Nucleon Spin Structure Functions (g_1 and g_2) from Polarized Inclusive Scattering

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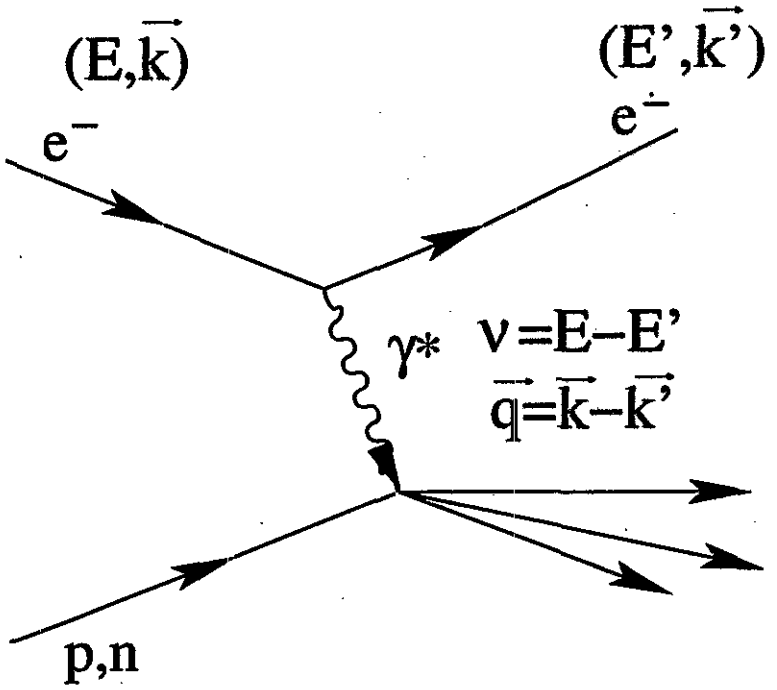
SPIN 2002

- **Polarized DIS: Spin crisis, world data, sum rules, NLO analyses**
- **A_1^n at large-x**
- **g_1 in the resonance region, Generalized GDH sum rule**
- **The g_2 structure function**
- **Duality in spin structure functions**

UNPOLARIZED DEEP INELASTIC SCATTERING



- θ = electron scattering angle (lab frame)
- $Q^2 = \vec{q} \cdot \vec{q} - \nu^2$ = 4-momentum transfer squared
- $\nu = E - E'$ = energy transfer
- $x = \frac{Q^2}{2M\nu}$
- x is the fraction of the nucleon momentum carried by the "struck" quark.

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

" ... F_1 and F_2 parameterize our ignorance of the detailed structure of the proton ... "

Halzen + Martin, Quarks and Leptons

POLARIZED DEEP INELASTIC SCATTERING
(INCLUSIVE)

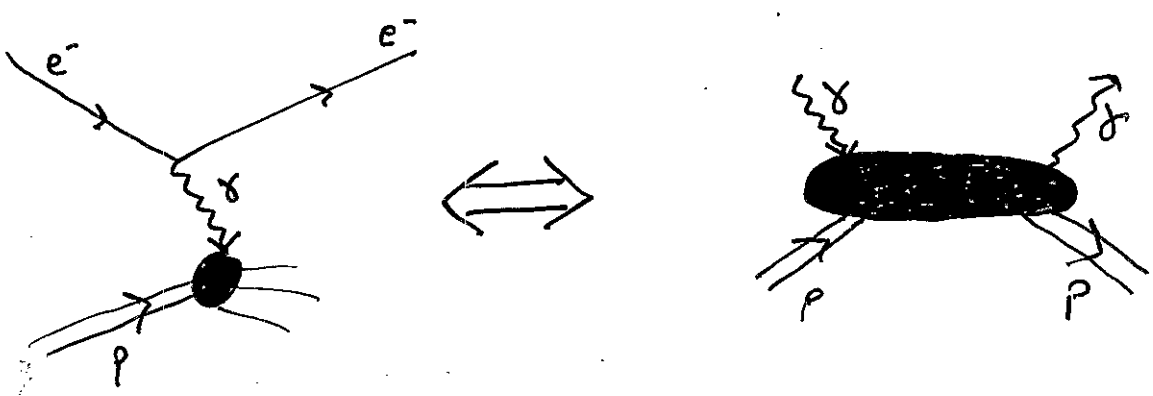
$$\frac{d\sigma}{d\Omega dE'}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2 E'}{MQ^2\nu E}\left[(E + E'\cos(\theta))\, g_1(x, Q^2) - \frac{Q^2}{\nu} g_2(x, Q^2)\right]$$

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

- Can also write in terms of virtual photon absorption cross-sections

$$\sigma_{TT} = \frac{1}{2}\left(\sigma^{\tau}_{1/2} - \sigma^{\tau}_{3/2}\right)$$

$$= \frac{8\pi^2\alpha}{2M\nu - Q^2}\left[g_1(x, Q^2) - \frac{Q^2}{\nu^2} g_2(x, Q^2)\right]$$



Polarized Deep Inelastic Scattering

- Measure asymmetries

$$A_{\parallel} = \left(\frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}\right)\frac{1}{fP_bP_t}$$

- f is a dilution factor to account for scattering from unpolarized nuclei.

- P_b and P_t are the beam and target polarizations

- Obtain polarized structure functions:

$$g_1(x, Q^2) = \frac{F_1(x, Q^2)}{D}\left[A_{\parallel} + \tan(\theta/2)A_{\perp}\right]$$

$$g_2(x, Q^2) = \frac{F_1(x, Q^2)}{D'}\left[\frac{E + E'cos(\theta)}{E'}A_{\perp} - \sin(\theta)A_{\parallel}\right]$$

- D and D' contain kinematic factors and unpolarized cross section

Quark Parton Model

In the limit where $Q^2 \to \infty$, the nucleon consists of 3 non-interacting valence quarks plus "sea" quark pairs. In this simple picture we can write:

$$F_1(x) = \frac{1}{2}\sum_i^{N_f} e_i^2 \left[(q_i^{\uparrow}(x) + \bar{q}_i^{\uparrow}(x)) + (q_i^{\downarrow}(x) + \bar{q}_i^{\downarrow}(x))\right]$$

$$g_1(x) = \frac{1}{2}\sum_i^{N_f} e_i^2 \left[(q_i^{\uparrow}(x) + \bar{q}_i^{\uparrow}(x)) - (q_i^{\downarrow}(x) + \bar{q}_i^{\downarrow}(x))\right]$$

$q^{\uparrow}$ is the probability of finding a quark with it's spin parallel to the nucleon spin.

e_i is the charge of the quark.

From this we can write the following sum rule:

$$\Gamma_1^p = \int_0^1 g_1^p(x)dx = \frac{4}{18}\Delta u + \frac{1}{18}\Delta d + \frac{1}{18}\Delta s$$

where

$$\Delta u = \int_0^1 \left[(u_i^{\uparrow}(x) + \bar{u}_i^{\uparrow}(x)) - (u_i^{\downarrow}(x) + \bar{u}_i^{\downarrow}(x))\right] dx$$

Or, expressed in terms of the SU(3) flavor combinations:

$$\Gamma_1^p = \int_0^1 g_1^p(x)dx = \frac{1}{12}\Delta q_3 + \frac{1}{36}\Delta q_8 + \frac{1}{9}\Delta\Sigma$$

where

$\Delta q_3 = \Delta u - \Delta d = F + D = 1.2601 \pm 0.0025$ *

$\Delta q_8 = \Delta u + \Delta d - 2\Delta s = 3F - D = 0.579 \pm 0.025$ *

$\Delta\Sigma = \Delta u + \Delta d + \Delta s$

and

$\Delta\Sigma$ is the fraction of the nucleon spin carried by the quarks.

* Δq_3 + Δq_8 Known from neutron and hyperon decay

Helicity Conservation
(Spin Sum Rule)

$$\frac{1}{2}\Delta\Sigma + \Delta G + < L_z > = \frac{1}{2}$$

quarks gluons angular momentum nucleon spin

Sum Rules

Ellis-Jaffe Sum Rule (assume $\Delta s = 0$)

$$\Delta\Sigma = \Delta q_8 = 0.579 \pm 0.025$$

$$\begin{aligned}
\Gamma_1^p &= \int_0^1 g_1^p(x)dx = \frac{1}{6}\left(\frac{1}{2}\Delta q_3 + \frac{5}{6}\Delta q_8\right) \\
&= 0.172 \pm 0.003,\ Q^2 = 3.0\ (GeV/c)^2 \\
\Gamma_1^n &= \int_0^1 g_1^n(x)dx = \frac{1}{6}\left(-\frac{1}{2}\Delta q_3 + \frac{5}{6}\Delta q_8\right) \\
&= -0.020 \pm 0.003,\ Q^2 = 3.0\ (GeV/c)^2
\end{aligned}$$

Bjorken Sum Rule

Derived before QCD using current algebra. Assumes isospin symmetry and QPM.

$$\begin{aligned}
\Gamma_1^{p-n} &= \int_0^1 (g_1^p(x) - g_1^n(x))dx = \frac{1}{6}\Delta q_3 \\
&= 0.181 \pm 0.003,\ Q^2 = 3.0\ (GeV/c)^2
\end{aligned}$$

Note: Essential element in above sum rules is knowledge of $g_1(x)$ for <u>all</u> x.

Also important is Q^2 dependence.

SUMMARY OF DIS EXPERIMENTS

Experiment	x–range	Q^2–range (GeV^2)	Ref.
Proton			
E143(p)	0.027 – 0.749	1.17 – 9.52	[1]
HERMES(p)	0.028 – 0.660	1.13 – 7.46	[2]
E155(p)	0.015 – 0.750	1.22 – 34.72	[3]
SMC(p)	0.005 – 0.480	1.30 – 58.0	[4]
EMC(p)	0.015 – 0.466	3.50 – 29.5	[5]
Deuteron			
E143(d)	0.027 – 0.749	1.17 – 9.52	[1]
E155(d)	0.015 – 0.750	1.22 – 34.79	[6]
SMC(d)	0.005 – 0.479	1.30 – 54.8	[4]
Neutron			
E142(n)	0.035 – 0.466	1.10 – 5.50	[7]
HERMES(n)	0.033 – 0.464	1.22 – 5.25	[8]
E154(n)	0.017 – 0.564	1.20 – 15.0	[9]/[10]

Source: Blümlein & Böttcher, hep-ph/0203155

References

[1] K. Abe et al., E143, Phys. Rev. **D58** (1998) 120003.

[2] A. Airapetian et al., HERMES collaboration, Phys. Lett. **B442** (1998) 484

[3] P.L. Anthony et al., E155, Phys. Lett. **B493** (2000) 19.

[4] B. Adeva et al., SMC collaboration, Phys. Rev. **D58** (1998) 112001.

[5] J. Ashman et al., EMC collaboration, Phys. Lett. **B206** (1988) 364; Nucl. Phys. **B328** (1989) 1.

[6] P.L. Anthony et al., E155, Phys. Lett. **B463** (1999) 339.

[7] P.L. Anthony et al., E142, Phys. Rev. **D54** (1996) 6620.

[8] K. Ackerstaff et al., HERMES collaboration, Phys. Lett. **B404** (1997) 383.

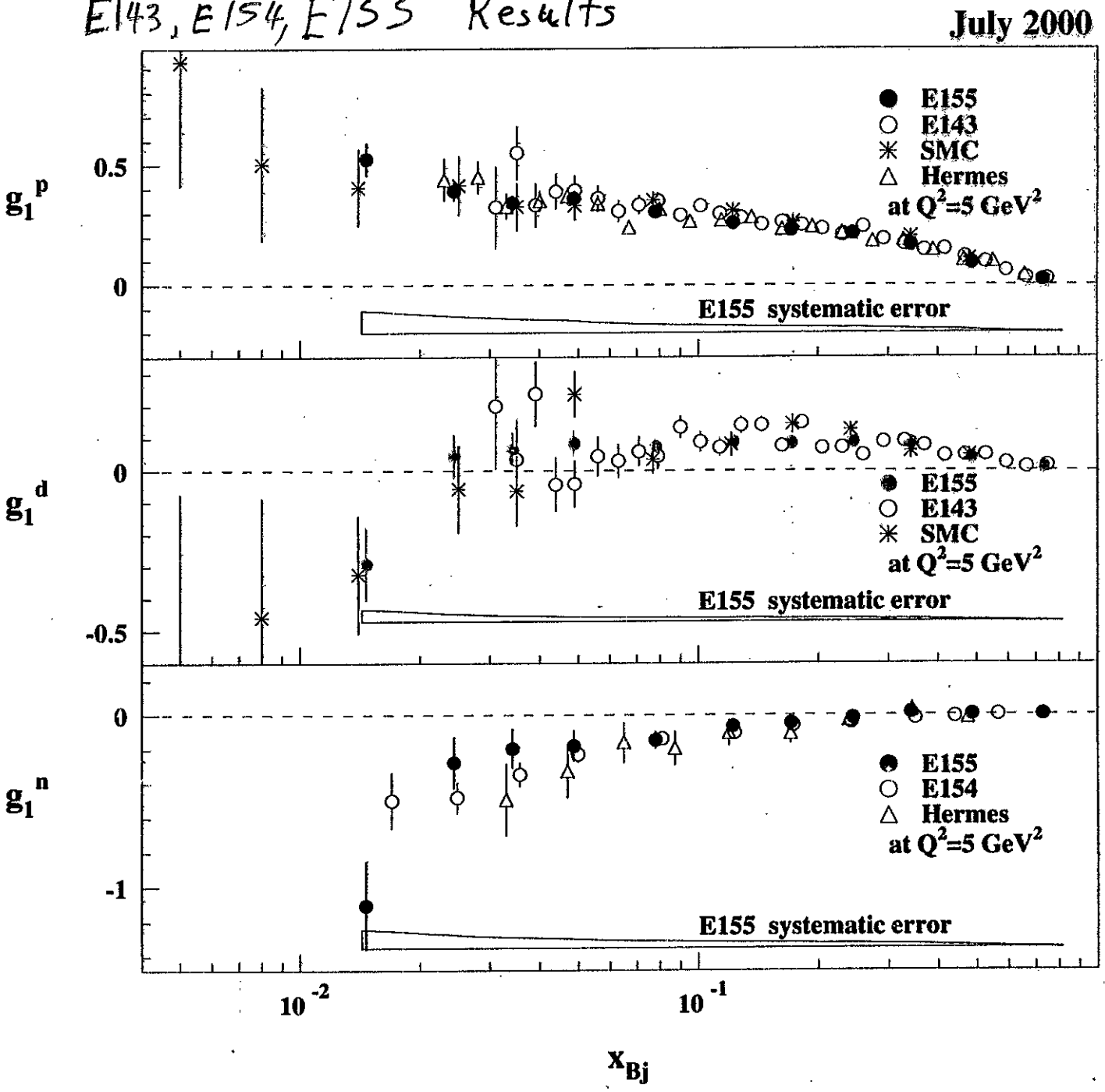
[9] K. Abe et al., E154, Phys. Rev. Lett. **79** (1997) 26.

[10] K. Abe et al. (E154), Phys. Lett. **B405** (1997) 180.

Hermes deuteron data – preliminary data at SPIN2002

SLAC

E143, E154, E155 Results

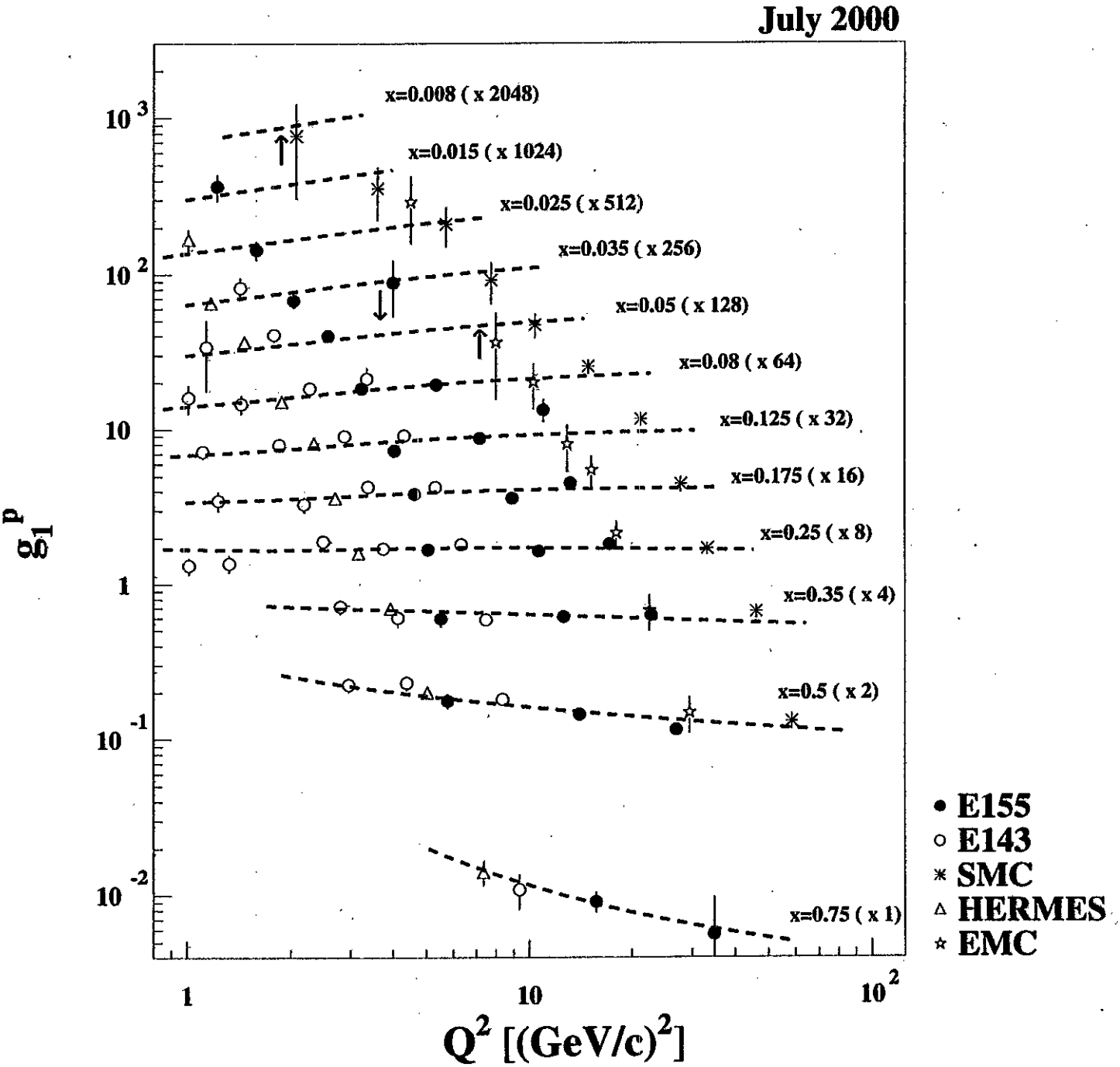


Data taken at different values of Q^2 evolved to a common $Q^2 = 5\ GeV^2$ assuming $g_1/F_1 \approx$ independent of Q^2.

PLB 493 (2000) 19.

World data for g_1^p

Proton



Broad kinematic coverage allows NLO analysis.

Factorization of g_1

Factorization theorem allows us to write:

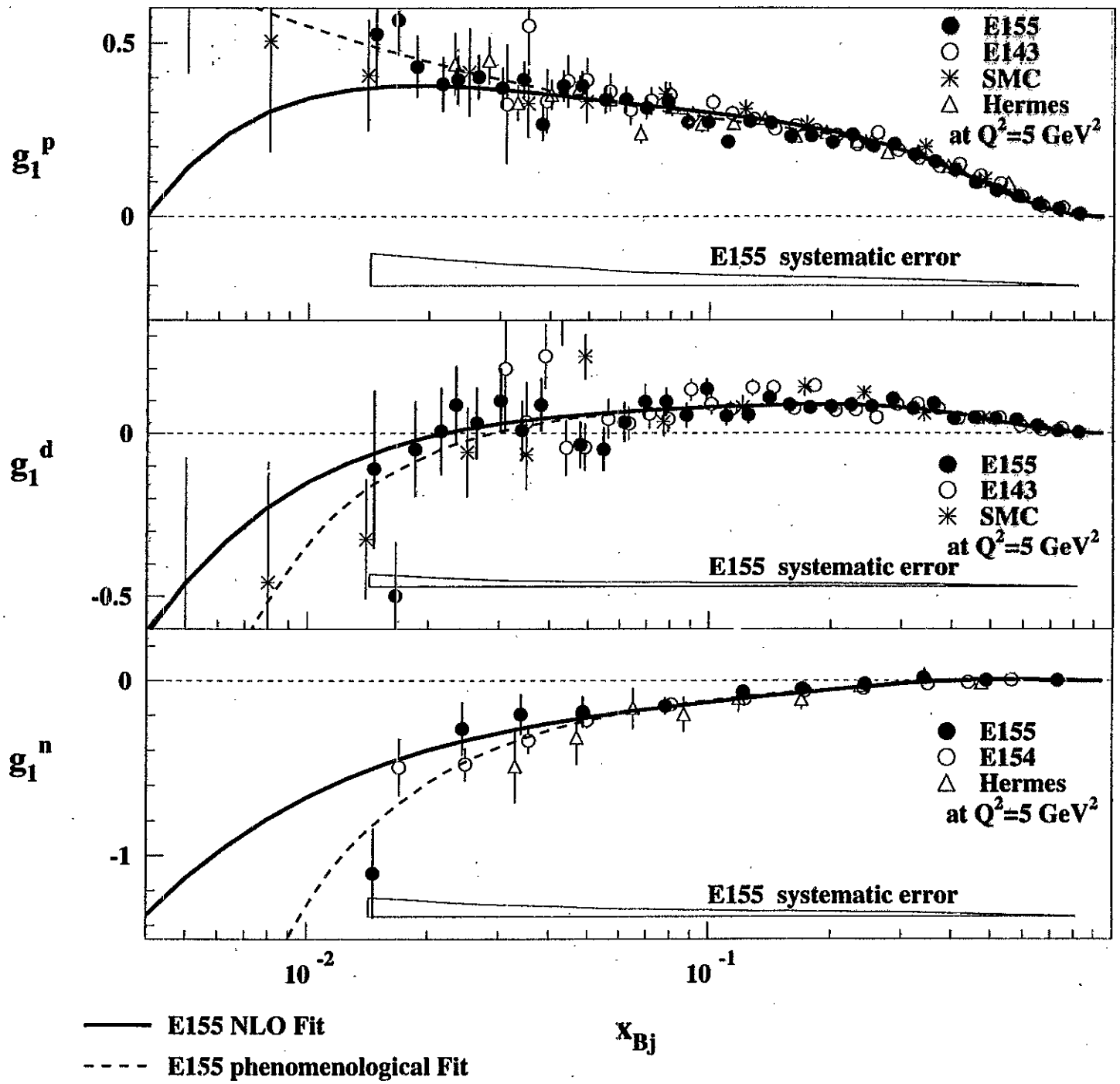
$$g_1(x, Q^2) = \frac{1}{2}\sum_q^{N_f} e_q^2 \left[C_q \otimes (\Delta q + \Delta\bar{q}) + \frac{1}{N_f} C_G \otimes \Delta G \right]$$

where

$$(C \otimes q)(x, Q^2) = \int_x^1 \frac{dz}{z} C\left(\frac{x}{z}, \alpha_S\right) q(z, Q^2)$$

- Choose $N_f = 3$
- $C_{q,G}(x, \alpha_S)$ correspond to hard scattering photon-quark and photon-gluon cross sections.
- Calculated in pQCD as an expansion in powers of α_S
  $C_p(x, \alpha_S) = C_p^{(0)}(x) + \frac{\alpha_S}{2\pi} C_p^{(1)}(x)$
- In leading order, we recover the simple QPM
  $C_q^{(0)}(x) = \delta(1-x)$, $C_G^{(0)} = 0$
- Δq, $\Delta\bar{q}$, ΔG are polarized parton distributions which cannot be calculated perturbatively.

SLAC E155 NLO fits



E155 NLO FIT RESULTS

$\Delta u_v = 0.71 \pm 0.02 \pm 0.04$
$\Delta d_v = -0.45 \pm 0.03 \pm 0.03$

- Quark Spin Contribution
  $\Delta\Sigma = 0.23 \pm 0.04 \pm 0.06$ at $Q^2 = 5$ GeV^2.

- Ellis-Jaffe Sum Rules predict $\Delta\Sigma = 0.58$.
  $\longrightarrow \Delta s \neq 0$

- Bjorken Sum Rule at $Q^2 = 5.0$ GeV^2:
  $\int [g_1^p(x) - g_1^n(x)]dx = 0.176 \pm 0.003 \pm 0.007$.

- Theory:
  $\int [g_1^p(x) - g_1^n(x)]dx = 0.182 \pm 0.005$
  (up to third order in α_s).

- $\Delta G = 1.6 \pm 0.8 \pm 1.1$.
- Spin Sum Rule $\frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z \rangle = \frac{1}{2}$

PLANS TO MEASURE ΔG

- Electrons don't directly interact with gluons.

- COMPASS at CERN–Photon-gluon fusion to produce charm mesons using high-energy muon beam.

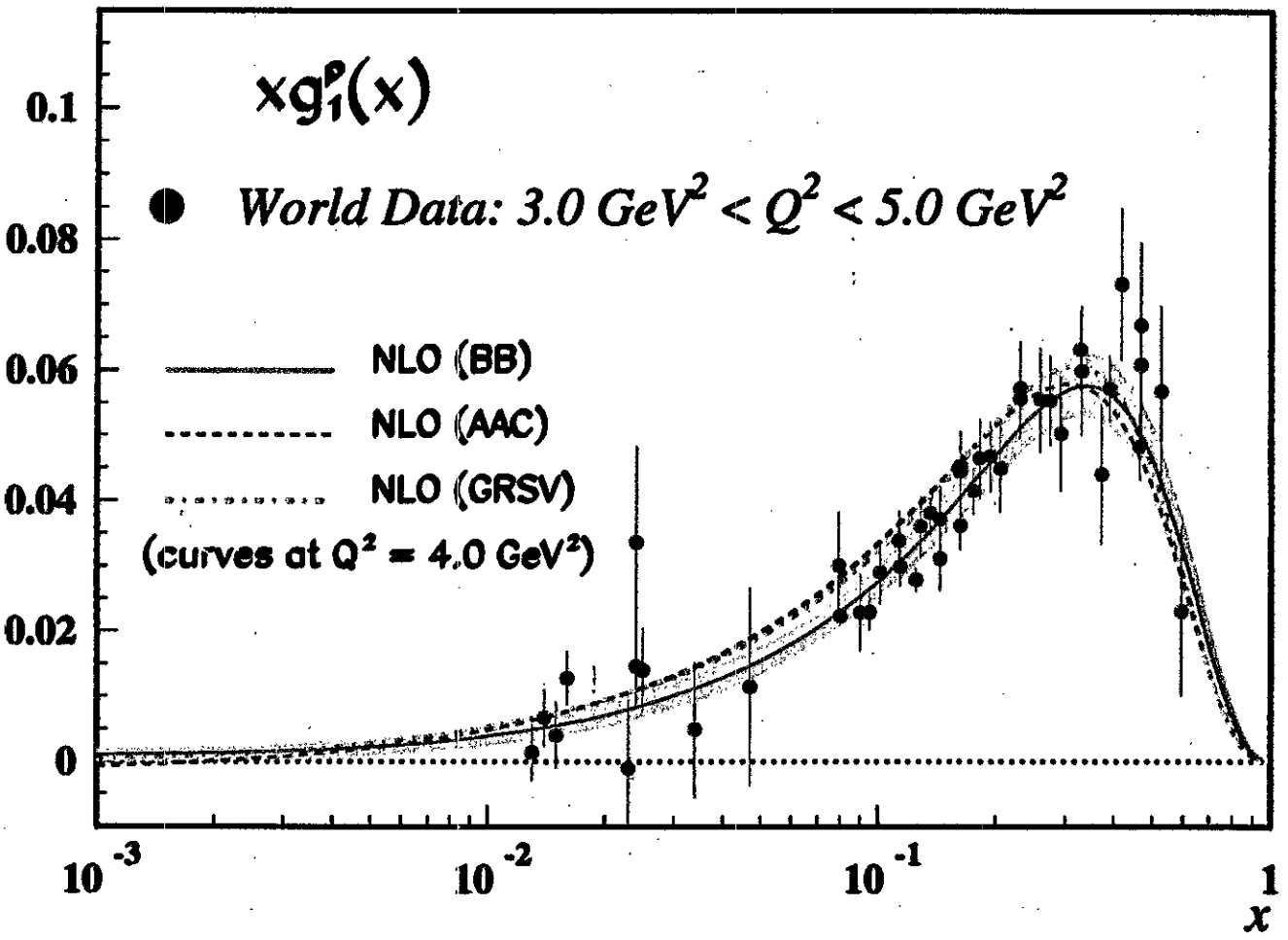
- RHIC Spin Physics Program–gluon-gluon fusion via polarized proton-polarized proton collisions.

- SLAC Experiment E161–Photon-gluon fusion using real photon beam.

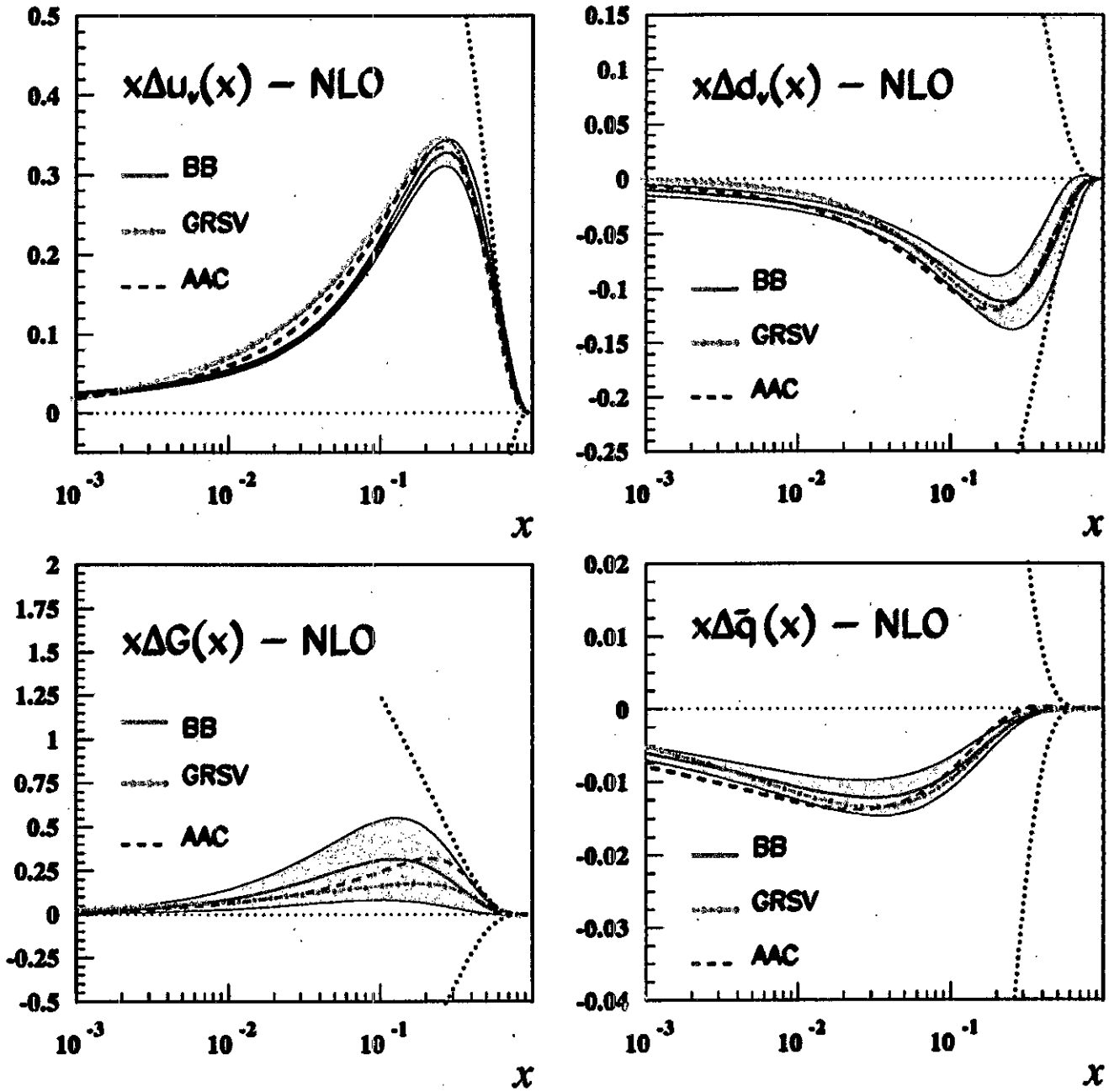
NLO Analysis

J. Blümlein and H. Böttcher

hep-ph/0203155
Nuc. Phys. B 636 (2002) 225



Blümlein and Böttcher NLO



$\Delta u_v = 0.926 \pm 0.071$

$\Delta d_v = -0.341 \pm 0.123$

$\Delta \bar{q} = -0.074 \pm 0.017$

$\Delta G = 1.026 \pm 0.549$

Virtual Photon-Nucleon Asymmetries

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

- For $\gamma^2 = Q^2/\nu^2 = 0$ (high energy), $A_1 \approx g_1/F_1$

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

- Positivity constraint, $|A_2| \leq \sqrt{R(x,Q^2)}$,where

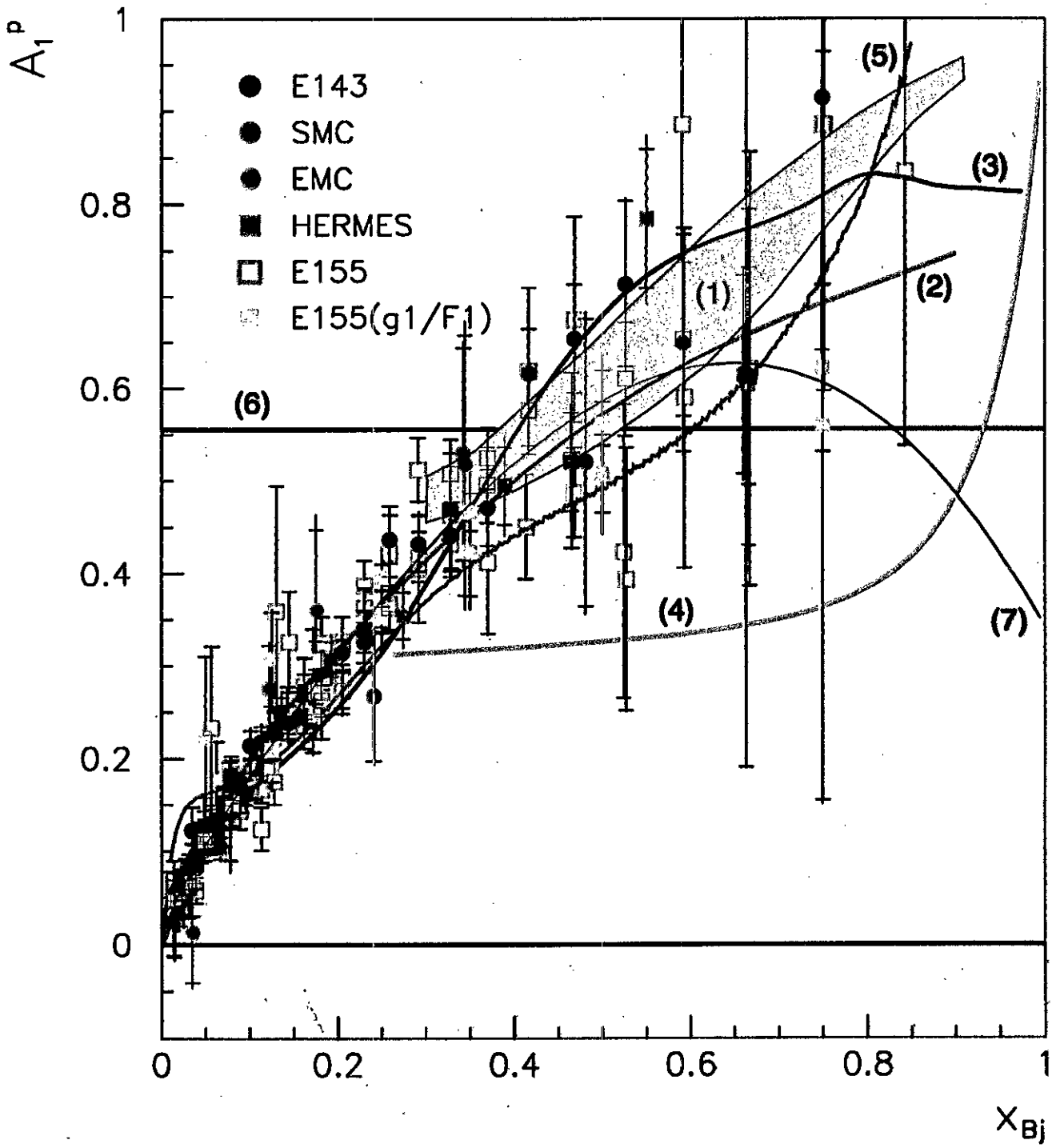
$$R(x,Q^2) = \frac{2\sigma_L}{\sigma_T^{1/2} + \sigma_T^{3/2}}$$

Also note: As $Q^2 \to \infty$ $A_2, R \to 0$

$\Longrightarrow$ A_2 sensitive to QCD at finite Q^2.

A_1^p World Data and Theoretical Predictions

Proton



A_1^p theory curves

(1) CQM

(2) LSS g_1/F_1 at $Q^2 = 5$ (GeV/c)^2

(3) Statistical Model A_1 at $Q^2 = 4$ (GeV/c)^2

(4) Local duality A_1

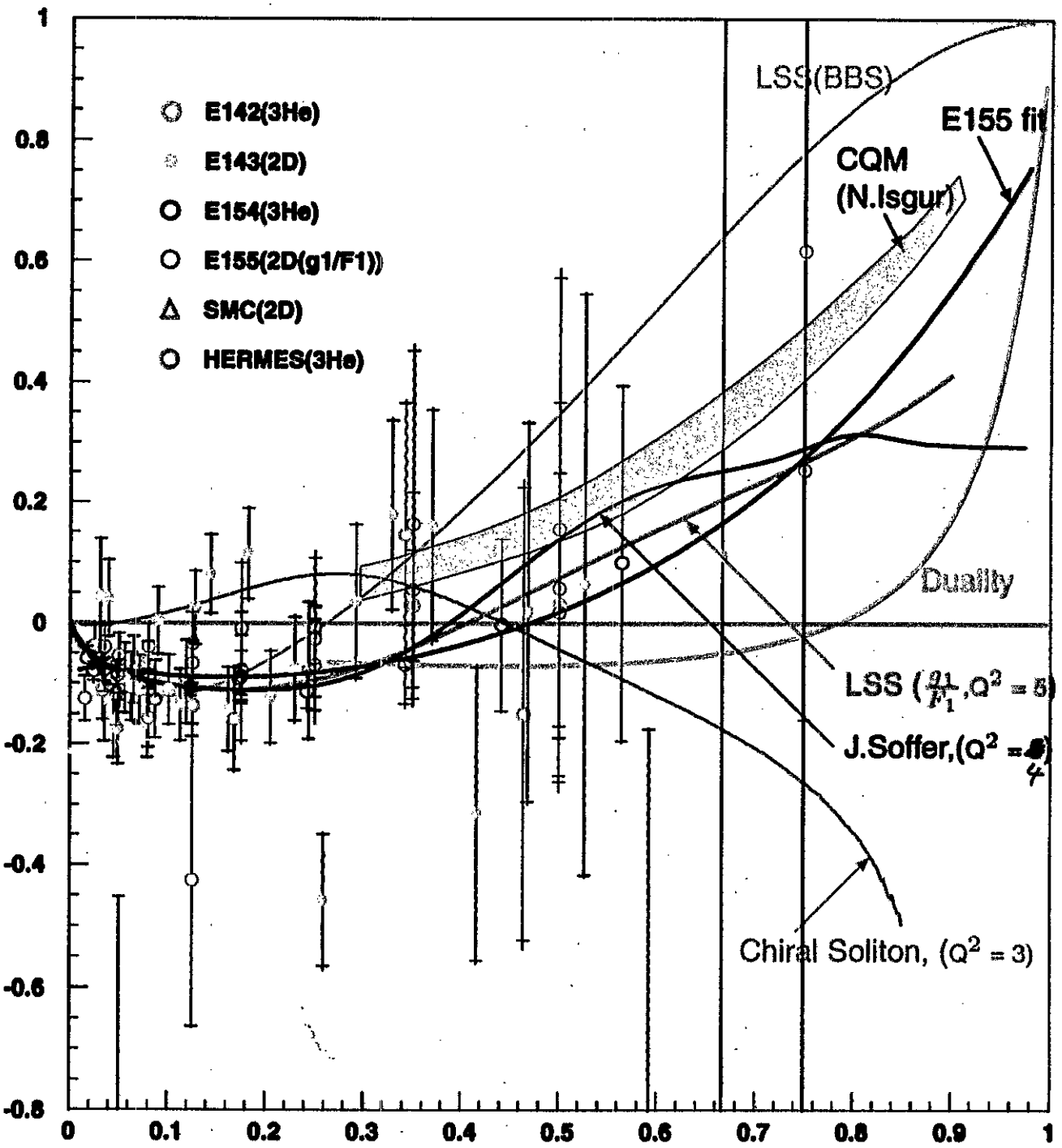
(5) Chiral soliton model at $Q^2 = 3$ (GeV/c)^2

(6) Basic SU(6) $A_1^p = 5/9$

(7) E155 fit g_1/F_1

A_1^n World Data and Theoretical Predictions

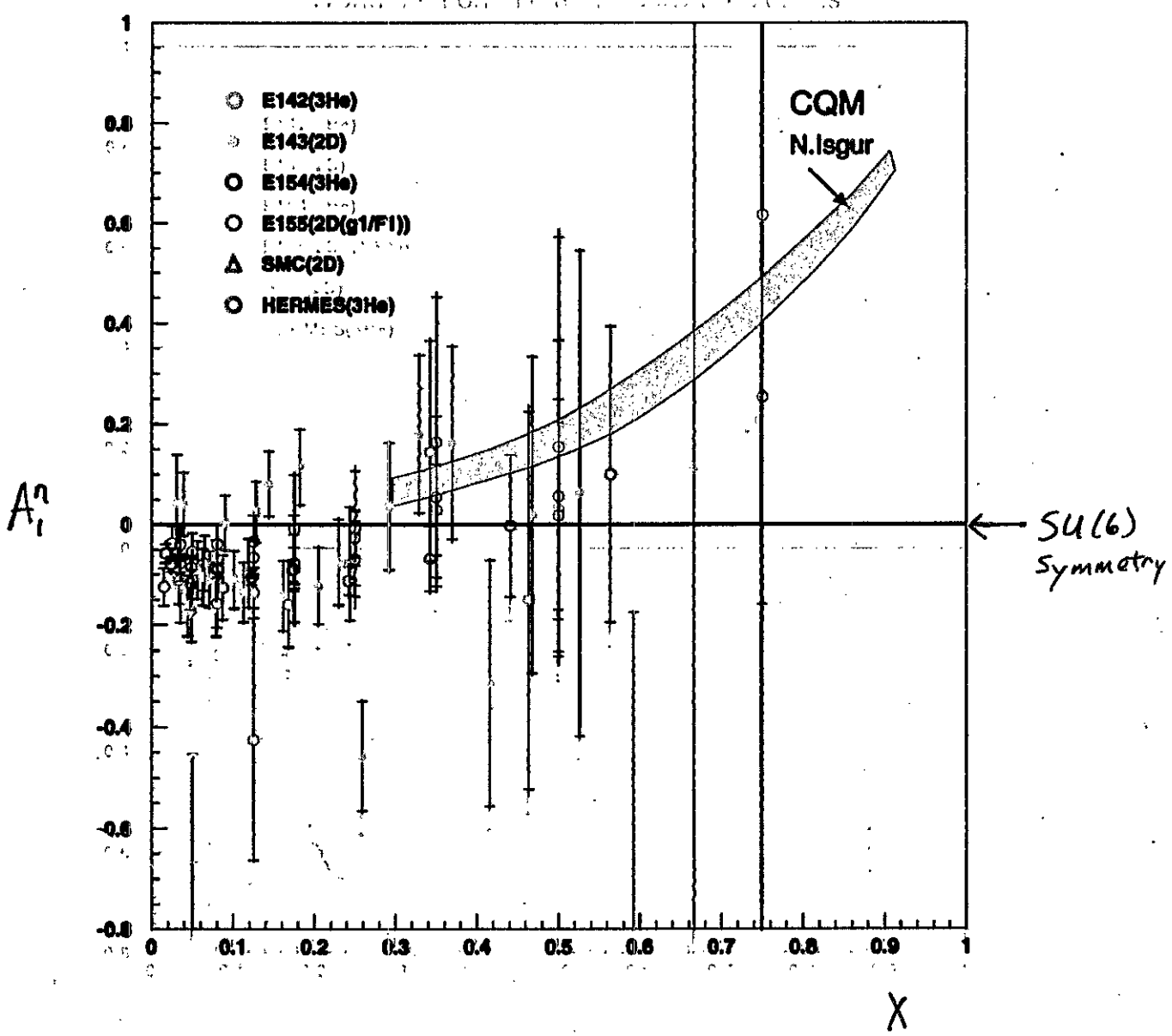
Neutron



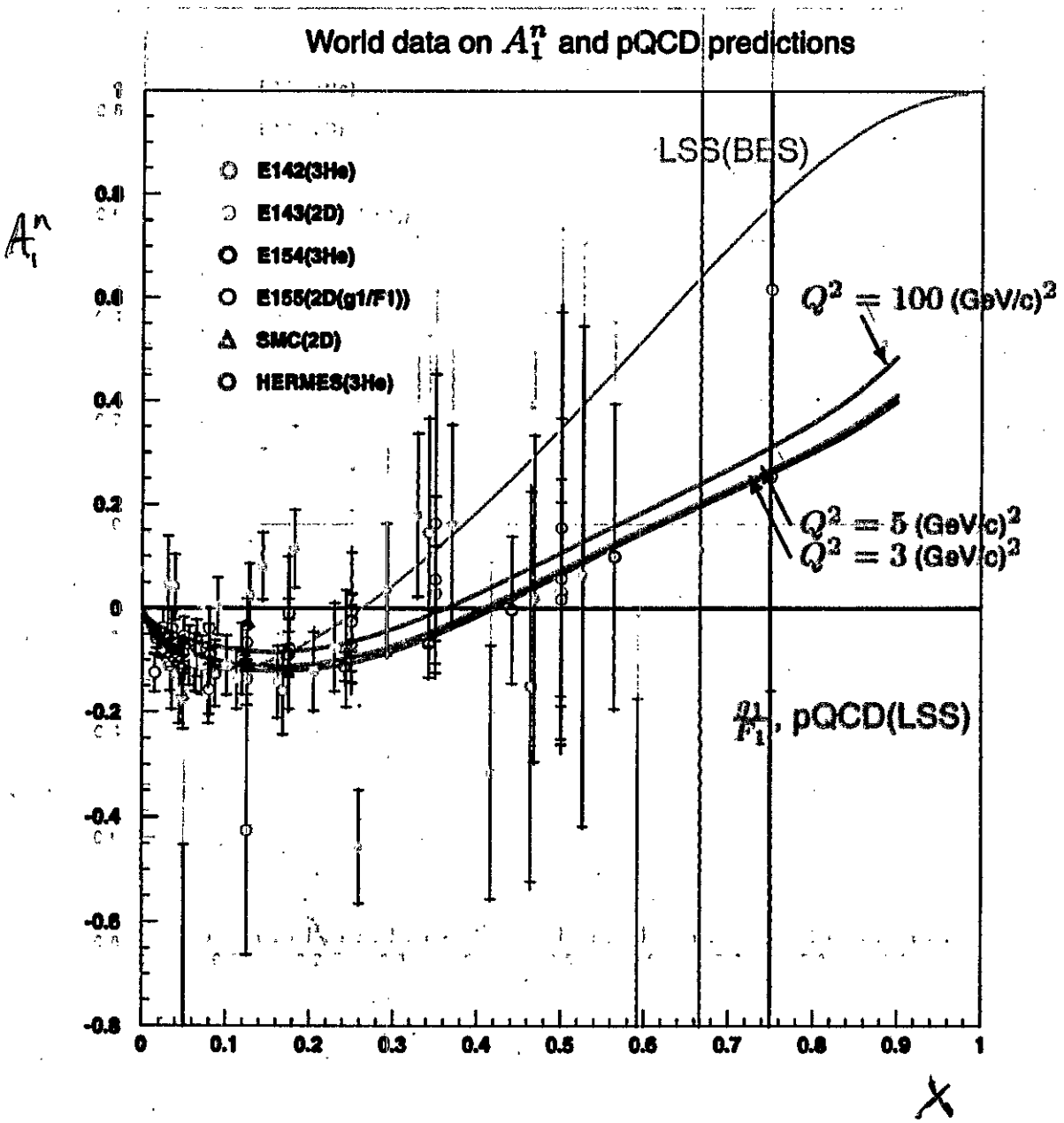
- CQM: N.Isgur, Phys.Rev. D59 (1999) 034013
  - Hyperfine perturbed
  - A (simple) parameterization: $\frac{d(x)}{u(x)} \approx \kappa(1-x)$ as $x \to 1$, $\kappa \approx 0.5 \sim 0.6$

    $$c_A(x) = nx(1-x)^n, n = 2 \sim 4$$
  - $A_1^n(x) = \frac{4\Delta d_v(x)+\Delta u_v(x)}{4d_v(x)+u_v(x)}$, $A_1^p(x) = \frac{4\Delta u_v(x)+\Delta d_v(x)}{4u_v(x)+d_v(x)}$
  - A_1^n and $A_1^p \to 1$ as $x \to 1$.

World data on A_1^n and prediction from CQM

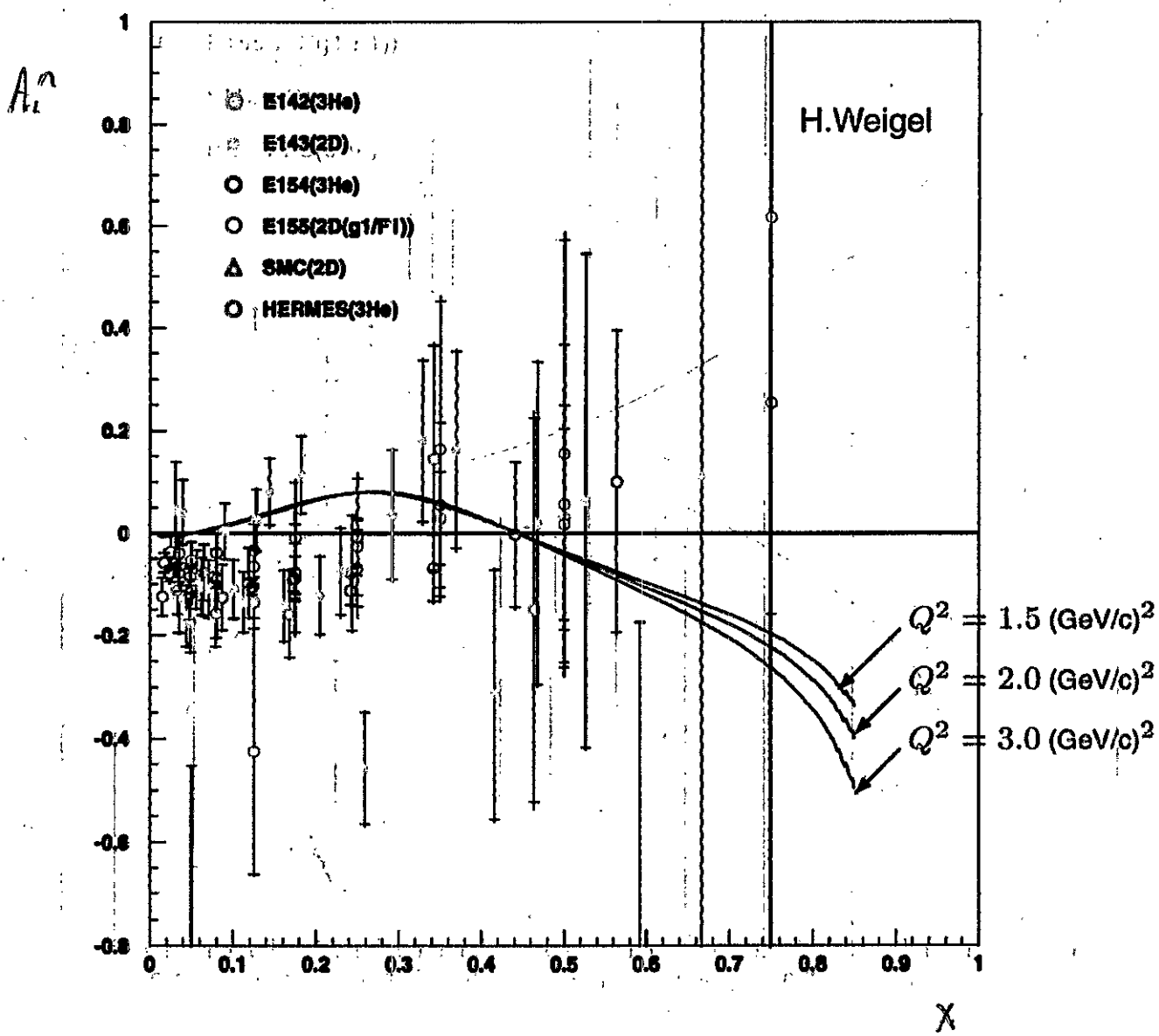


- pQCD (LSS-BBS): E. Leader, A.V.Sidorov, D.B.Stamenov, hep-ph/9708335
  - Polarized & unpolarized parton densities by Brodsky, Burkhardt and Schmidt (BBS);
  - $\frac{\Delta u}{u} \to 1, \frac{\Delta d}{d} \to 1$ at $x \to 1$.
- pQCD (LSS2001): E. Leader, A.V.Sidorov, D.B.Stamenov, hep-ph/0111267
  - A new evaluation of NLO polarized parton densities in the nucleon;
  - calculation done for g_1/F_1 at Q^2= 3, 5, 100 (GeV/c)^2.

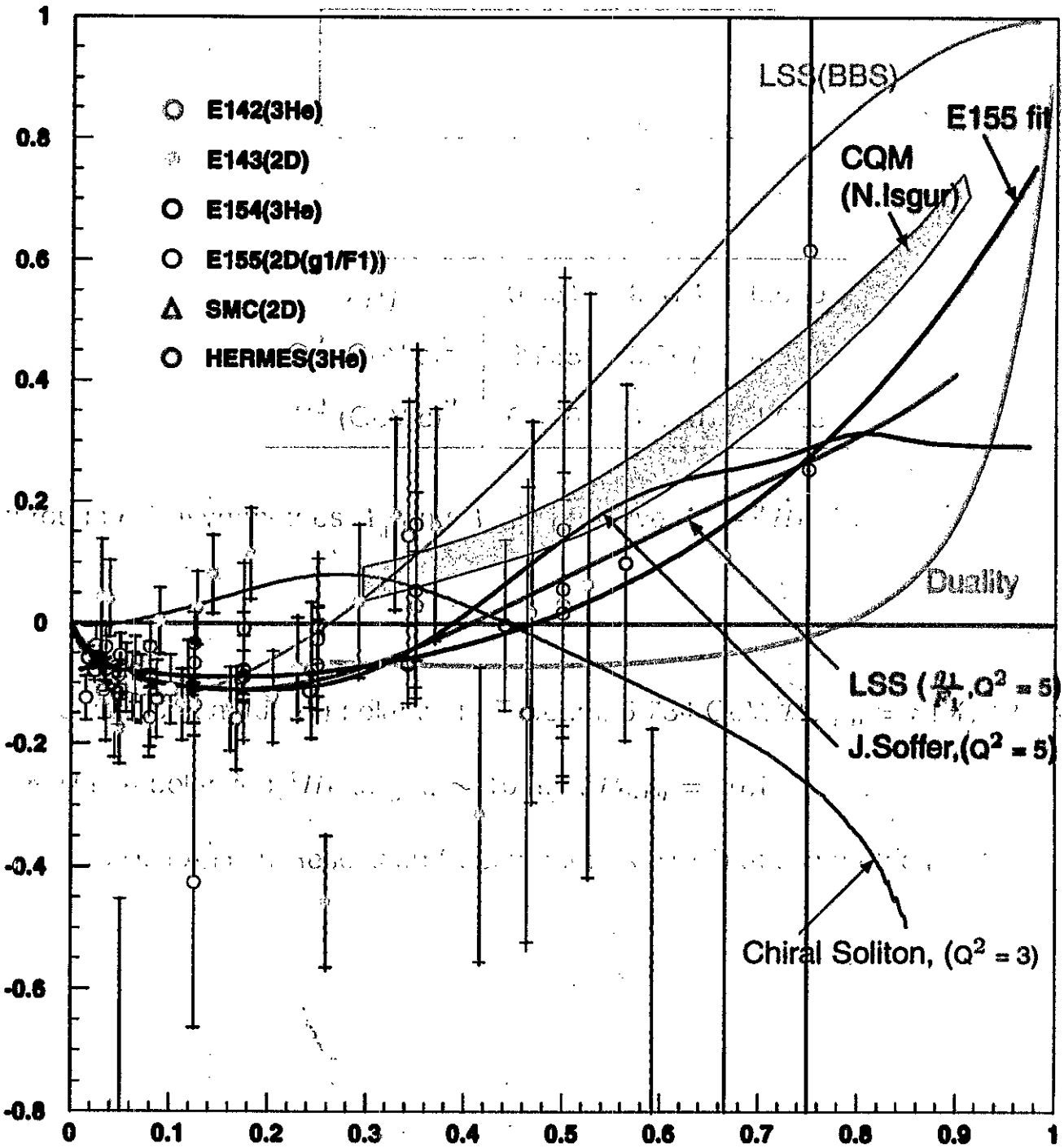


- **Chiral Quark-Soliton Model:**
  H.Weigel, L.Gamberg and H.Reinhardt, Phys. Lett. B399, 287 (1997), Phys. Rev. D55, 6910 (1997).
  - Two flavor chiral soliton approach to baryons, based on the Bosonized Nambu-Jona-Lasinio (NJL) model;
  - Model degrees of freedom are effective constituent quarks;
  - Tentative calculation done for $\frac{g_1}{F_1}$ at Q^2=1.5, 2.0, 3.0 (GeV/c)^2.

World data on A_1^n and chiral quark-soliton model



A_1^n World Data and Theoretical Predictions



Experiment E99-117

MEASURED A_1^n AT

x_{Bj}	0.331	0.474	0.609
Q^2 (GeV/c)^2	2.738	3.567	4.887
W^2 (GeV/c)^2	6.426	4.846	4.023

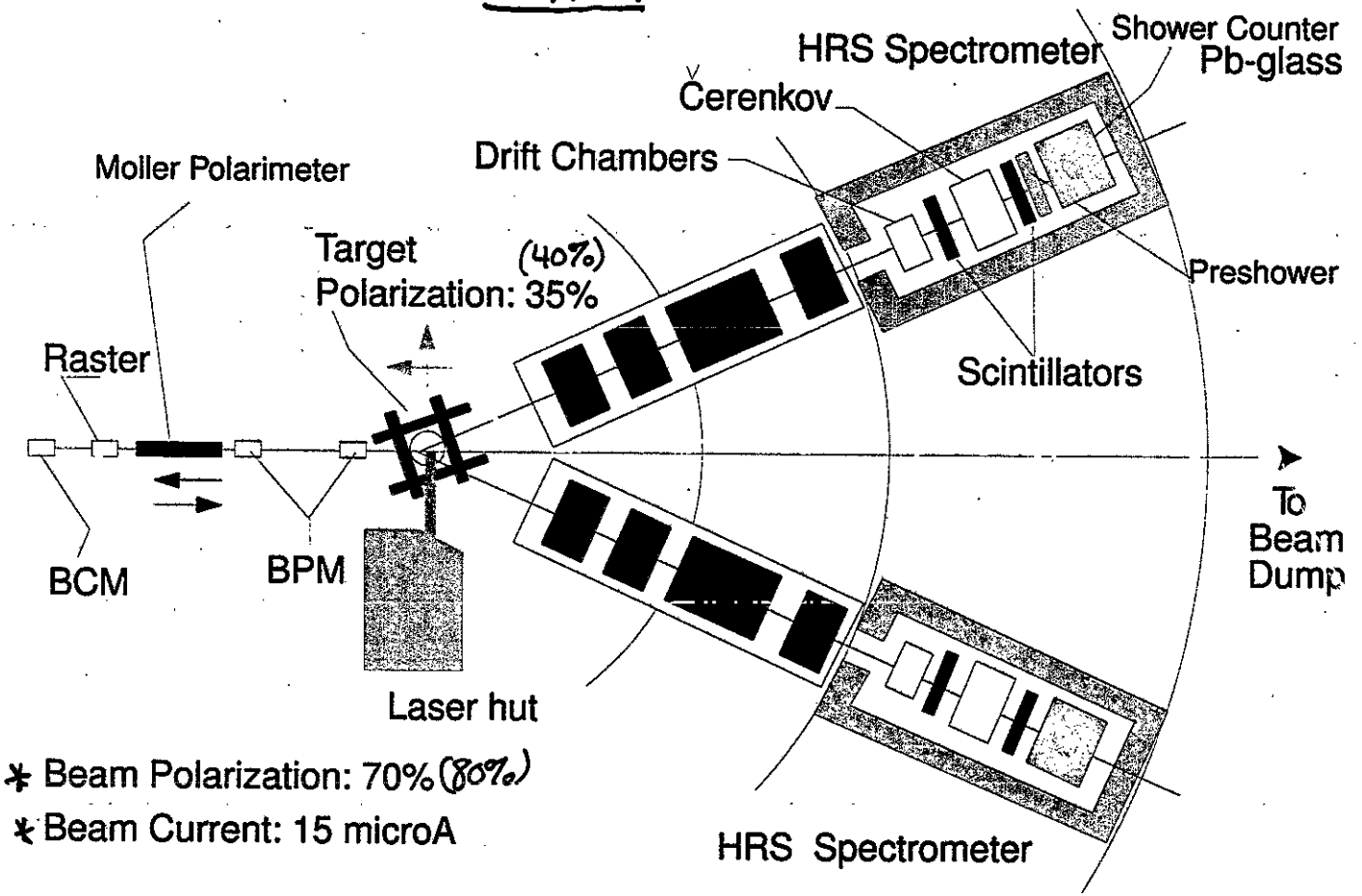
through e^- asymmetries $A_{\parallel}$ and $A_{\perp}$ in inclusive $\vec{e}^- - {}^3\vec{He}$ DIS;

EXPERIMENTAL SETUP

- Jefferson Lab(JLab) polarized e^- beam, 5.734 GeV, $P_{beam} = 81\%$, 12 μA
- Hall A polarized ${}^3He$ target, $\sim$ 10 atm, $P_{targ} = 40\%$
- Two Hall A High Resolution Spectrometers (HRS) at symmetric positions

JLab E94010 Floor Configuration

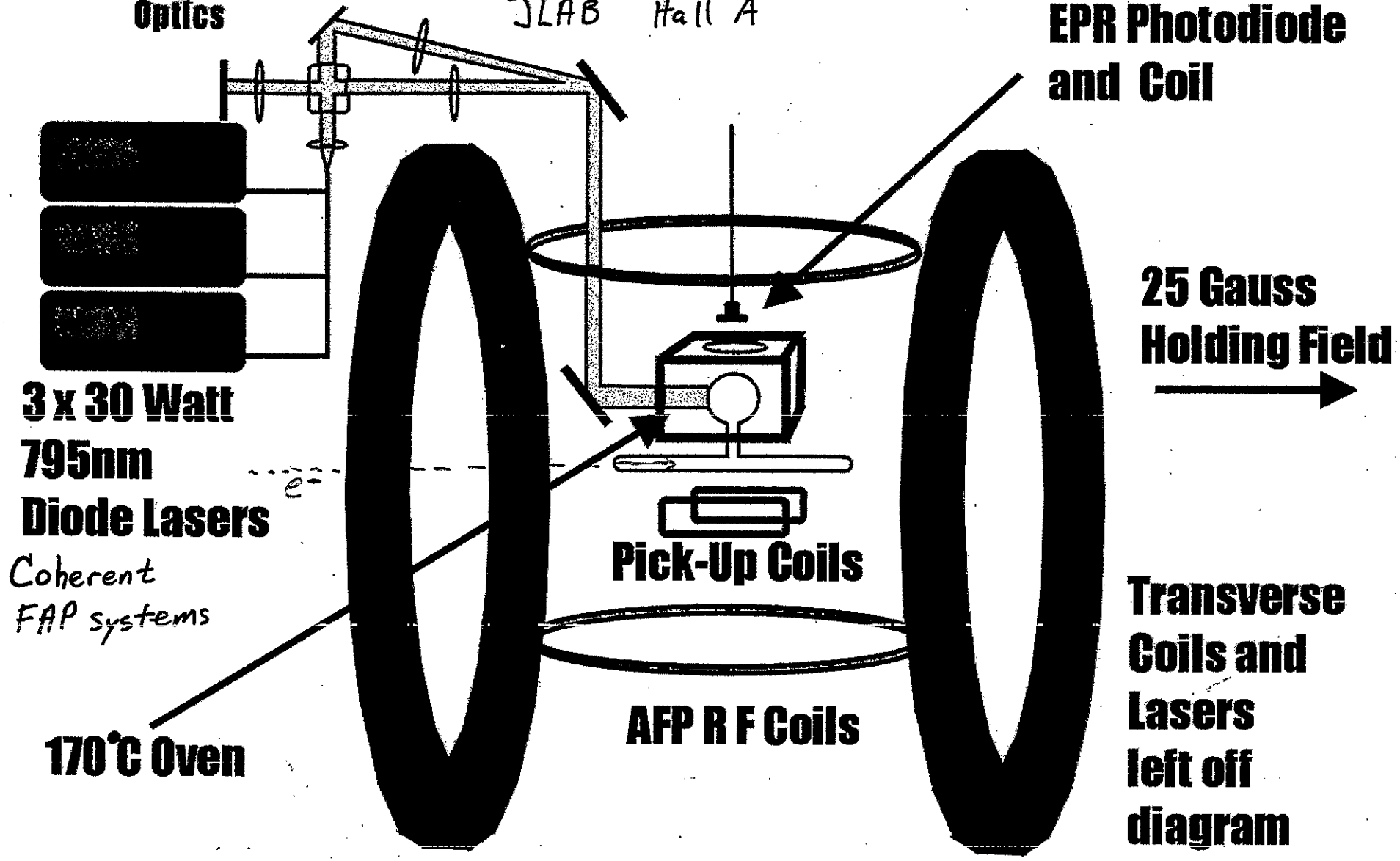
Hall A



* Beam Polarization: 70% (80%)
* Beam Current: 15 microA

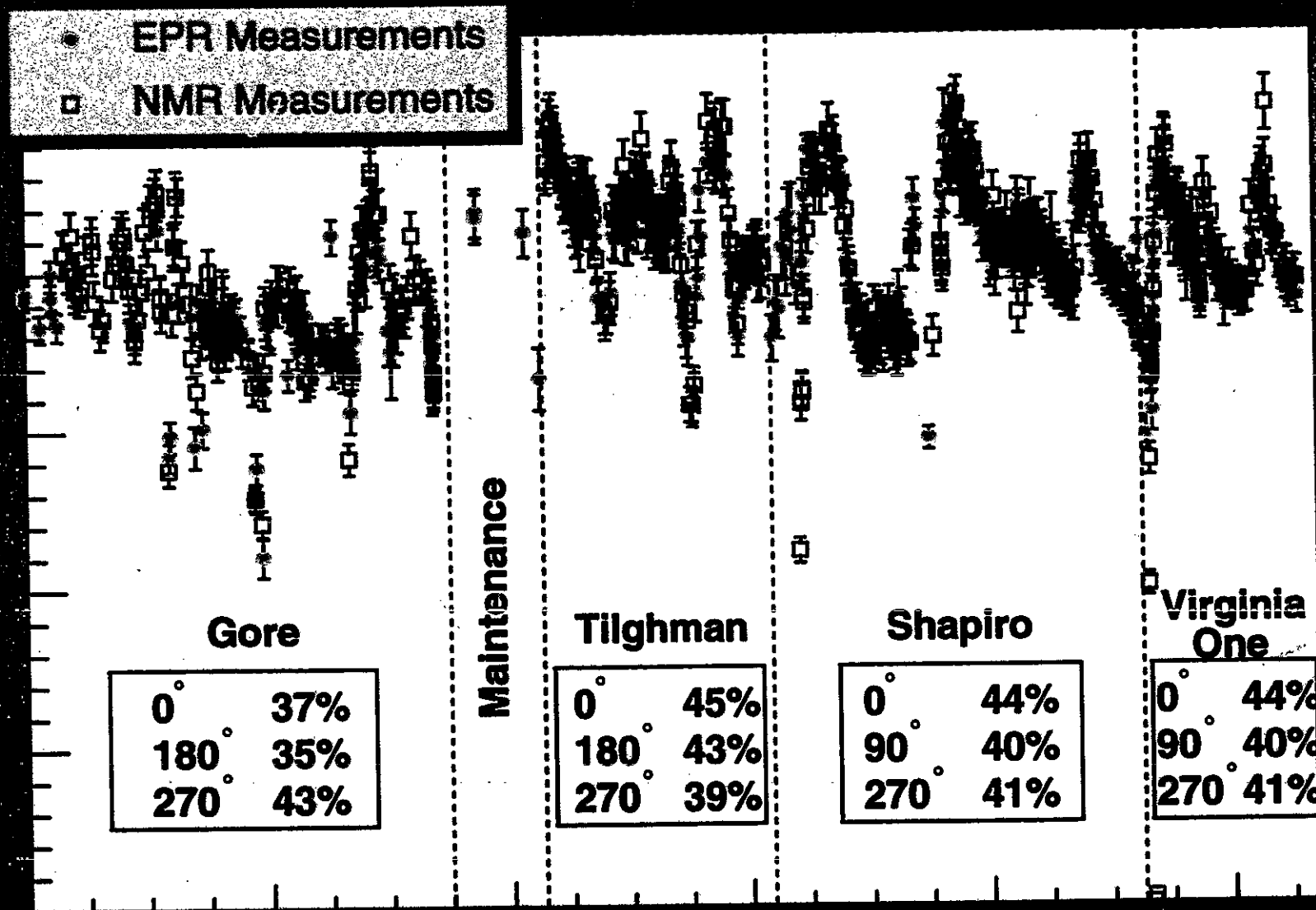
Target Setup

JLAB Hall A

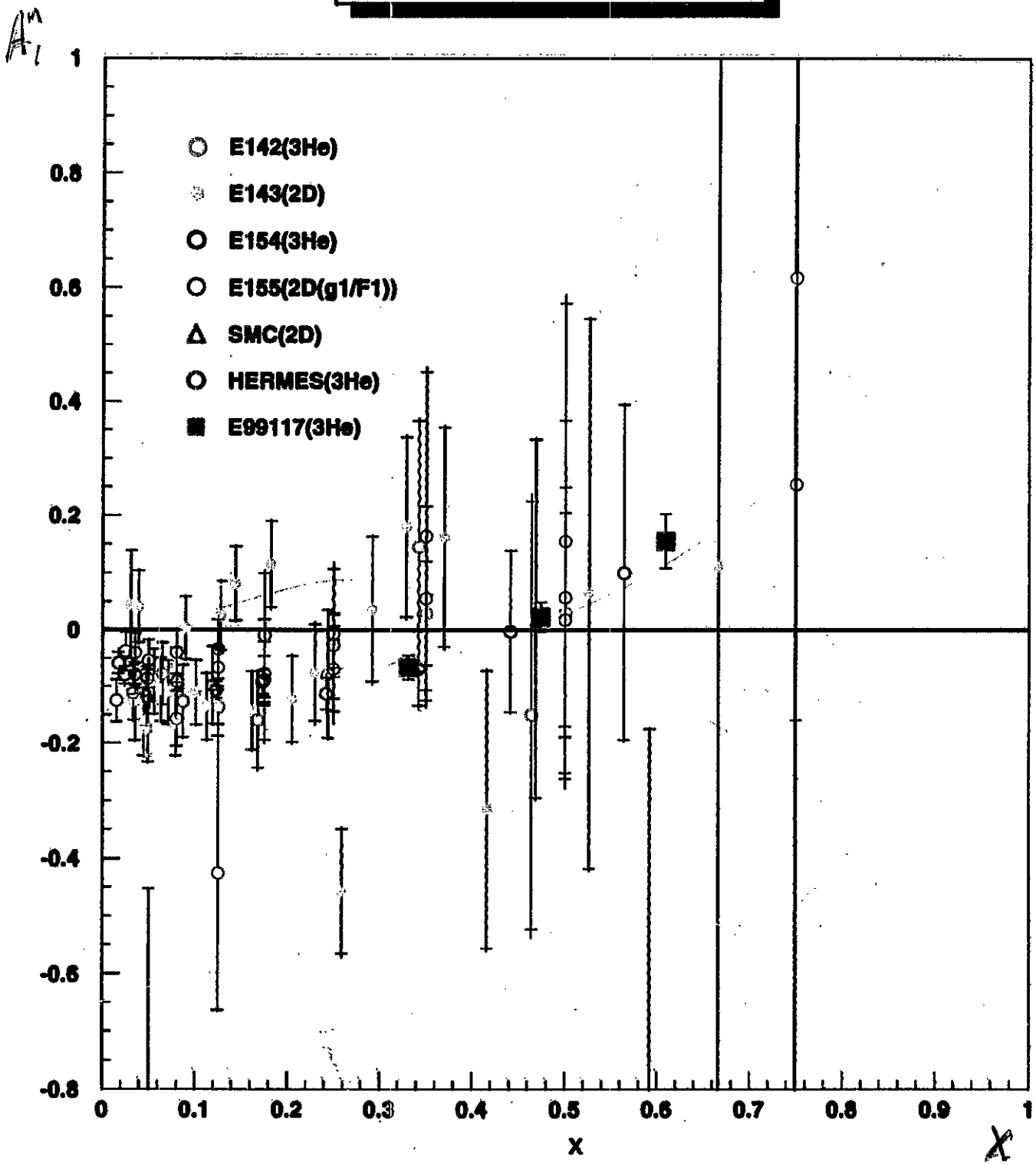


Polarized ^{3}He Target

Target Polarizations for E99-117 and E97-103

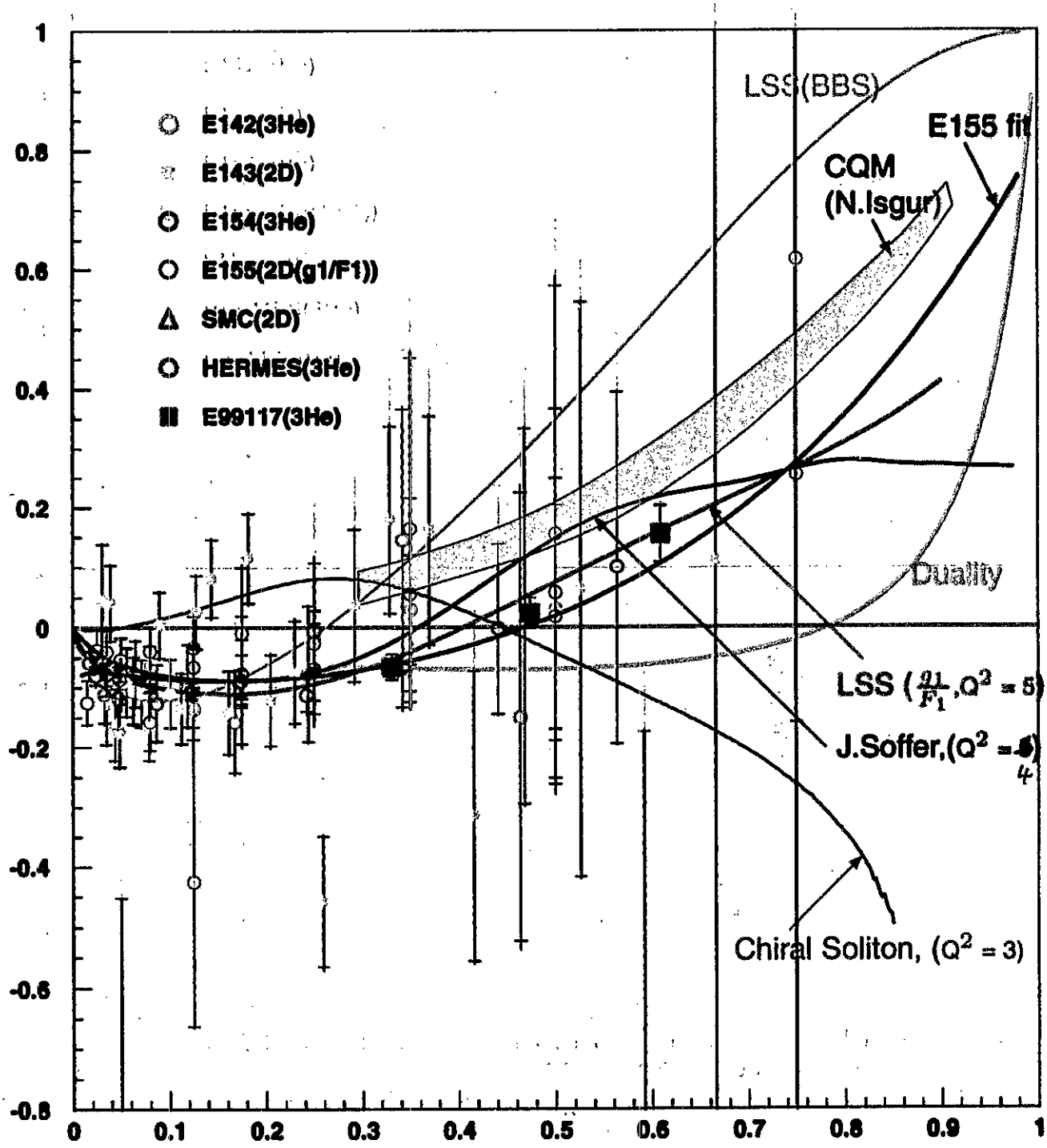


A_1^n Preliminary Result

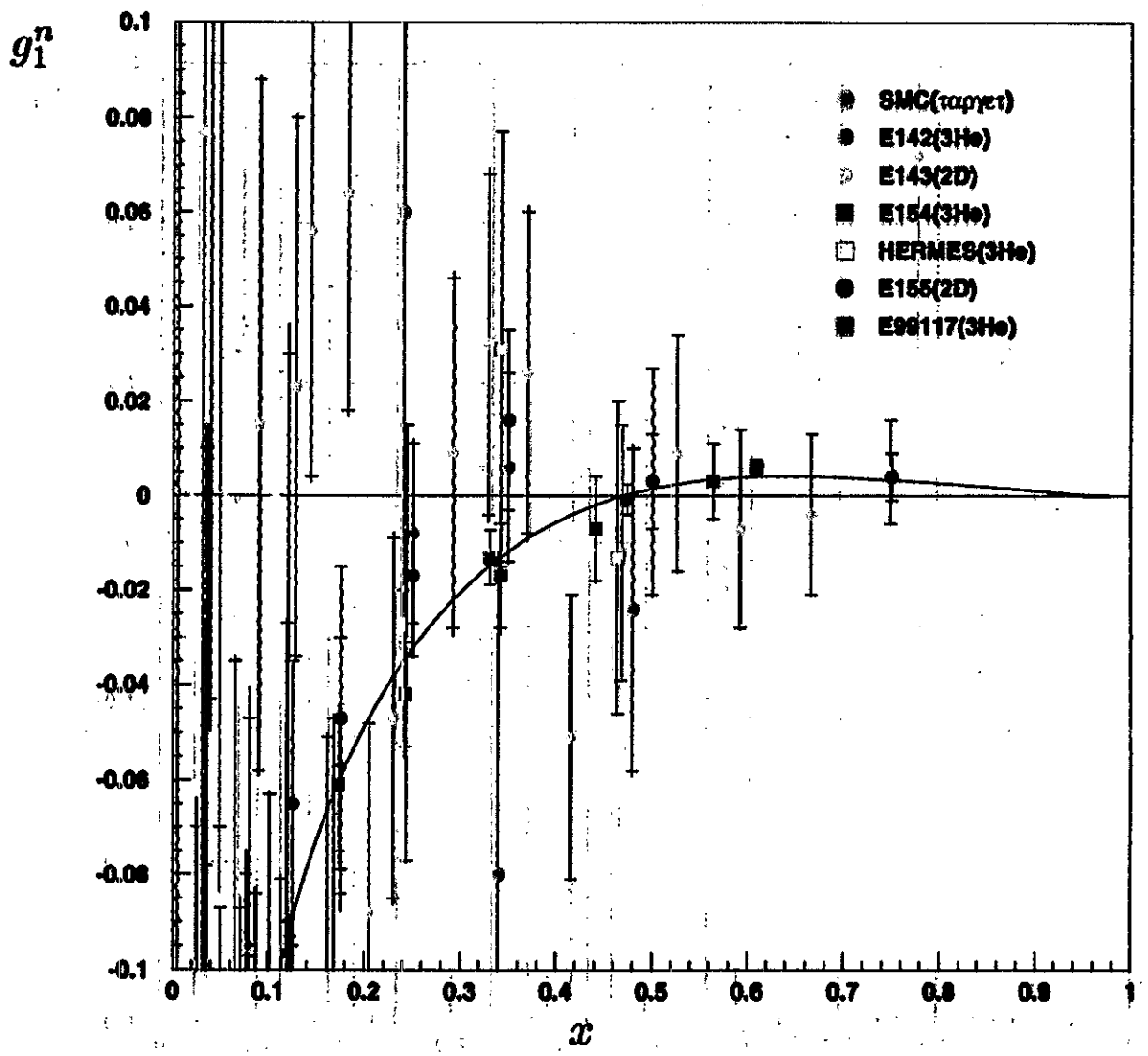


JLAB E99-117

A_1^n Preliminary Result



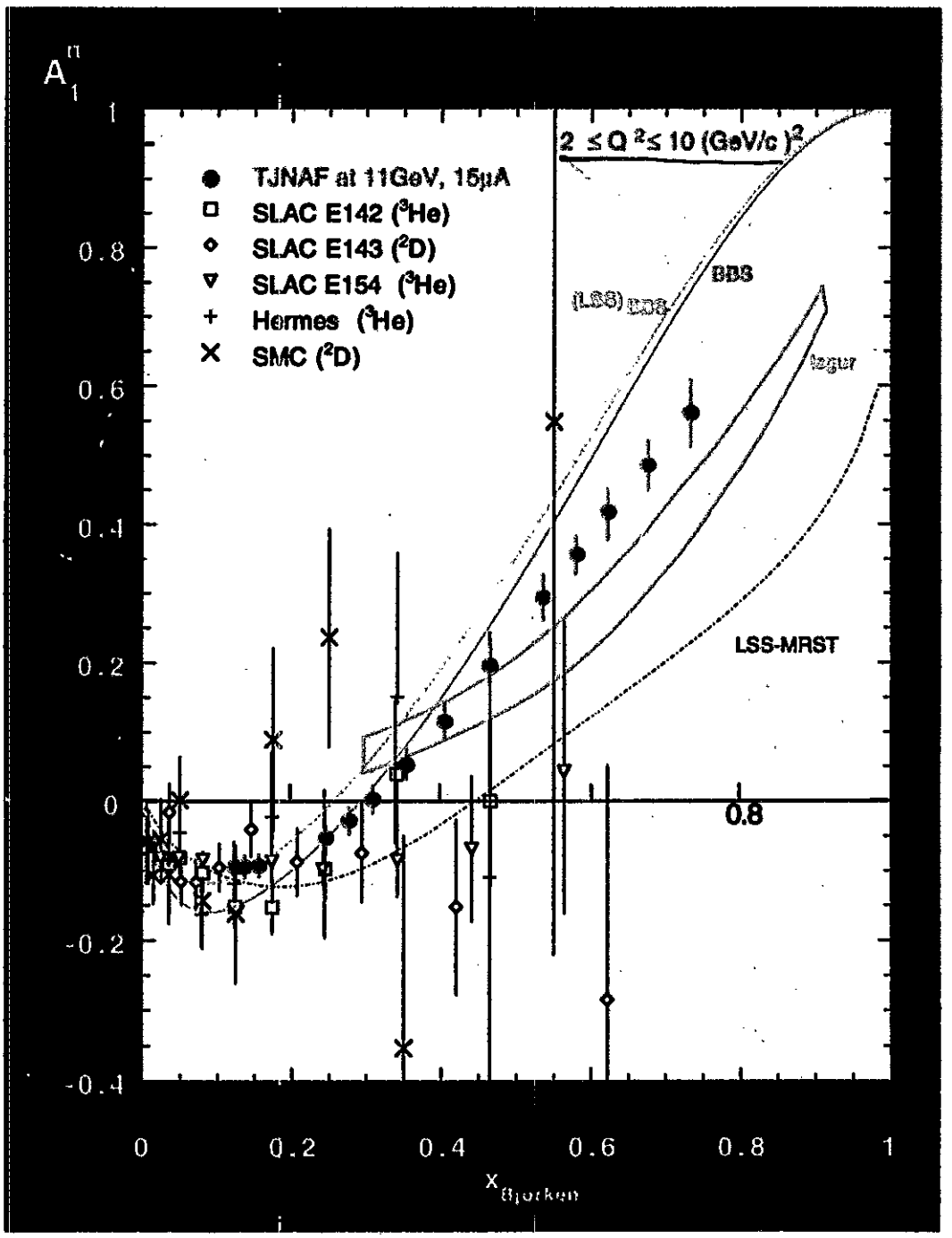
Preliminary Result



black solid curve: g_1^n obtained from E155 fit for $\frac{g1}{F1}$ and NMC95 fit for F_1, at $Q^2 = 4.0$ (GeV/c)^2

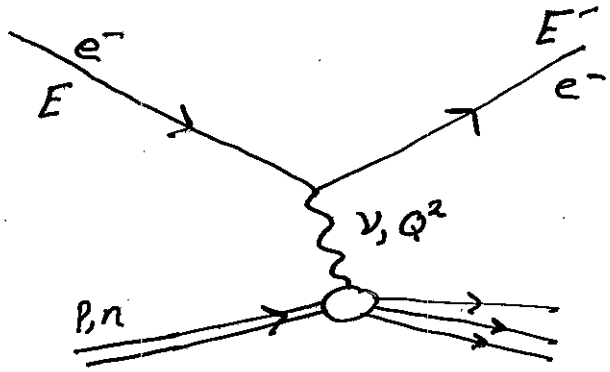
A_1^n @ JLab 12 GeV Upgrade

- Precision measurement of spin asymmetry in valence quark region
- Decisive test of pQCD vs quark model, insight to quark-gluon wavefunctions



Resonance Region

Polarized Electron-Nucleon Scattering



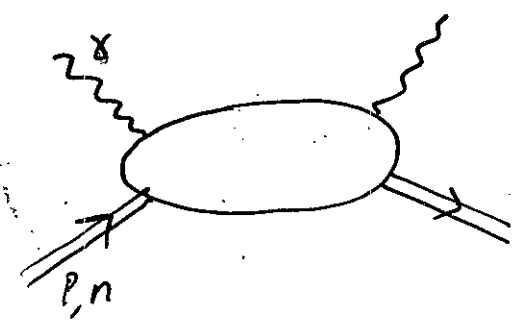
$\nu = E - E'$

$-Q^2$ = 4-momentum transfer squared

- Inelastic scattering described by two spin structure functions, $g_1(x,Q^2)$ and $g_2(x,Q^2)$ which are well known for $Q^2 > 1.0\ \mathrm{GeV}^2$.

- Not well-known in resonance region and at low Q^2.

- Closely related to virtual Compton scattering which is described by spin-dependent amplitudes $S_1(\nu,Q^2)$ and $S_2(\nu,Q^2)$.



Gerasimov-Drell-Hearn Sum Rule

- Dispersion relation connects virtual Compton amplitude S_1 to spin structure function G_1, $\rightarrow$ or $g_1(x,Q^2)$

$$S_1(\nu,Q^2) = 4\int_{Q^2/2M}^{\infty} d\nu' \frac{G_1(\nu',Q^2)\nu'}{\nu'^2-\nu^2}$$

- At $\nu, \underline{\underline{Q^2=0}}$, low energy theorem states,

$$S_1(0,0) = -\frac{\kappa^2}{M^2}$$

also, $G_1(\nu',0) = \frac{1}{8\pi^2\alpha}\left[\sigma_{1/2}(\nu') - \sigma_{3/2}(\nu')\right]$

- σ_i are photon absorbtion cross sections
  κ is the anomalous magnetic moment of the nucleon

$Q^2=0 \iff$ real photon absorbtion

GDH sum rule:

- S. D. Drell, A. C. Hearn, PRL 16 (908) 1966
- S. B. Gerasimov, Sov. J. Nucl. Phys. 2 (430) 1966

Gerasimov-Drell-Hearn Sum Rule

- From these relations, we obtain the original (Q^2=0) GDH sum rule.

$$I_{GDH} = \int_{\nu_{thr}}^{\infty} \left[\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)\right] \frac{d\nu}{\nu} = -\frac{2\pi^2\alpha}{M^2}\kappa^2$$

$$I_{GDH}^{proton} = -204.5\mu b \quad I_{GDH}^{neutron} = -232.5\mu b$$

- For $Q^2 > 0$, substitute virtual cross sections,

$$\int_{\nu_{thr}}^{\infty} \left[\sigma_{1/2}^{T}(\nu, Q^2) - \sigma_{3/2}^{T}(\nu, Q^2)\right](1-x)\frac{d\nu}{\nu}$$

$$= \int_{\nu_{thr}}^{\infty} 2\sigma_{TT}(\nu, Q^2)(1-x)\frac{d\nu}{\nu} = ???$$

- σ_{TT} related to the spin structure functions,

$$\sigma_{TT}(\nu, Q^2)(1-x) = \frac{4\pi^2\alpha}{M\nu}\left[g_1(x, Q^2) - \frac{Q^2}{\nu^2} g_2(x, Q^2)\right]$$

Generalized GDH Sum Rule

Ji and Osborne, hep-ph/9905410

- Generalize the GDH sum rule for any Q^2 as follows:

(reduces to $Q^2=0$ GDH sum rule!!)

$$\boxed{S_1(0,Q^2) = 4\int_{Q^2/2M}^{\infty} G_1(\nu,Q^2)\frac{d\nu}{\nu}}$$

- For $Q^2 < 0.2\ \mathrm{GeV}^2$, the nucleon is hadron-like, and $S_1(Q^2)$ can be described using chiral perturbation theory.

- For $Q^2 > 0.5\ \mathrm{GeV}^2$, the nucleon is quark-like, and $S_1(Q^2)$ can be described using a twist expansion and pQCD.

- In the transition region, $0.2 < Q^2 < 0.5\ \mathrm{GeV}^2$, the behavior is not well known.

Connection to the Bjorken Sum Rule

- Using the relations

$$g_1(x,Q^2) = M\nu G_1(\nu,Q^2) \quad \text{and} \quad x = \frac{Q^2}{2M\nu}$$

we can re-write the generalized GDH sum:

$$S_1(0,Q^2) = 4\int_{Q^2/2M}^{\infty} G_1(\nu,Q^2)\frac{d\nu}{\nu}$$

$$= \frac{8}{Q^2}\int_0^1 g_1(x,Q^2)dx$$

- Using the OPE, it can be shown as $Q^2 \to \infty$,

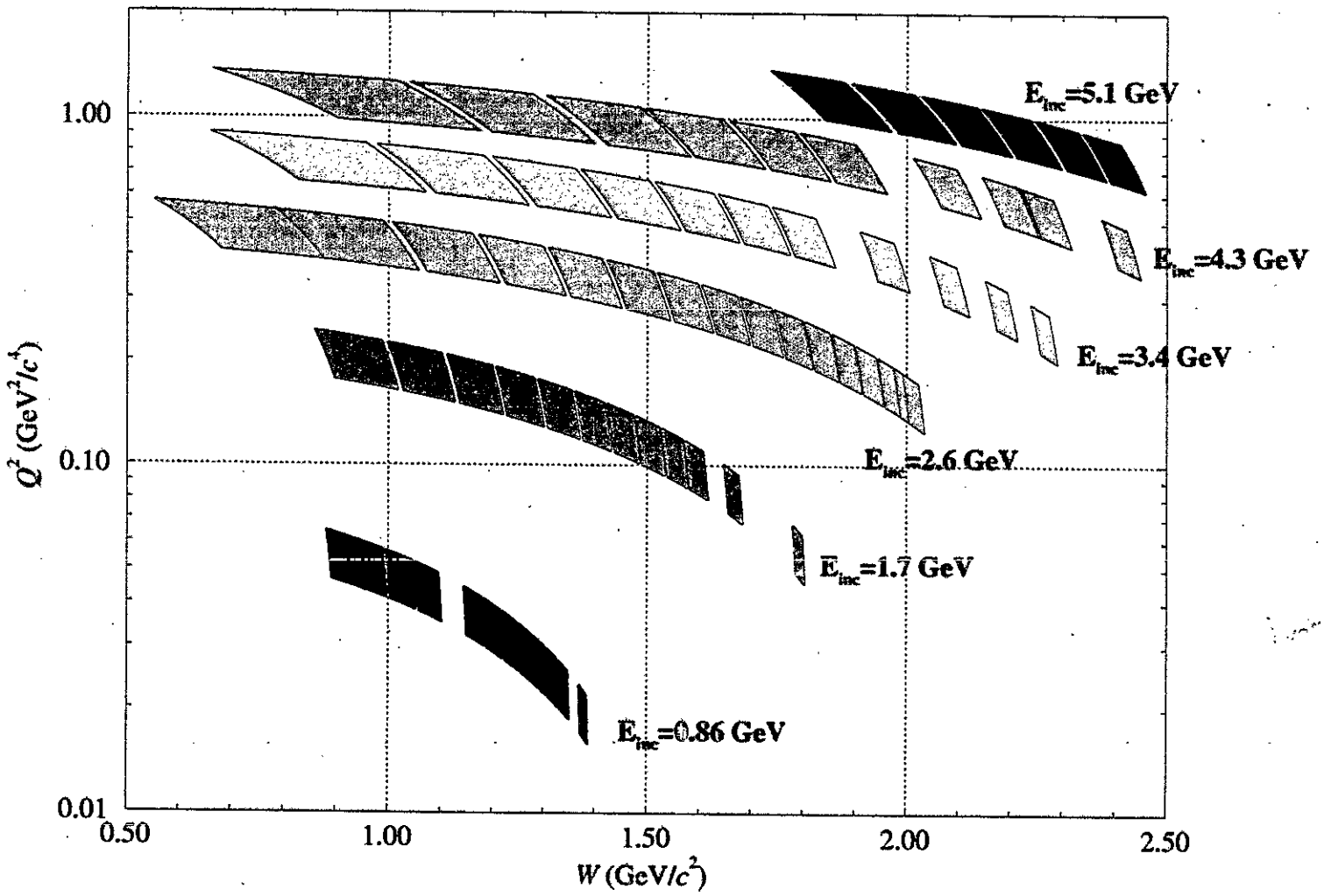
$$S_1^p(0,Q^2) - S_1^n(0,Q^2) = \frac{4}{3Q^2} g_A$$

which gives the Bjorken Sum Rule:

$$\int_0^1 [g_1^p(x,Q^2) - g_1^n(x,Q^2)]dx = \frac{1}{6} g_A$$

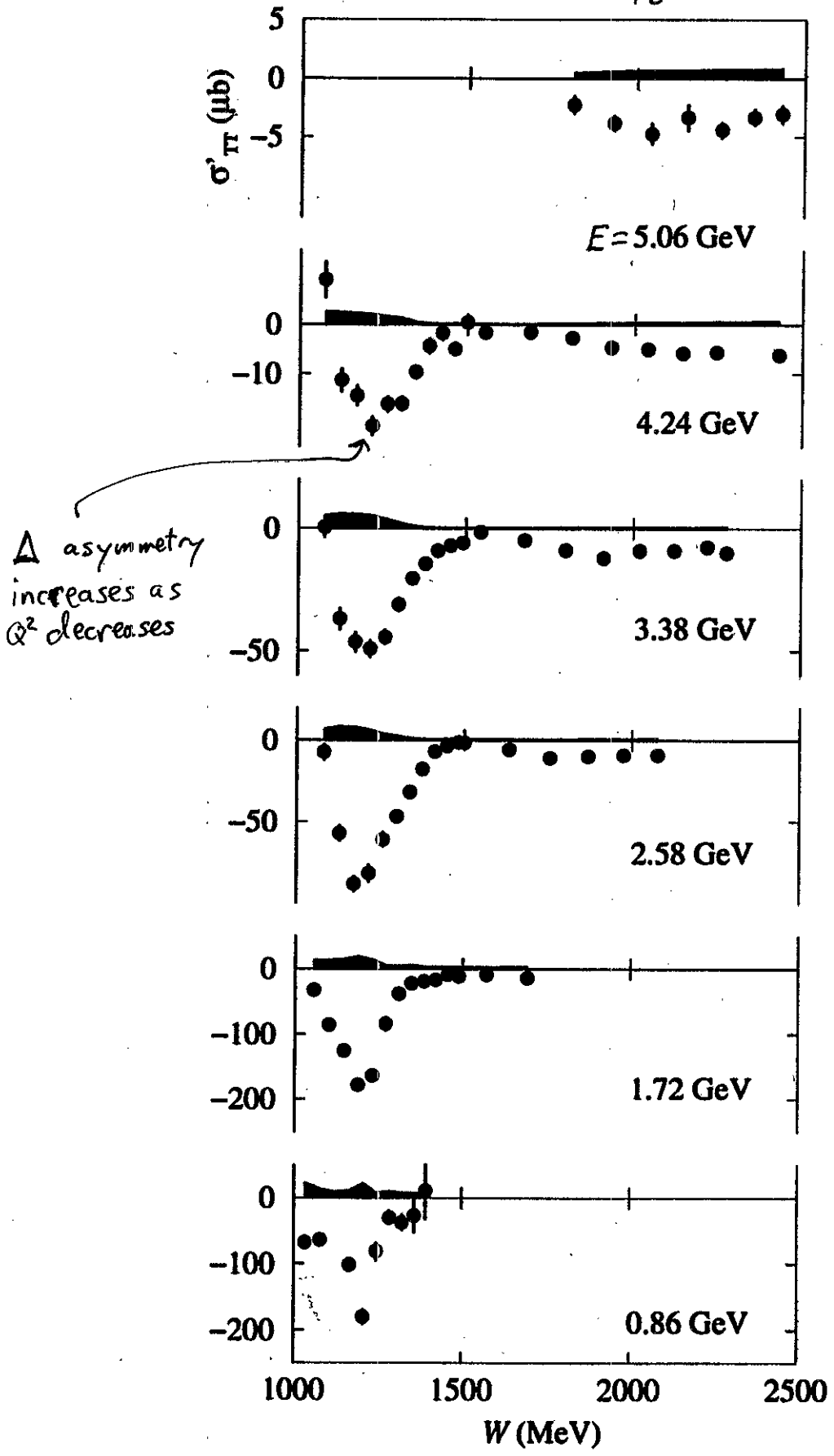
Polarized ^3He

JLab E94010 Kinematic Coverage



E94-010 Measured σ'_{TT}

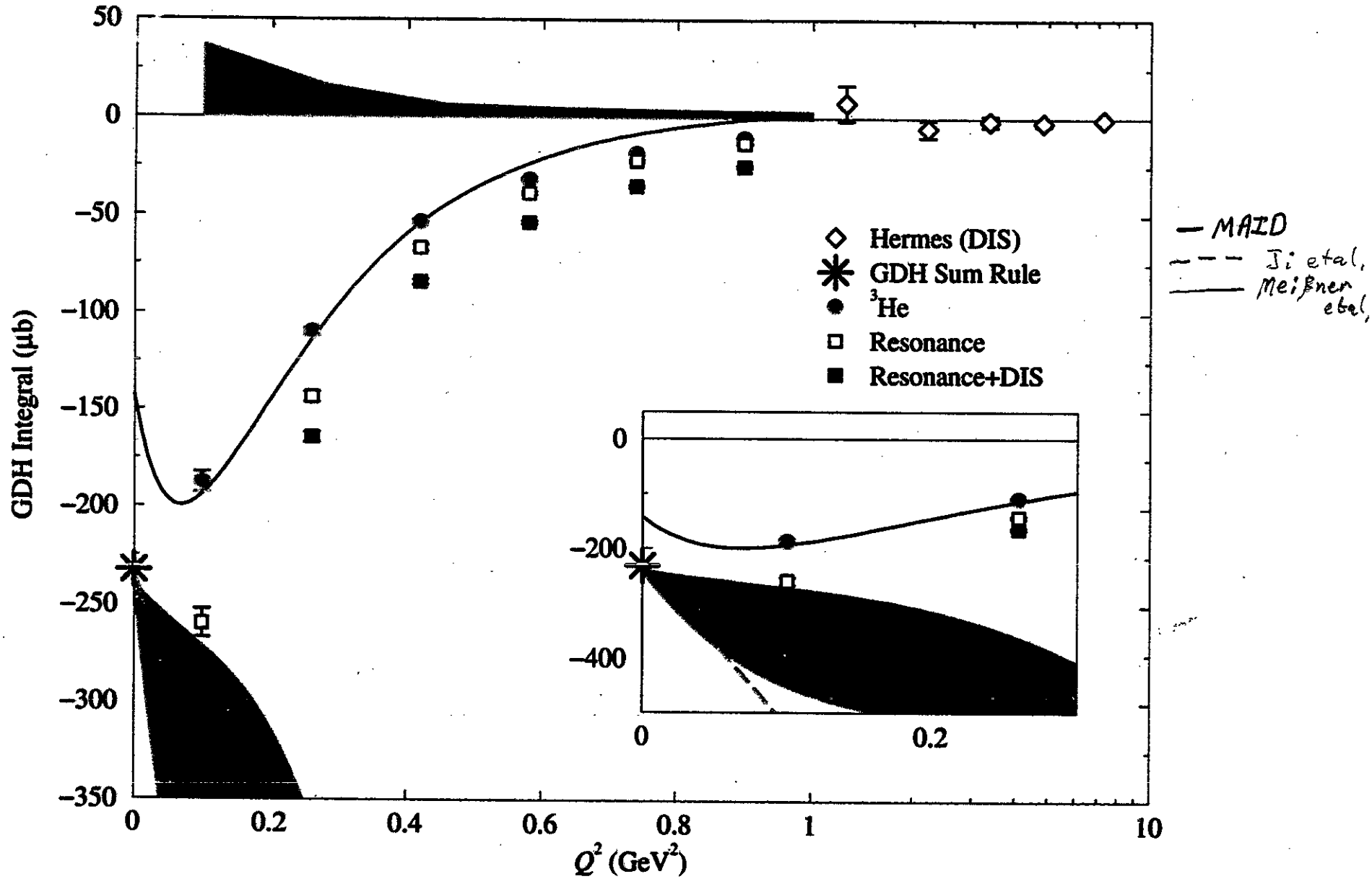
$$\sigma'_{TT} = \sigma^T_{1/2} - \sigma^T_{3/2}$$



GDH Integral on the Neutron

nucl-ex/0205020
Submitted to PRL

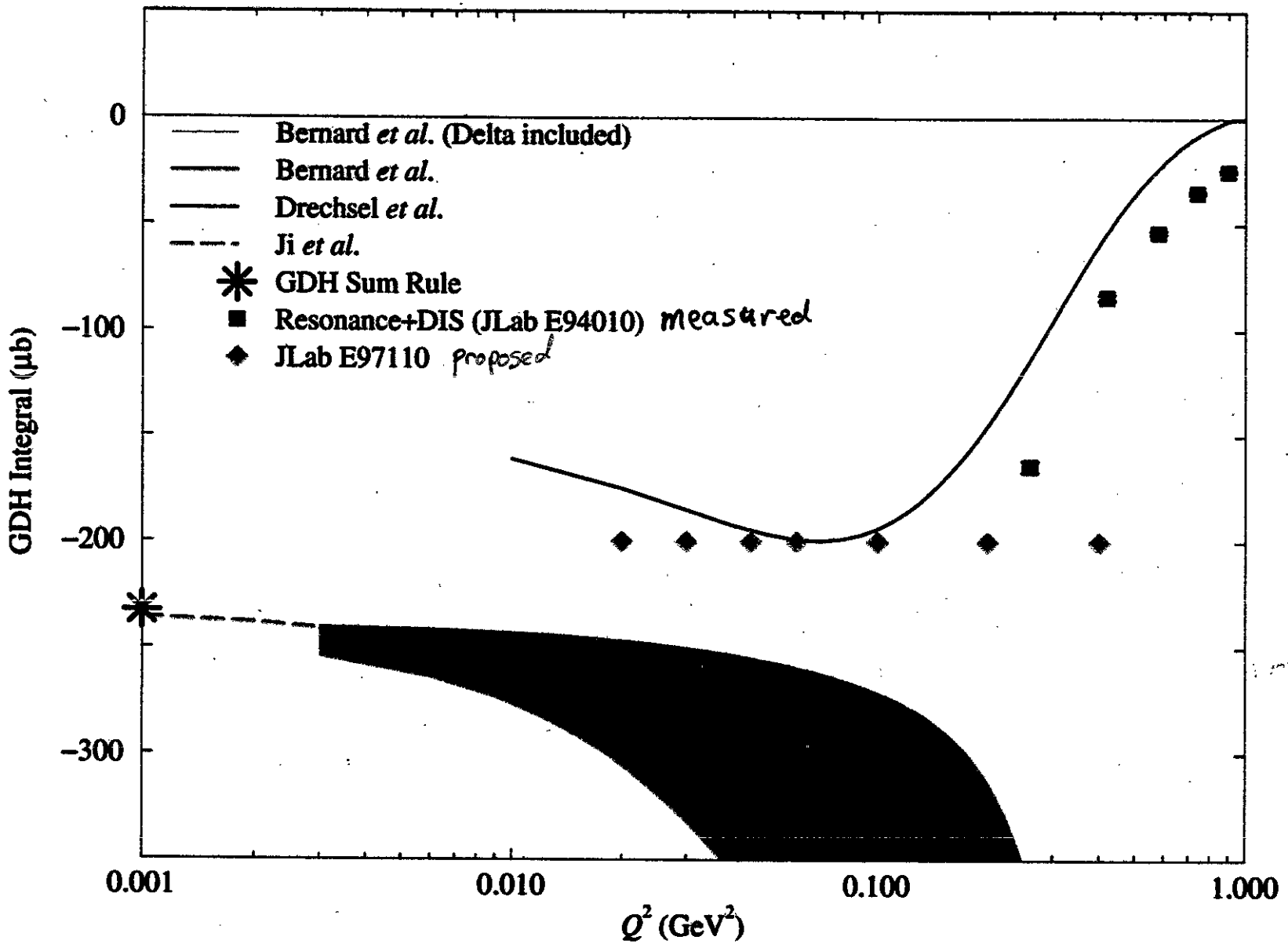
Jefferson Lab E94010



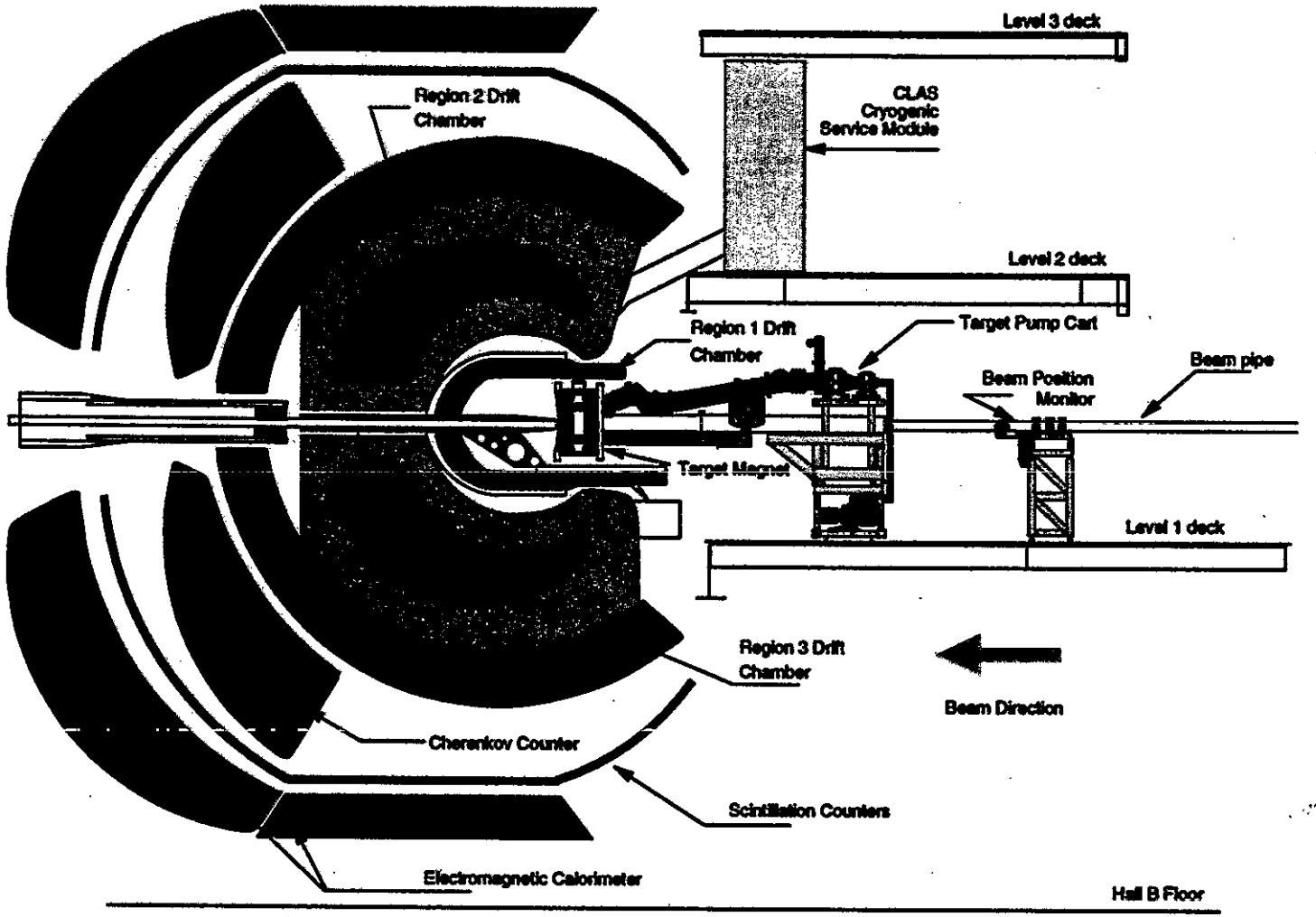
Hermes PLB 444 (1998) 531
hep-ex/9809015

Hall A - Jefferson Lab

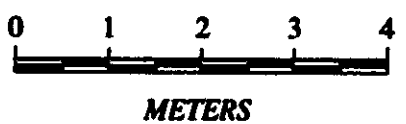
E97-110 Low Q^2 GDH, expected results

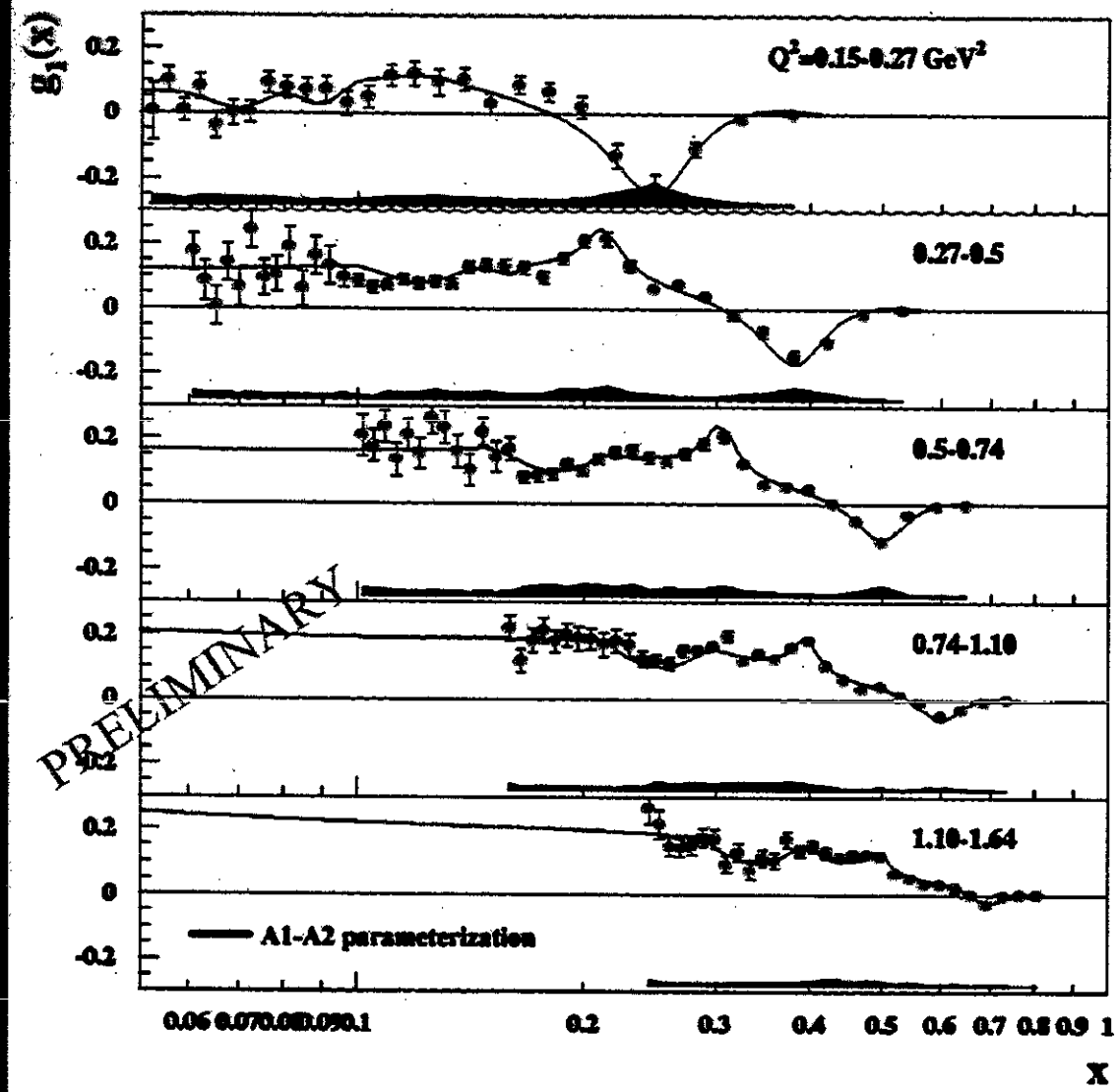


Hall B/CLAS



Polarized proton and deuteron targets.





JLab/CLAS

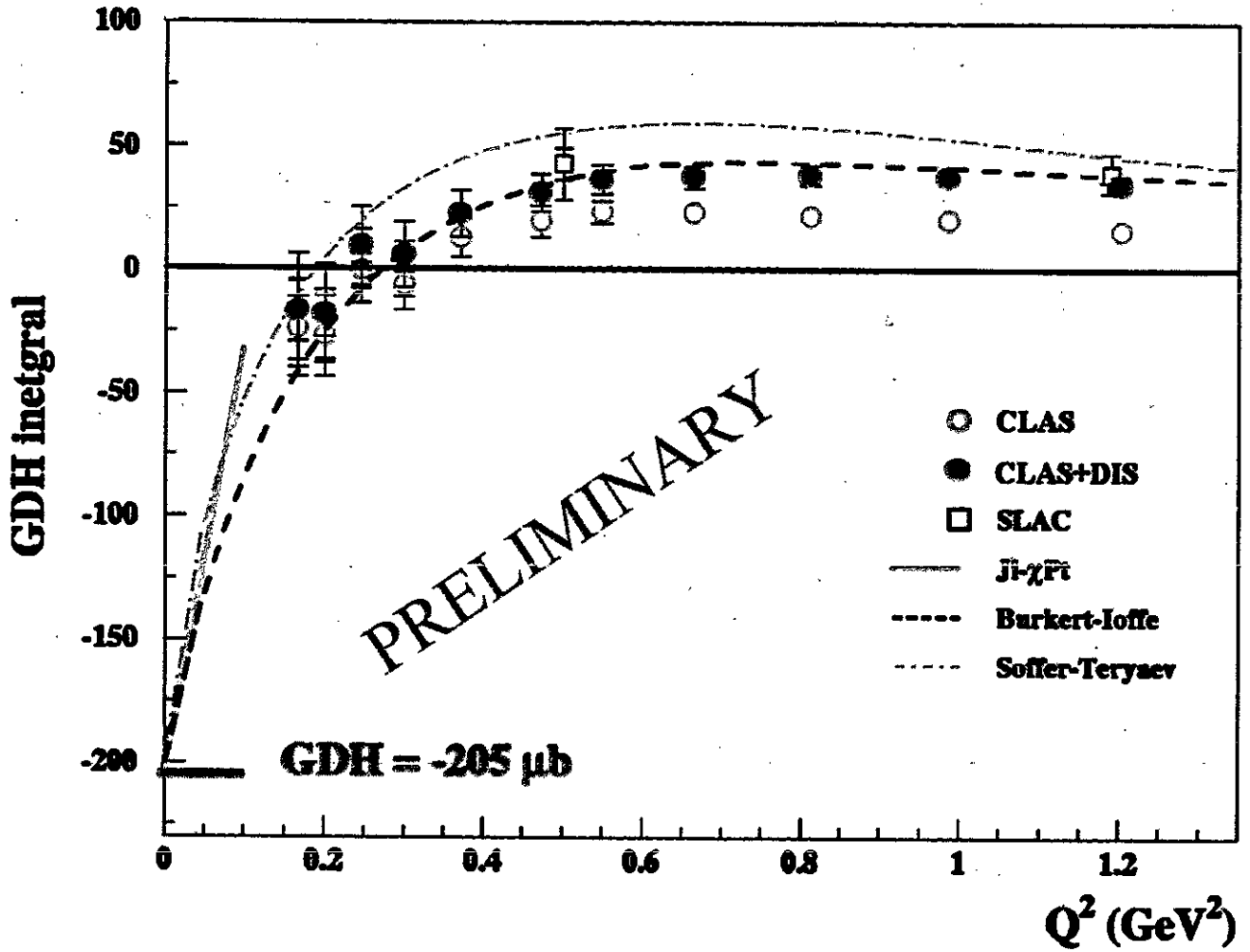
R. DeVita

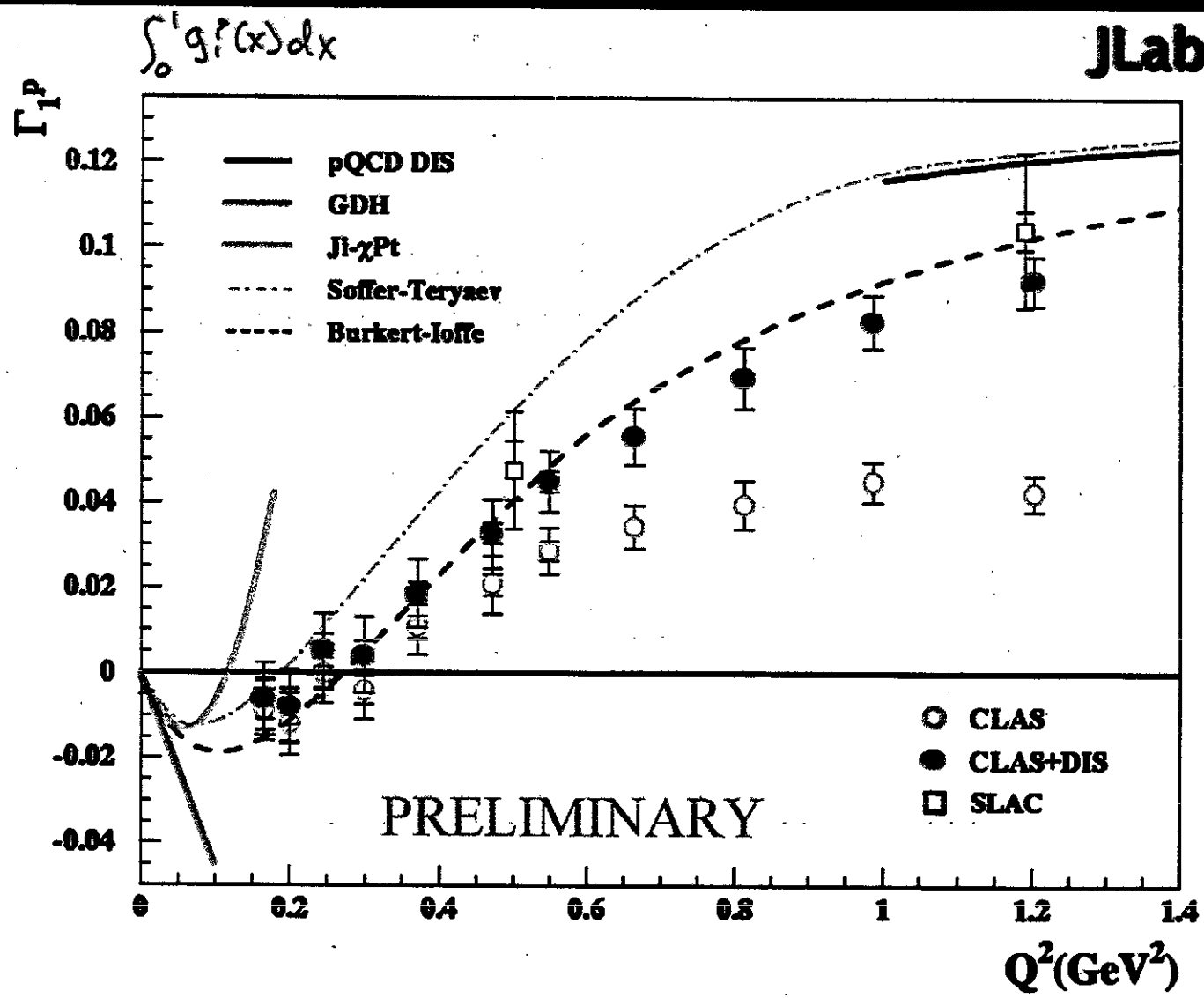
strong Q^2 dependence

evident resonance structures

~30% of data

JLab/Hall B

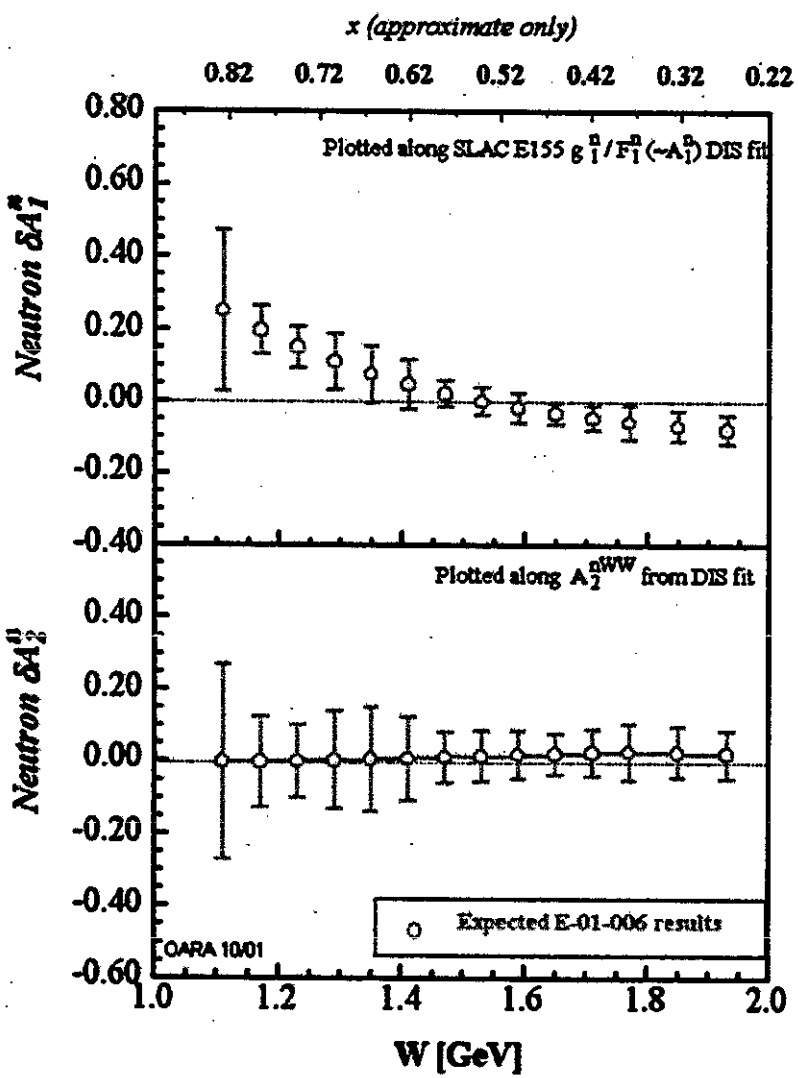

GDH inetgral
100
50
0
-50
-100
-150
-200
0
0.2
0.4
0.6
0.8
1
1.2
Q^2 (GeV^2)
PRELIMINARY
GDH = -205 μb
CLAS
CLAS+DIS
SLAC
Ji-χPt
Burkert-Ioffe
Soffer-Teryaev

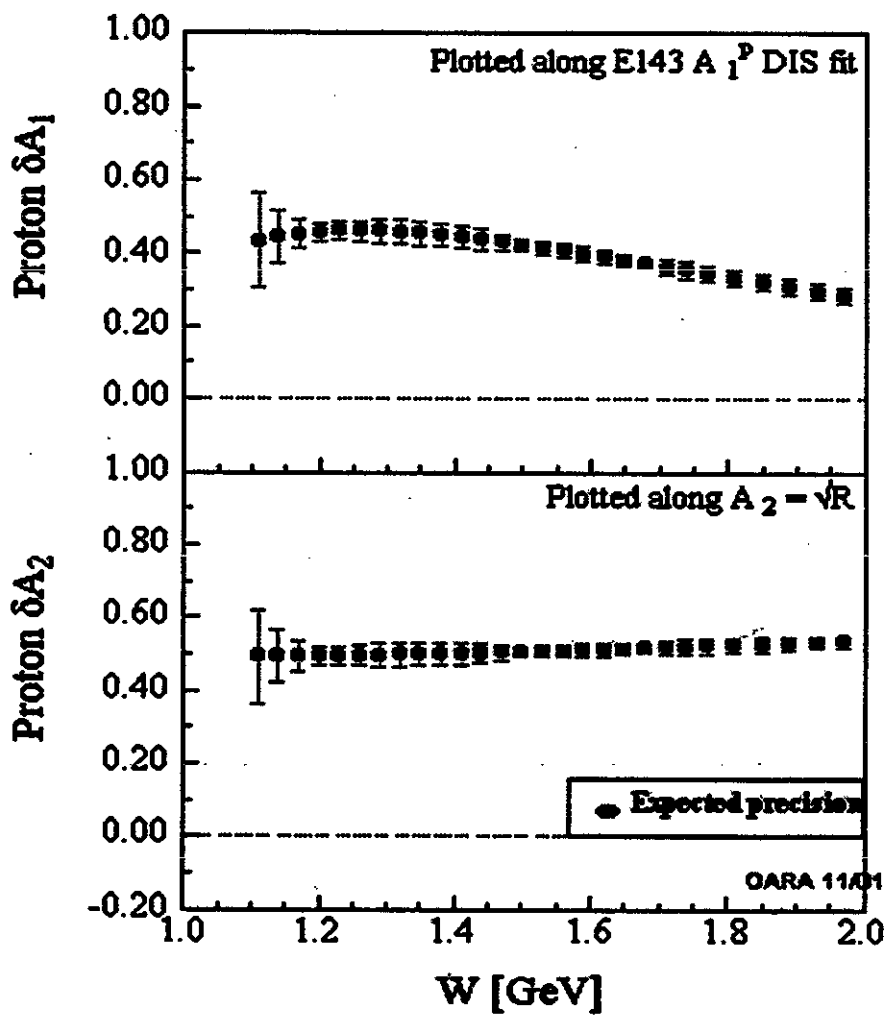

$\int_0^1 g_1^p(x)dx$
JLab/CLAS
Γ_1^p
pQCD DIS
GDH
Ji-χPt
Soffer-Teryaev
Burkert-Ioffe
CLAS
CLAS+DIS
SLAC
PRELIMINARY
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
0.2
0.4
0.6
0.8
1
1.2
1.4
$Q^2(GeV^2)$

Resonance A_1 and A_2 for proton and deuteron
Hall C - recently completed, $Q^2 \sim 1-2\,GeV^2$

E-01-006: expected results

O. Rondon, M. Jones



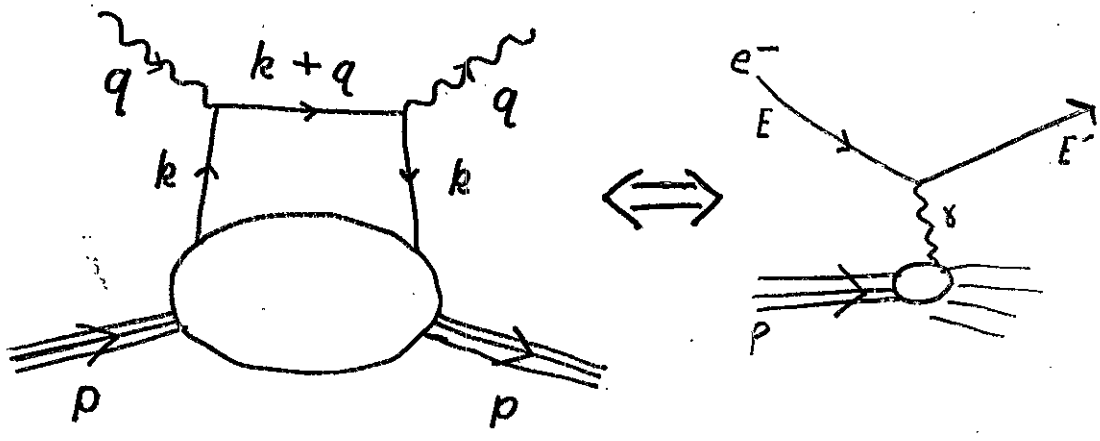


The g_2 Structure Function

- Unlike g_1, the g_2 structure function does not have a simple QPM interpretation.
- It is sensitive to quark-gluon exchange between constituent quarks, as well as quark mass contributions.
- Usually interpreted in the framework of the Operator Product Expansion:

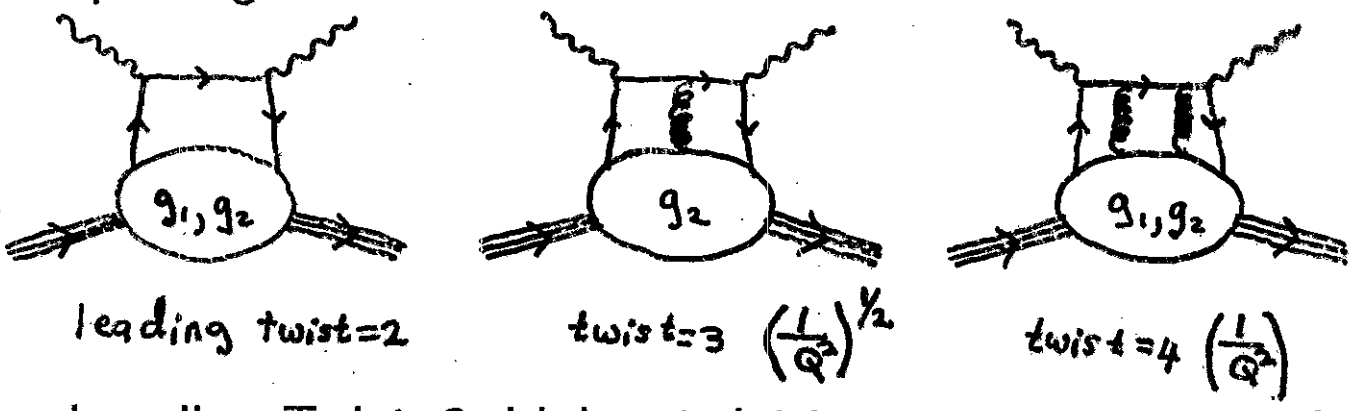
Operator Product Expansion

DIS related to the virtual Compton scattering via the Optical Theorem.



The g_2 Structure Function

Higher twist terms represent contributions from quark-gluon interactions:



Leading Twist=2, higher twist terms are supressed by additional powers of $1/Q$.

g_2 is a unique place to look for higher twist due to the following decomposition from Wandzura & Wilczek:

$$g_2(x,Q^2) = \left[-g_1(x,Q^2) + \int_x^1 \frac{1}{y} g_1(y,Q^2)dy\right] + \bar{g}_2$$

$$g_2(x,Q^2) = \underbrace{g_2^{ww}(x,Q^2)}_{\text{twist-2}} + \underbrace{\bar{g}_2(x,Q^2)}_{\text{higher twist}}$$

So, by measuring g_1 and g_2 precisely, we can directly access higher twist effects. JLAB E97-103, K. Kramer

* Note: The g_1 structure function does <u>not</u> contain twist-3 contributions.

Jefferson Lab

E97-103 OVERVIEW

n measurement of $g_2^n(x, Q^2)$ as a function of Q^2
.2.

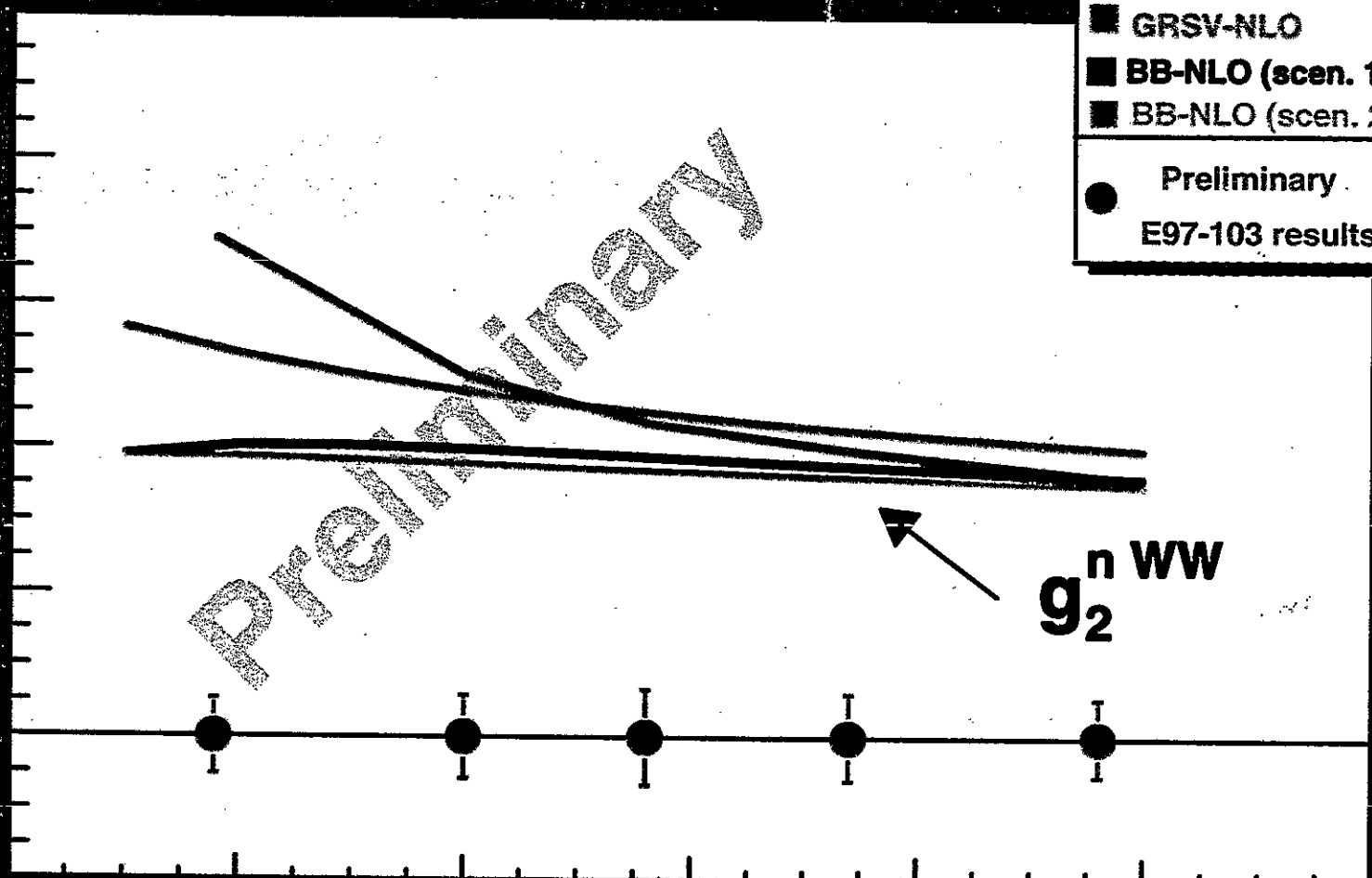
n Aug-Sept, 2001.

ized electron scattering from longitudinally and
larized ^{3}He target, $^3\vec{\mathrm{He}}(\vec{e}, e')$.

ent spectrometers measuring at same kinematics.

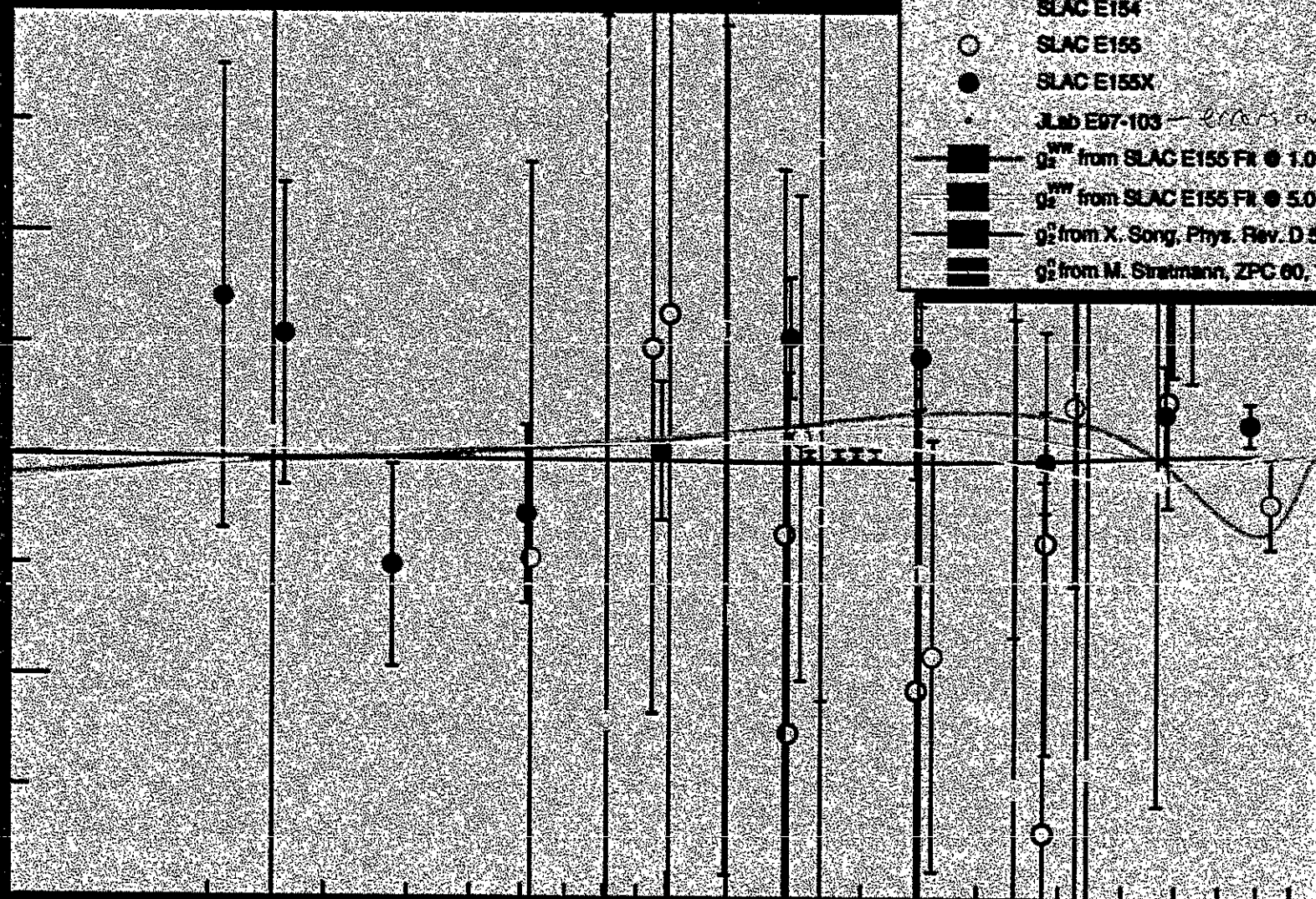
lems: Raw asymmetry $\sim 700 \pm 200$ ppm. Sensi-

Preliminary E97-103 statistical error bars for $g_2^n(x,Q^2)$ at $x \approx 0.2$



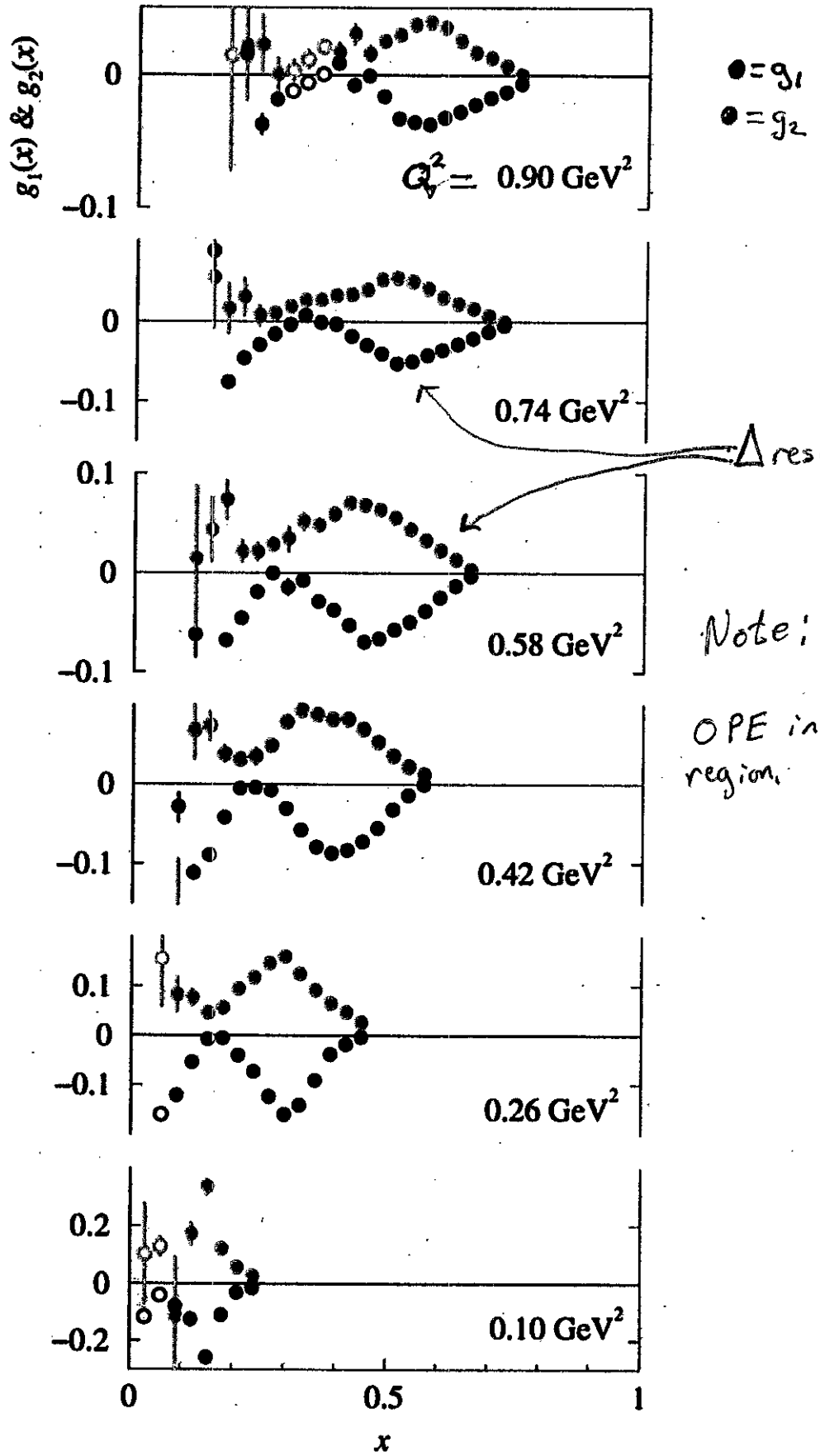
g_2^{WW} from E155 fit to g_1^n/F_1^n data	NLO Fits
GRSV-NLO	
BB-NLO (scen. 1)	
BB-NLO (scen. 2)	
Preliminary E97-103 results	JLab

World Data on $xg_2^n(x,Q^2)$



E94-010 g_1^n and g_2^n at fixed Q^2

Resonance region



Note: $g_2 \approx -g_1$

OPE in the resonance region.

Future g_2 measurements over a wide x-range could test these sum rules:

Moments and Sum Rules

twist-2 contribution

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

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

$$\Longrightarrow d_n = 2\int_0^1 x^n \left[g_1(x) + \frac{n+1}{n} g_2(x)\right] dx, \quad n = 2, 4, \ldots$$

$= \frac{2}{3}\left(x_B + \frac{x_E}{2}\right)$ *

"Twist-3 matrix element"
Theoretically Calculable

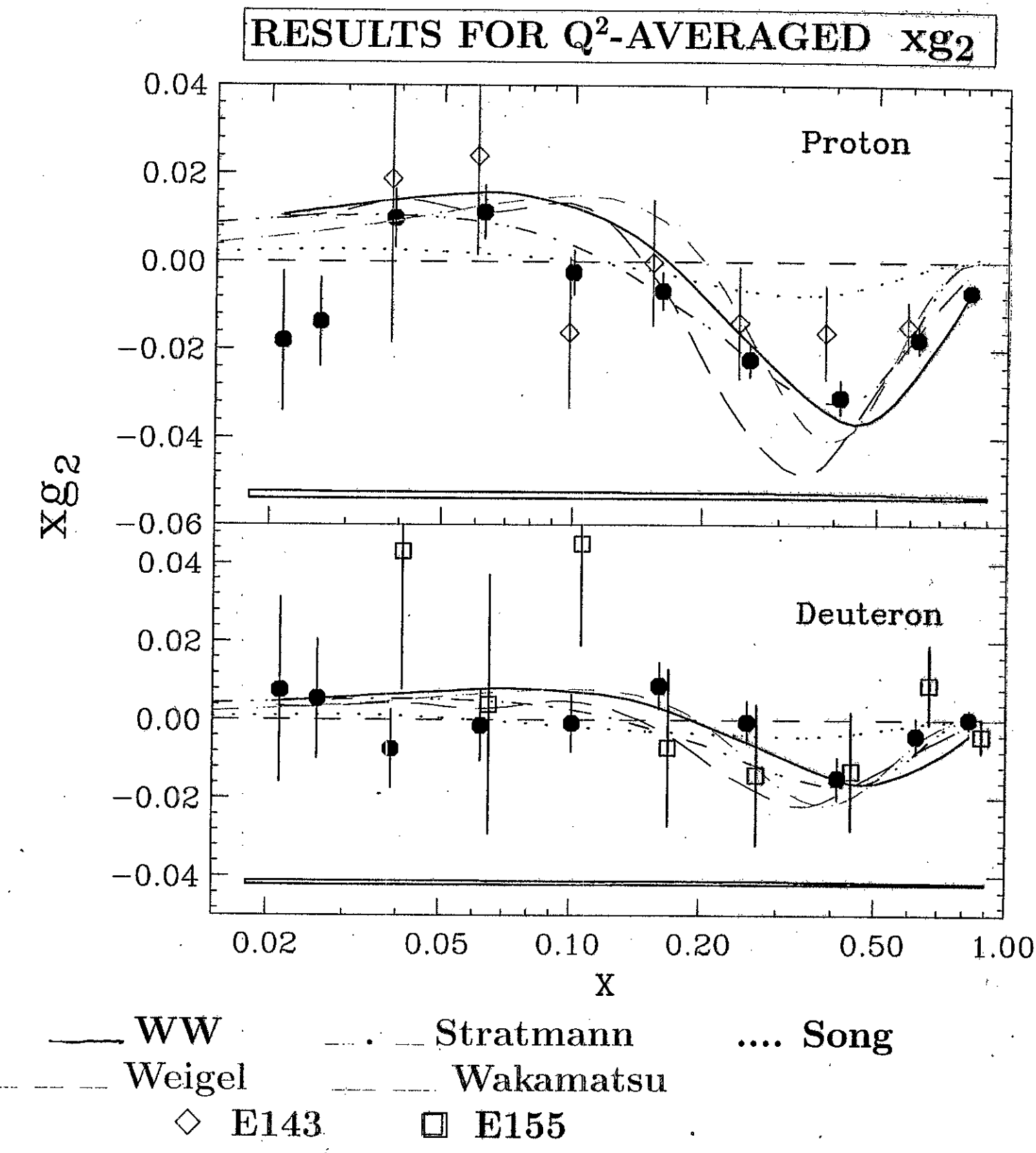
Burkhardt-Cottingham Sum Rule

$$\int_0^1 g_2(x, Q^2)dx = 0, \quad \text{as } Q^2 \to \infty$$

Experimentally difficult to test because low-x behavior is completely unknown.

Also valid at finite Q^2.

* PLB 353, 107 (1995) E. Stein et al.



χ^2/df agreement with $g_2^{WW} = 3.1(p) \quad 1.2(d)$

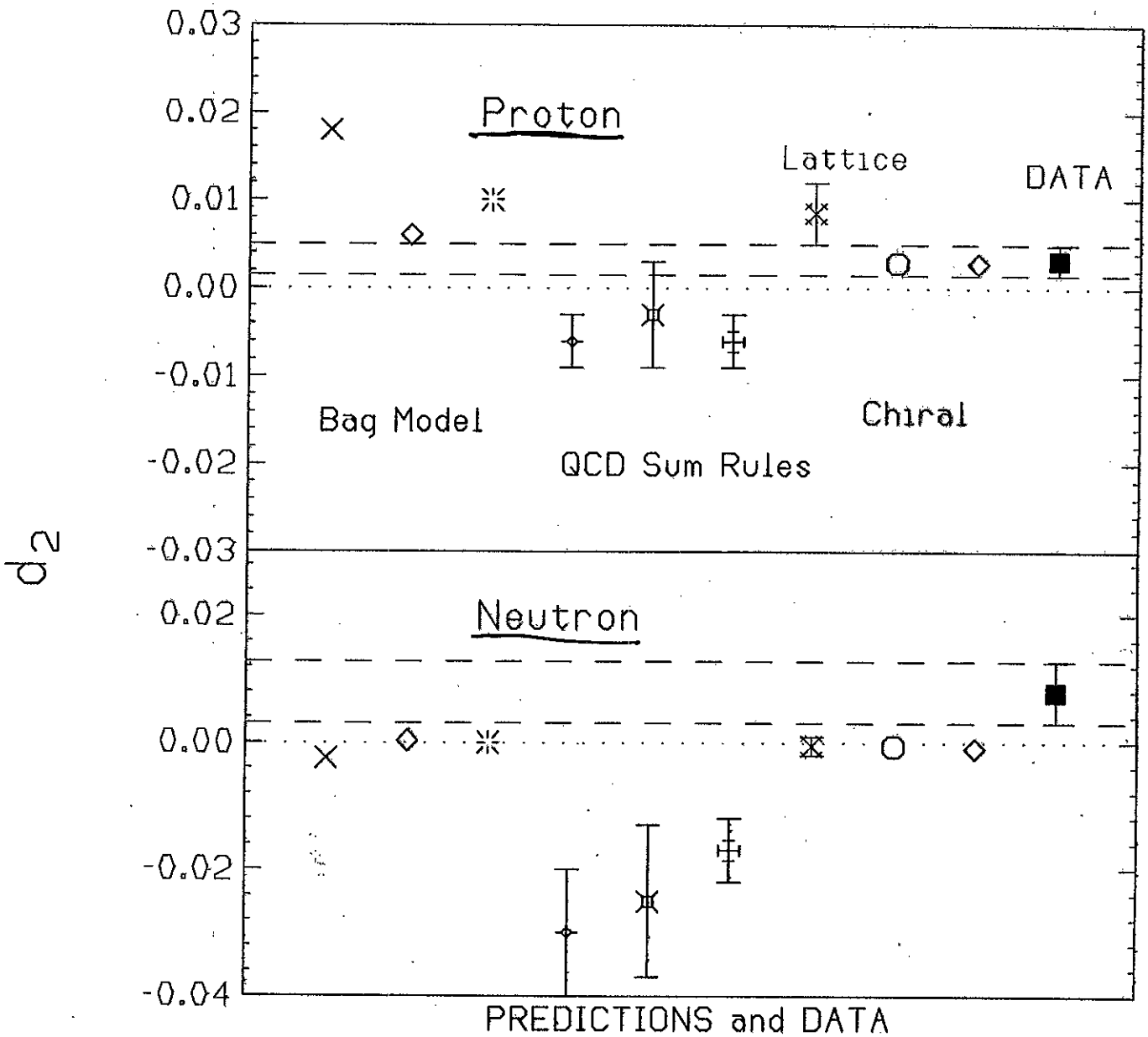
THE TWIST-3 d_2 MATRIX ELEMENT

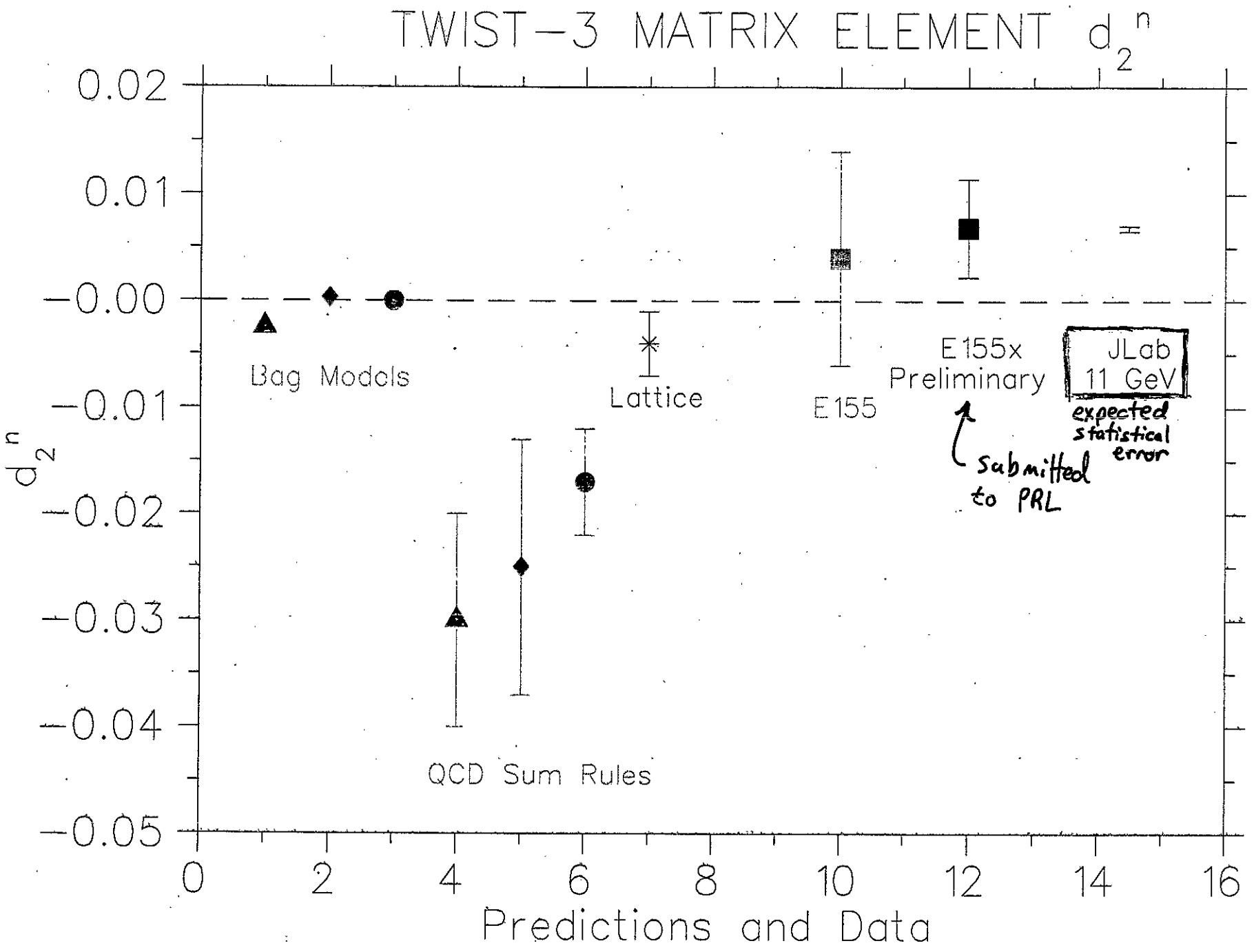
$$d_2 = 3\int_0^1 x^2[g_2(x,Q^2) - g_2^{WW}(x,Q^2)]dx$$

E155X: $0.0025 \pm .0016 \pm .0010$(proton)

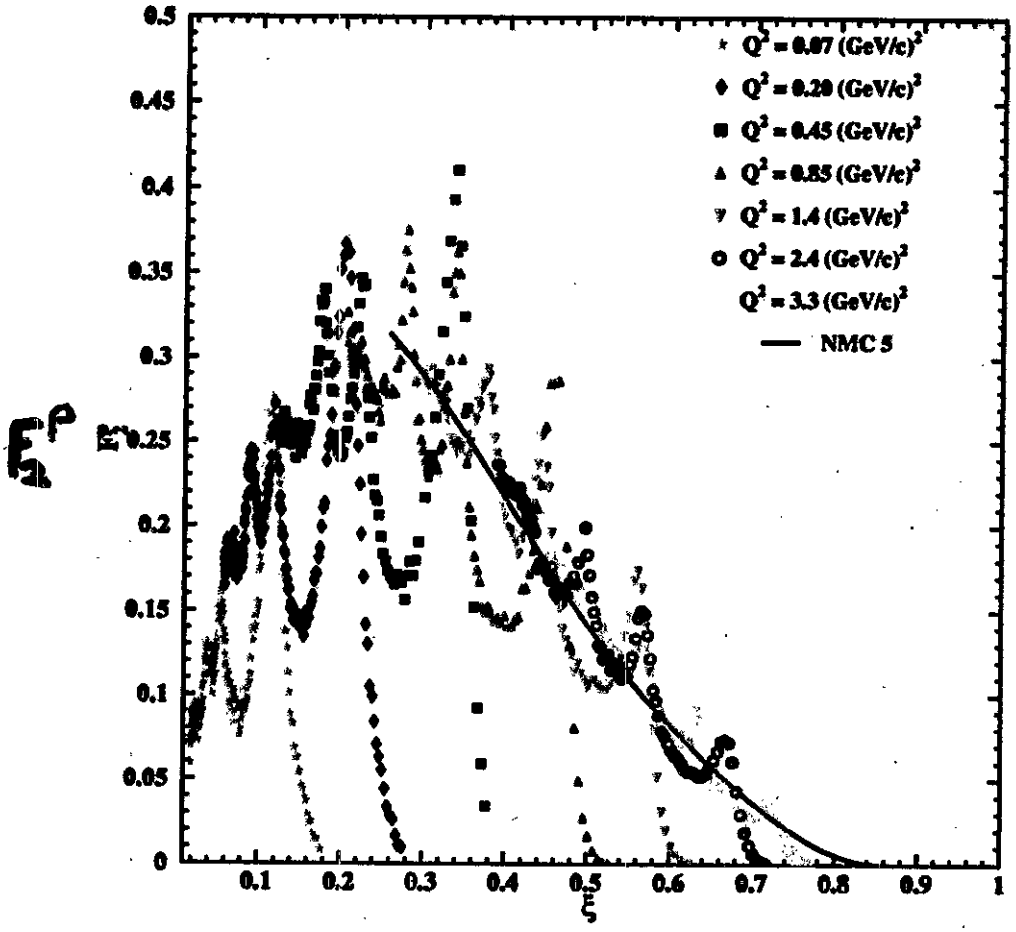
$0.0054 \pm .0023 \pm .0005$(deuteron)

AVERAGE: $0.0032 \pm .0017$(p) $0.0079 \pm .0048$(n)




TWIST-3 MATRIX ELEMENT d_2^n
0.02
0.01
-0.00
-0.01
-0.02
-0.03
-0.04
-0.05
d_2^n
Bag Models
Lattice
E155
E155x
Preliminary
JLab
11 GeV
expected
statistical
error
submitted
to PRL
QCD Sum Rules
0
2
4
6
8
10
12
14
16
Predictions and Data

Parton-Hadron duality



$$\xi = 2x/(1+\sqrt{1+4M^2x^2/Q^2})$$

I. Niculescu *et al.*

Experiment E01-012

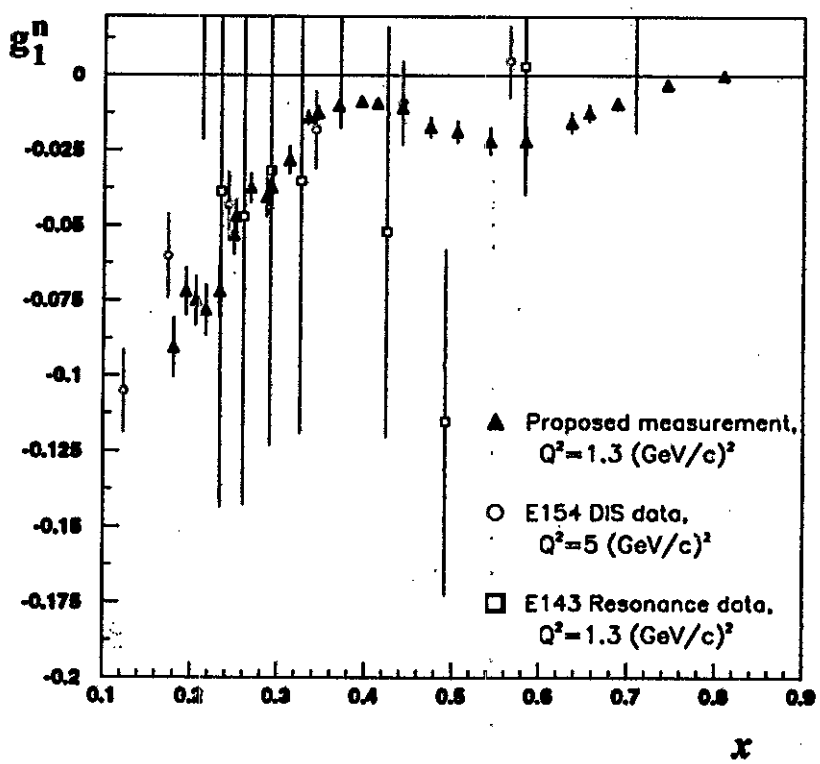
Measurement of neutron (^{3}He) spin structure functions in the resonance region.

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

1. 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

2. If duality established
   Powerful tool to study very high x behavior.

3. **Understanding quark-hadron duality will help us understand confinement of quarks in protons and neutrons**



SUMMARY

(Nearly)

- DIS: All DIS results from SLAC, HERMES, SMC/EMC now published. Bjorken Sum rule satisfied. Spin of nucleon not primarily carried by quark spin. HERMES deuteron!

- Large-x region: New precision data from JLab E99-117 show A_1^n increasing with x for the first time. Now able to discriminate between models in valence quark region.

- g_1 in resonance region: New precision data for both proton and neutron coming from all three Halls at Jefferson Lab. Allow careful study of hadronization of nucleon, quarks→nucleon, pQCD→non-pQCD. Precision determination of Q^2 evolution of GDH sum rule.

- g_2 structure function: New precision data from SLAC (E155x) and JLab now allow us to quantify specific higher-twist contributions to nucleon.

- Spin Duality: Approved experiment to look for duality in spin structure functions. If duality holds, opens new door to studying large-x region.

- Future: Rich program of nucleon spin structure studies using inclusive scattering at 12 GeV at Jefferson Lab, A_1, g_2.

- Not covered: Semi-inclusive physics at HERMES, JLAB. ΔG at COMPASS, SLAC, RHIC. Transversity, DVCS,.....

Many Thanks for Plots and Analyses

- DIS: SLAC E142-E155x collaborations, HERMES, SMC/EMC
  See hep-ph/0203155 for references.
- NLO: J. Blümlein, H. Böttcher, hep-ph/0203155
- A_1^n, E99-117: X. Zheng, JLab polarized ^{3}He and Hall A collab., J.P. Chen, G. Cates, Z.E. Meziani, P. Souder
- Resonance, E94-010–A. Deur, S. Choi, nucl-ex/0205020
  Hall B/CLAS collaboration, S. Kuhn, K. Griffioen, R. DeVita
  E01-006–O. Rondon, F. Wesselmann, M. Jones
- g_2: SLAC E155x collab., E97-103 K. Kramer, W. Korsch
- Spin Duality: N. Liyanage, J.P. Chen, S. Choi