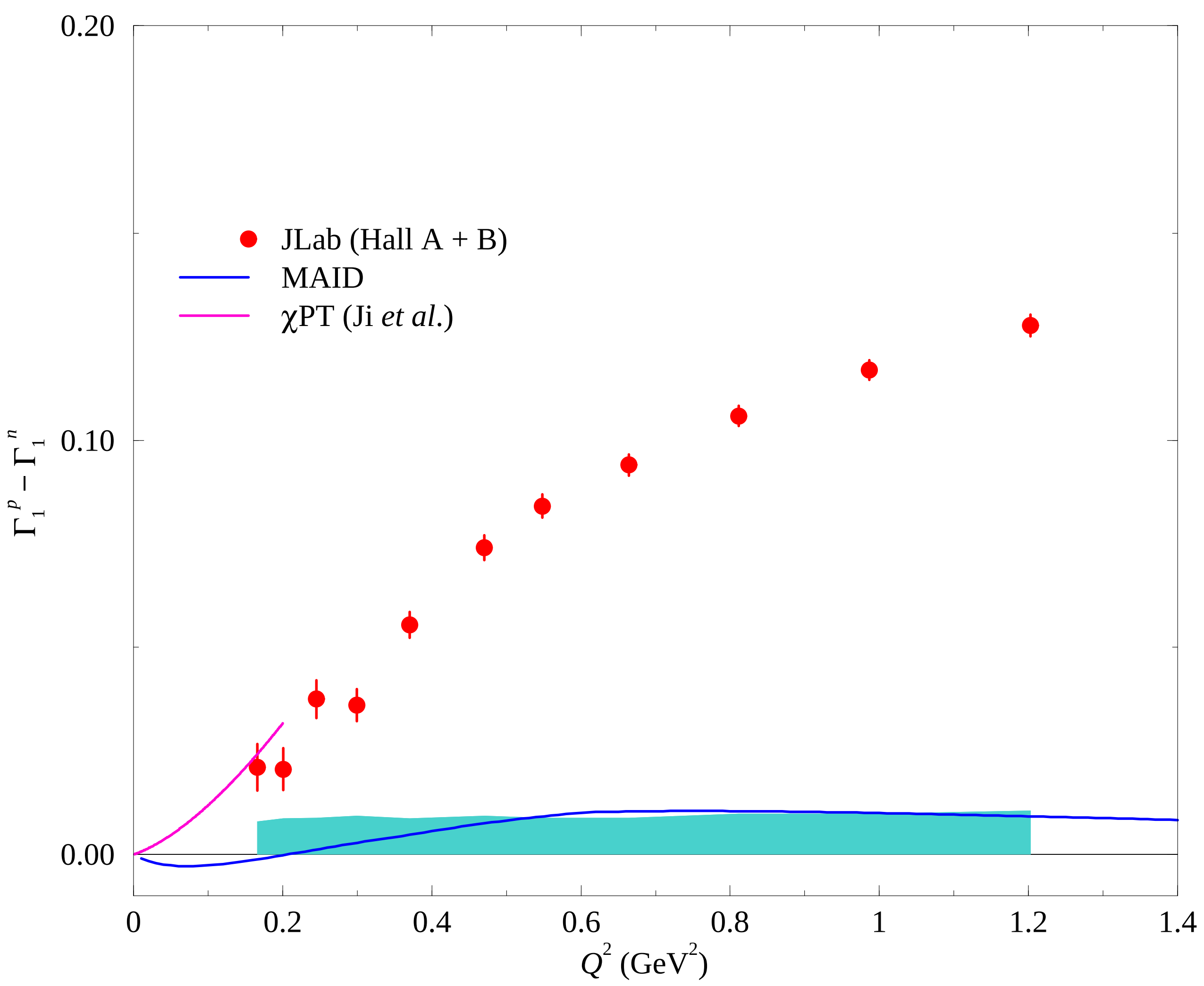
Spin Polarizabilities





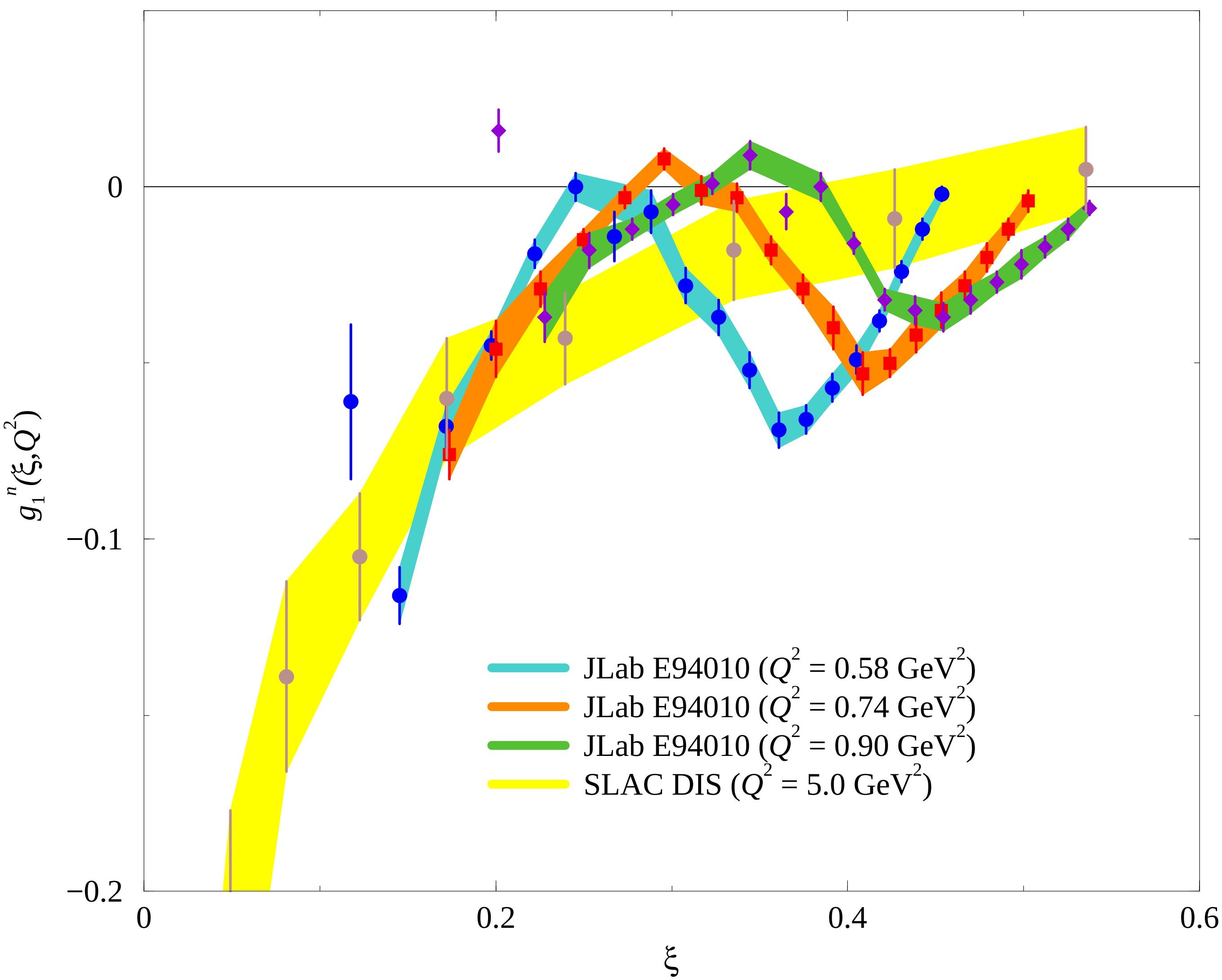
$I_3(Q^2)$
HBχPT Calculation
MAID Neutron
E94010 (Neutron, Resonance)
E94010 (Neutron, DIS for g_1 included)
0.2
0.1
0
−0.1
0
0.5
1
1.5
$I_3(Q^2)$
Q^2 (GeV^2)

Bjorken Sum



0.20
0.10
0.00
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Q2 (GeV2)
Γ1p – Γ1n
JLab (Hall A + B)
MAID
χPT (Ji et al.)

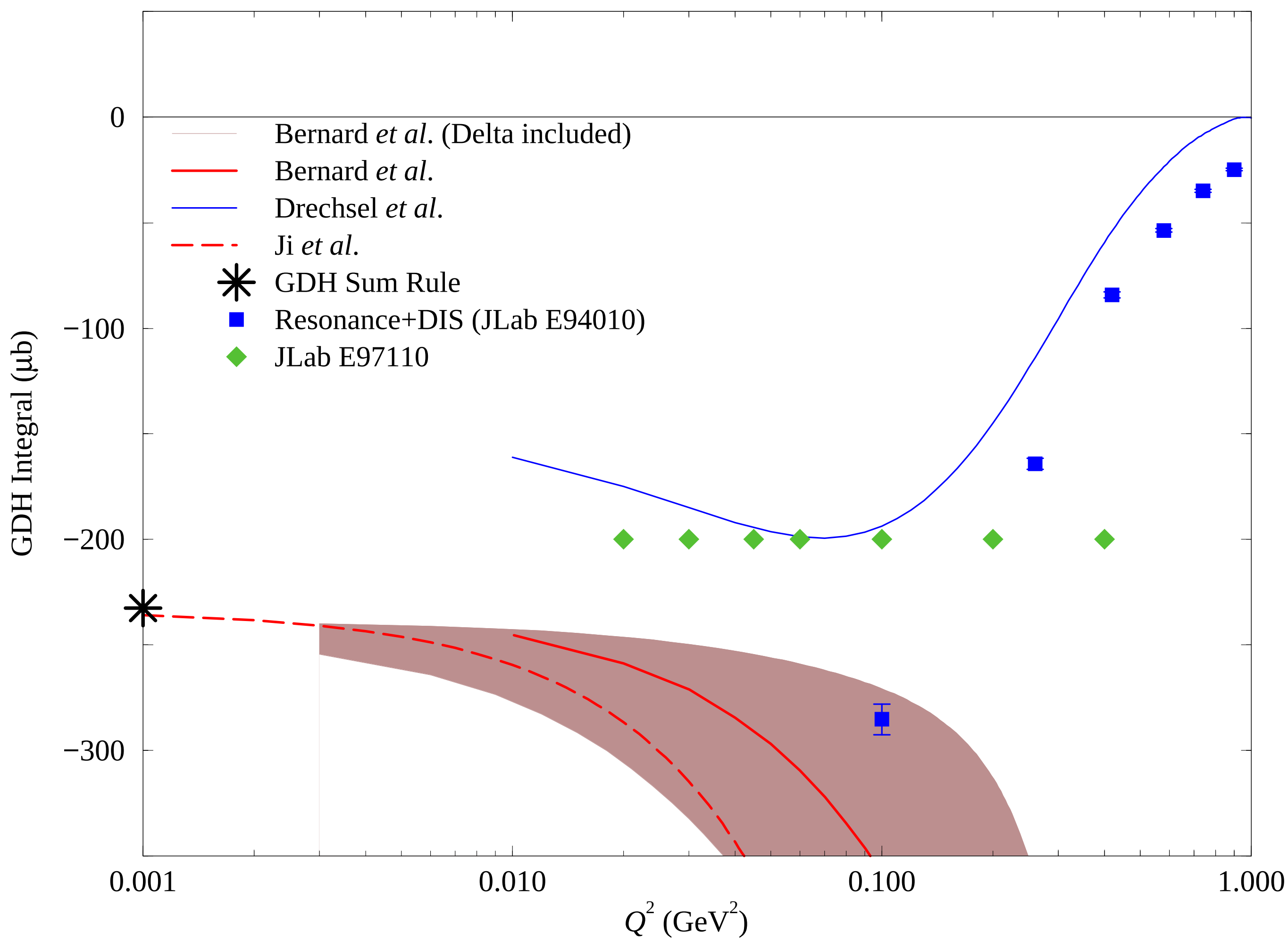
Spin Duality



Conclusion

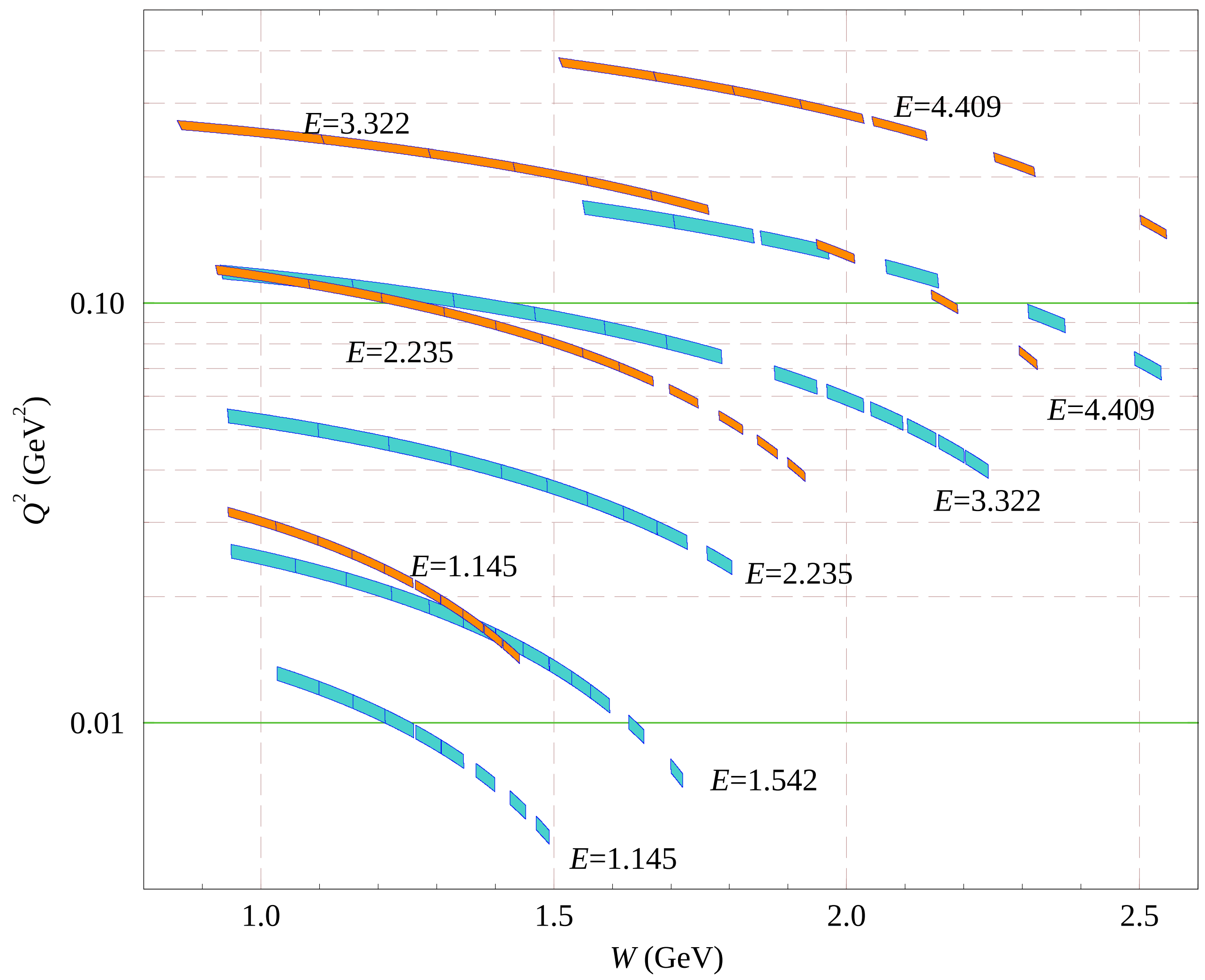
- $g_1(x,Q^2)$ and $g_2(x,Q^2)$ for the neutron have been measured at $Q^2 < 1\mathrm{GeV}^2$ region
- Various integrals have been evaluated
  - ➜ GDH Sum Rule
    - Transition from $Q^2 > 1$ to small Q^2 observed
    - More interesting results expected from future JLab experiment at even smaller Q^2
  - ➜ $\Gamma_1(Q^2)$
    - Much improved precision compared to SLAC data
    - With JLab Hall-B data combined, study of Bjorken Sum
  - ➜ $\Gamma_2(Q^2)$. $d_2(Q^2)$, $\gamma_0(Q^2)$ and δ_{LT} have been measured at small Q^2 for the first time.
  - ➜ Hint of neutron spin duality for $g_1(x,Q^2)$ at $Q^2 < 1.0$ GeV^2
- Future
  - ➜ Small angle GDH experiment
  - ➜ Spin duality for the neutron at 1 $< Q^2 <$ 4 GeV^2

JLab E97-110



Bernard et al. (Delta included)
Bernard et al.
Drechsel et al.
Ji et al.
GDH Sum Rule
Resonance+DIS (JLab E94010)
JLab E97110
GDH Integral (μb)
0
−100
−200
−300
0.001
0.010
0.100
1.000
Q^2 (GeV^2)

JLab E97-110 (Kinematics)



Experiment E01-012

Measurement of Neutron (^{3}He) Spin Structure Functions in the Resonance Region

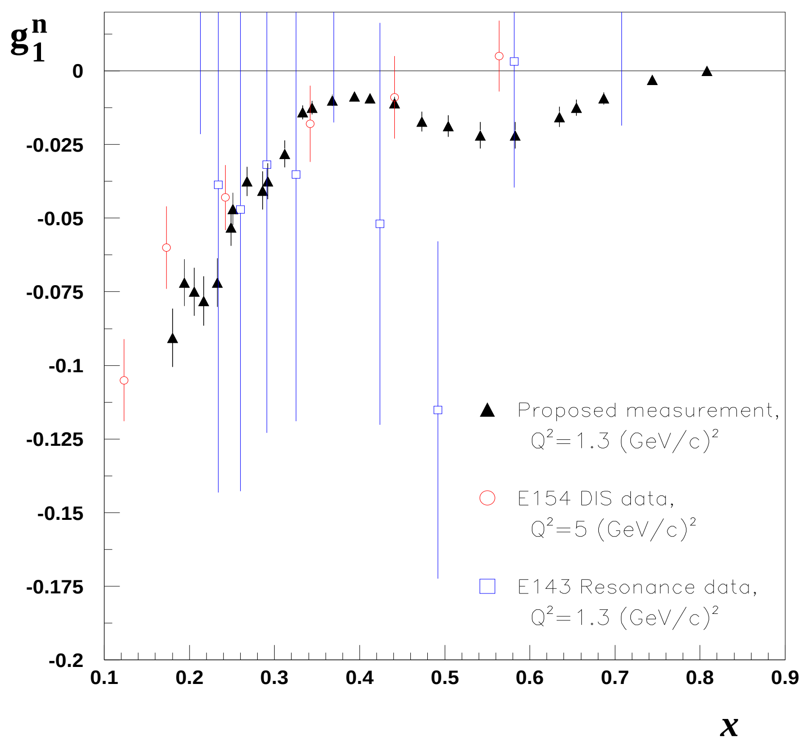
Spokespeople: N. Liyanage, J.P.Chen, S.Choi

- A precision measurement of neutron spin structure functions in the resonance region up to $Q^2 = 5.5$ GeV^2.

  Test quark-hadron duality in spin structure functions.

  A first test of spin-flavor dependence of duality

- Duality$\longrightarrow$ Powerful tool to study very high x behavior.
- **Understanding quark-hadron duality will help us understand confinement of quarks in protons and neutrons**



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