Measurements of the Nucleon Spin-Structure Functions in and Above the Resonance Region for the Hall-B EG1Experiment at Jefferson Laboratory

Robert Fersch
Christopher Newport University
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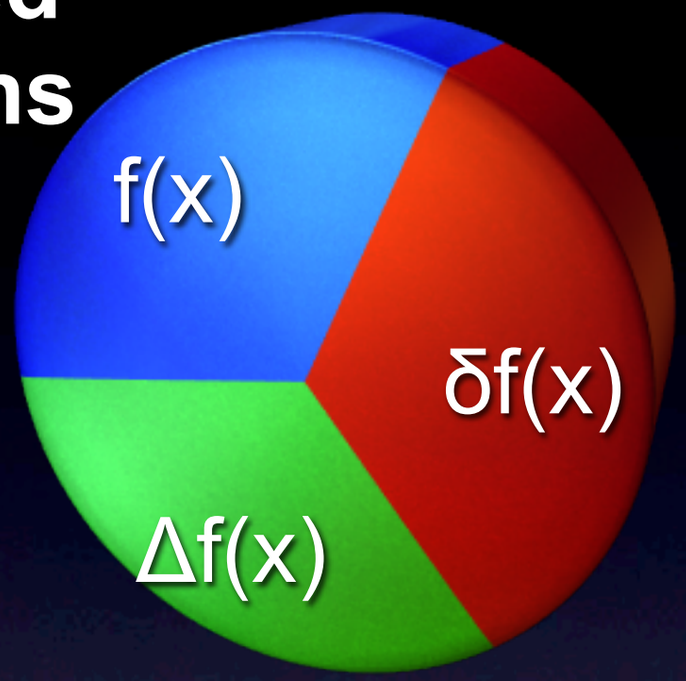
Structure of the Nucleon

Unpolarized distributions
q, g



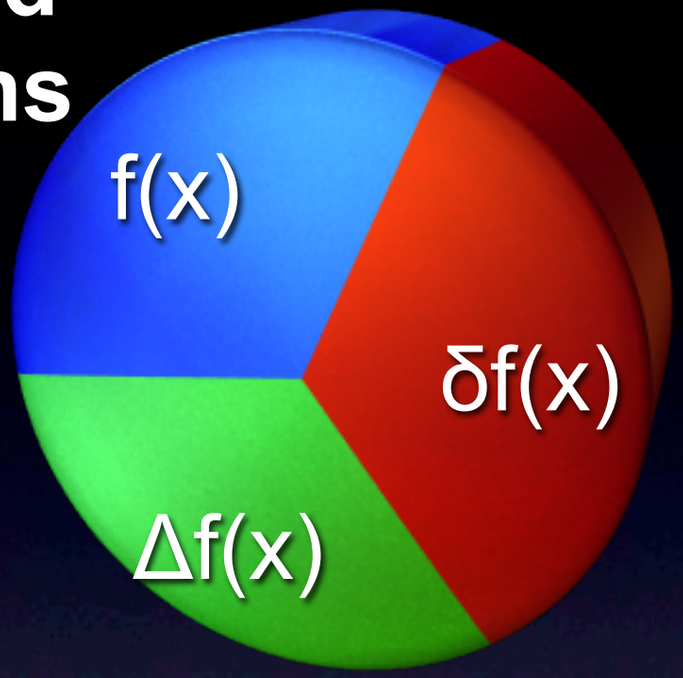
Transversity δq

Helicity
Δq, Δg

3 d.o.f. completely describe the nucleon at leading twist when $k_T = 0$

Structure of the Nucleon

Unpolarized distributions q, g



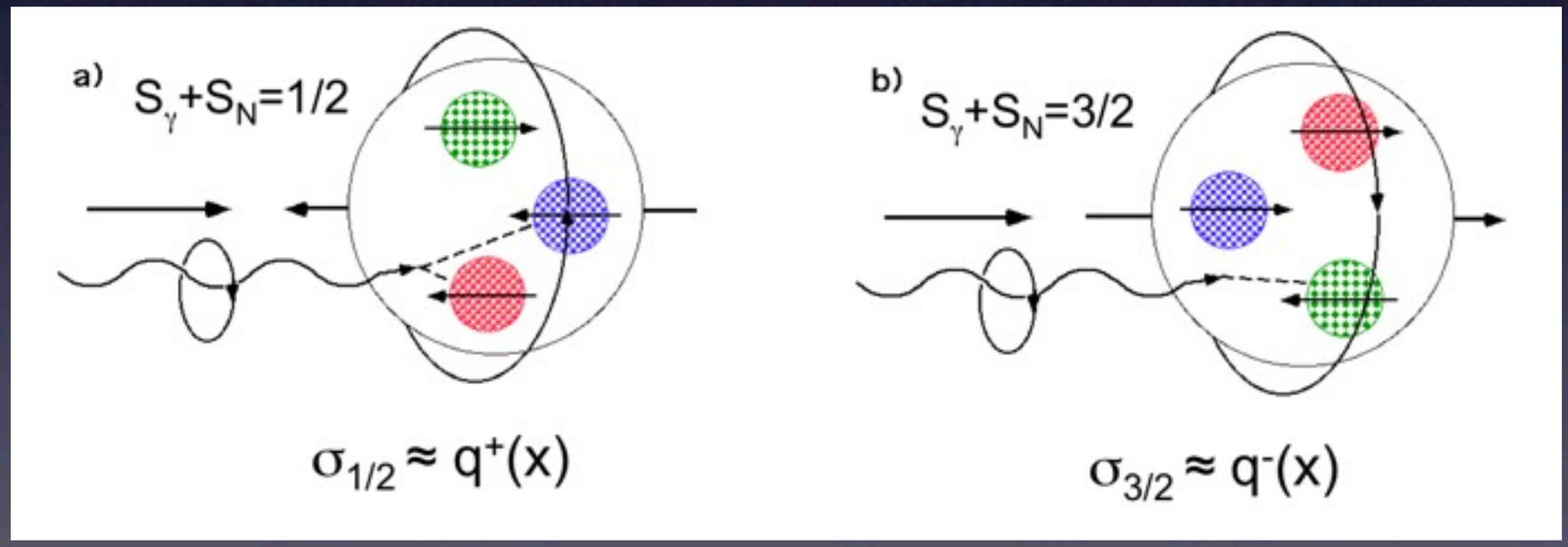
Transversity δq

3 d.o.f. completely describe the nucleon at leading twist when $k_T = 0$

Helicity
Δq, Δg

Helicity: $\Delta q = q^+ - q^-$

Incident electron couples to quarks of opposite longitudinal spin



Structure function $g_1(x,Q^2) \sim \sigma_{1/2} - \sigma_{3/2}$

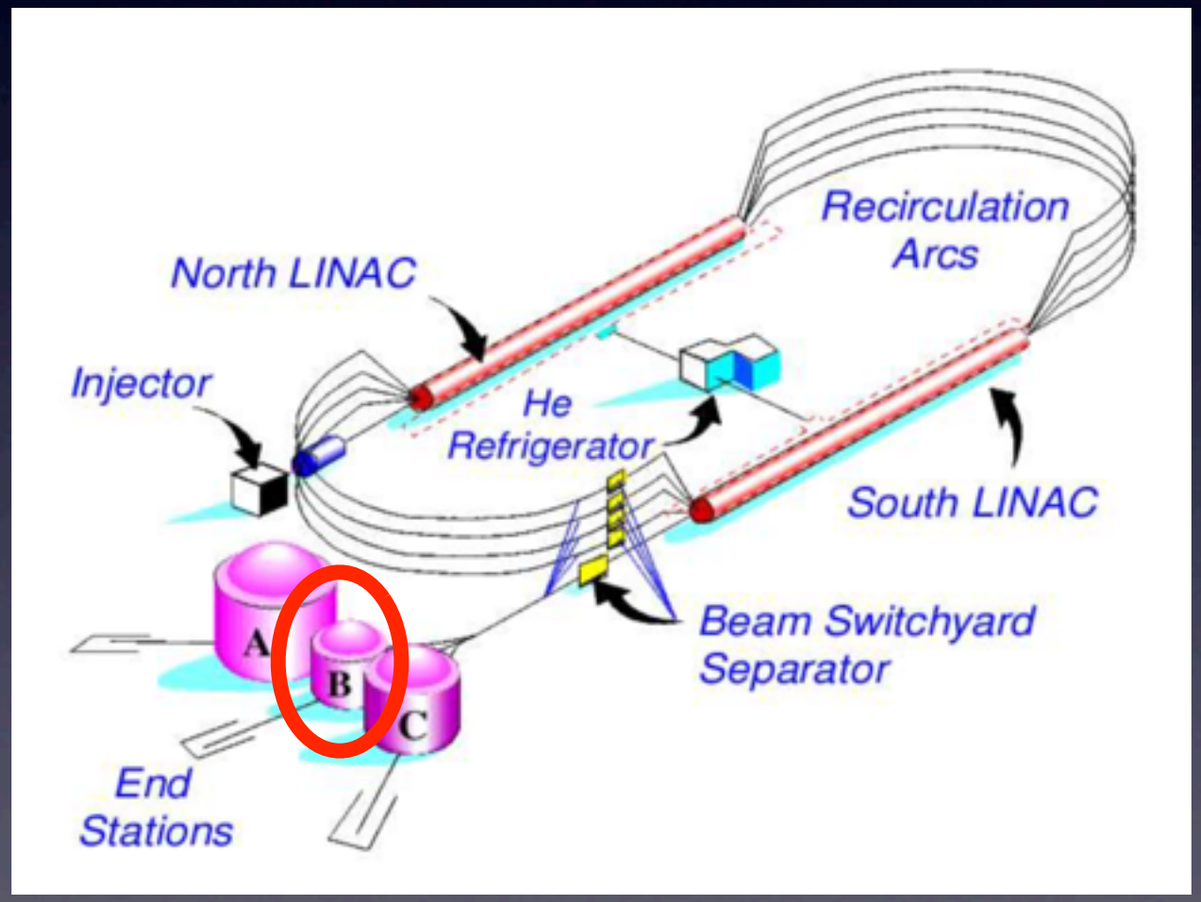
Requires longitudinally polarized beam *and* target

The EG1 experiment

ran in CLAS for 7 months 2000-2001

4 beam energies used (1.6, 2.5, 4.2, 5.7 GeV)

CEBAF Large Acceptance Spectrometer (Hall-B) at Jefferson Lab



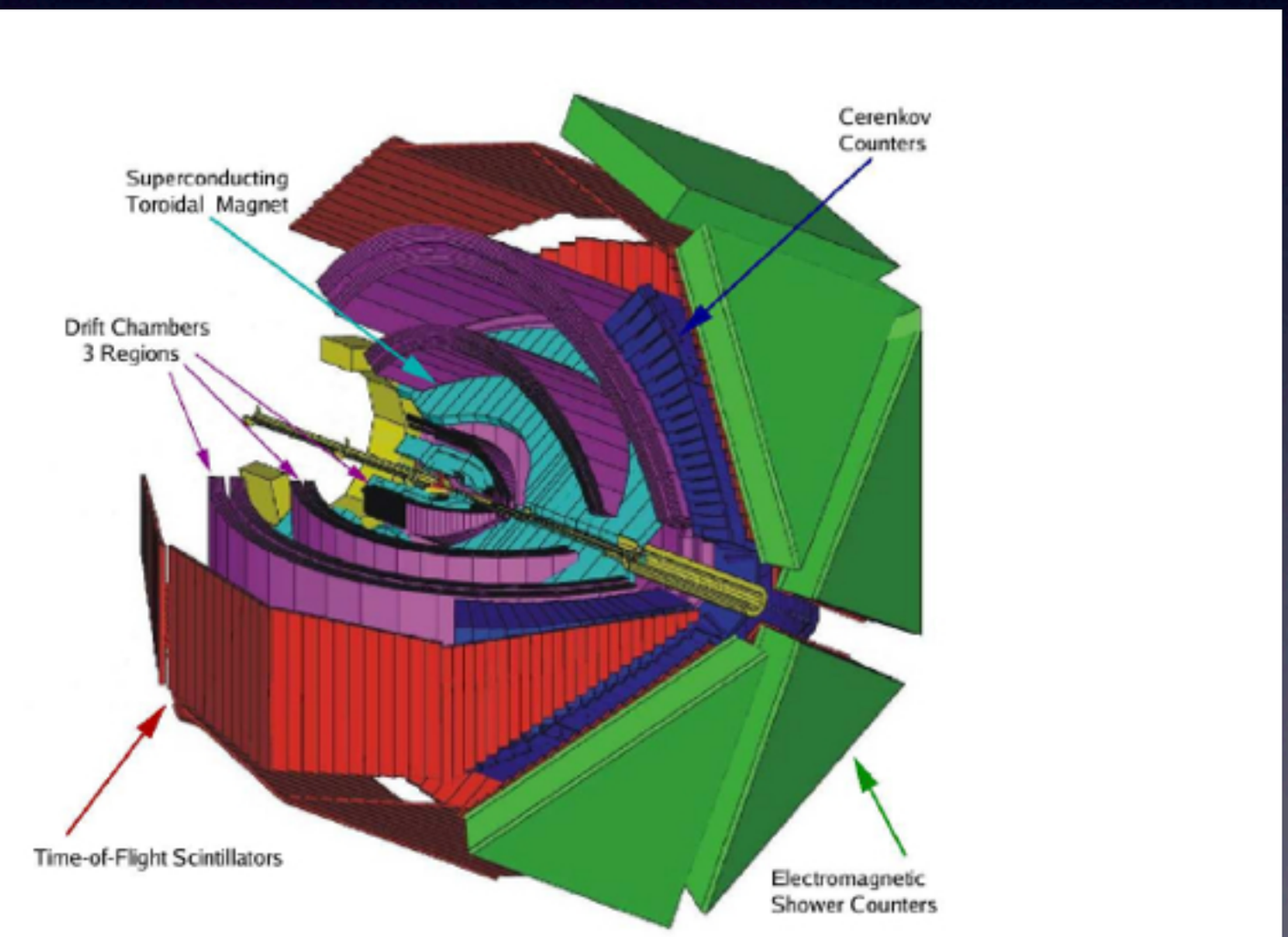
(~70%) polarized electron beam in energies up to 6 GeV

The EG1 experiment

ran in CLAS for 7 months 2000-2001

4 beam energies used (1.6, 2.5, 4.2, 5.7 GeV)

CEBAF Large Acceptance Spectrometer (Hall-B) at Jefferson Lab



Drift Chambers (momentum reconstruction)

Scintillation Counters (time-of-flight, PID)

Cherenkov Counters and Electromagnetic Calorimeters (separation of electrons from light hadrons)

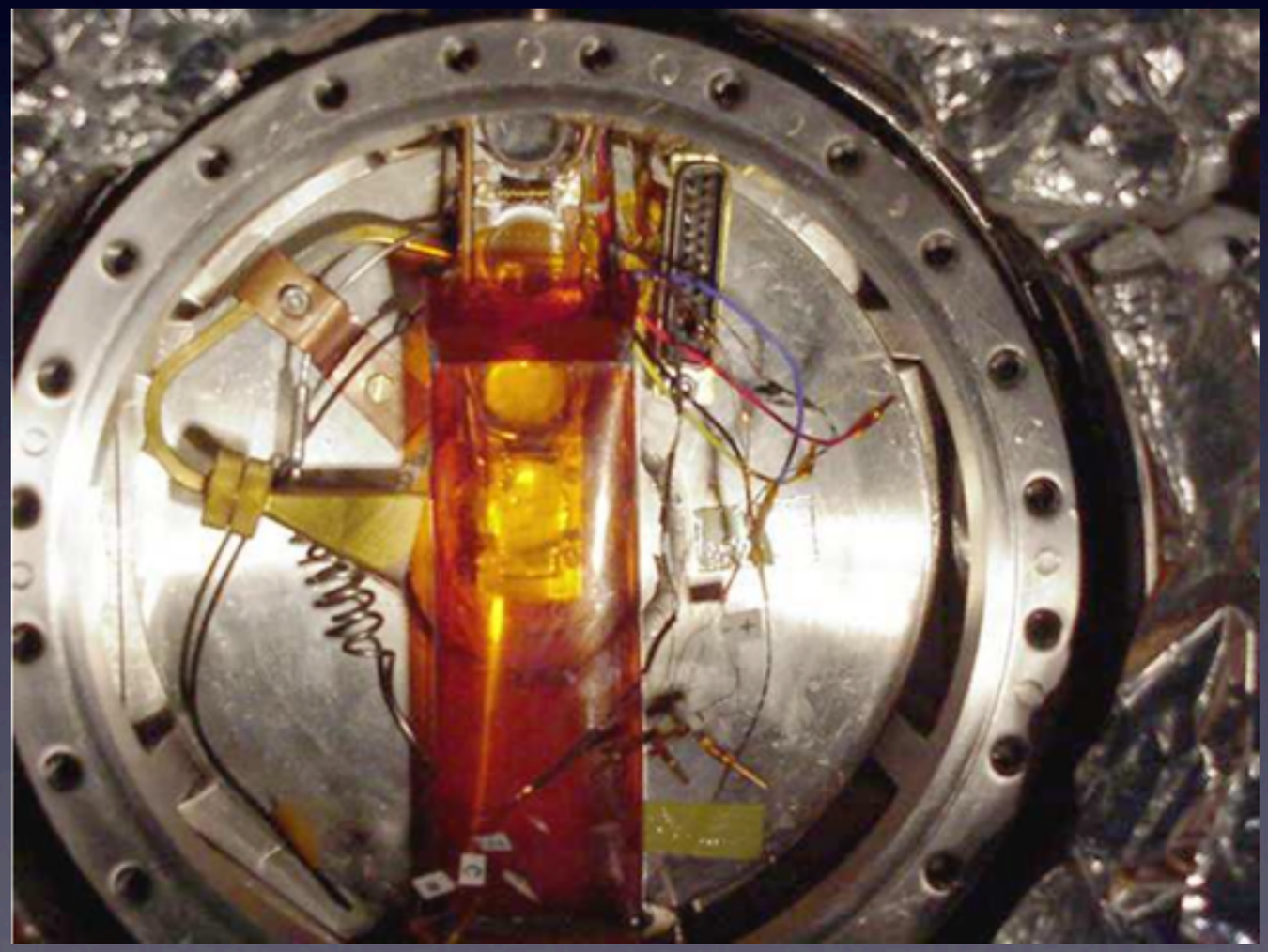
The EG1 experiment

ran in CLAS for 7 months 2000-2001

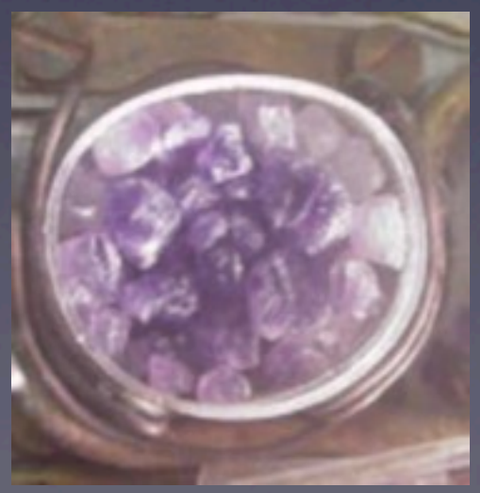
4 beam energies used (1.6, 2.5, 4.2, 5.7 GeV)

CLAS Longitudinally Polarized Target

- $^{15}NH_3$ and $^{15}ND_3$ target cells
- Typical polarizations of 75% (H) and 30% (D)
- ^{12}C and LHe target cells for unpolarized background subtraction



ammonia target cell

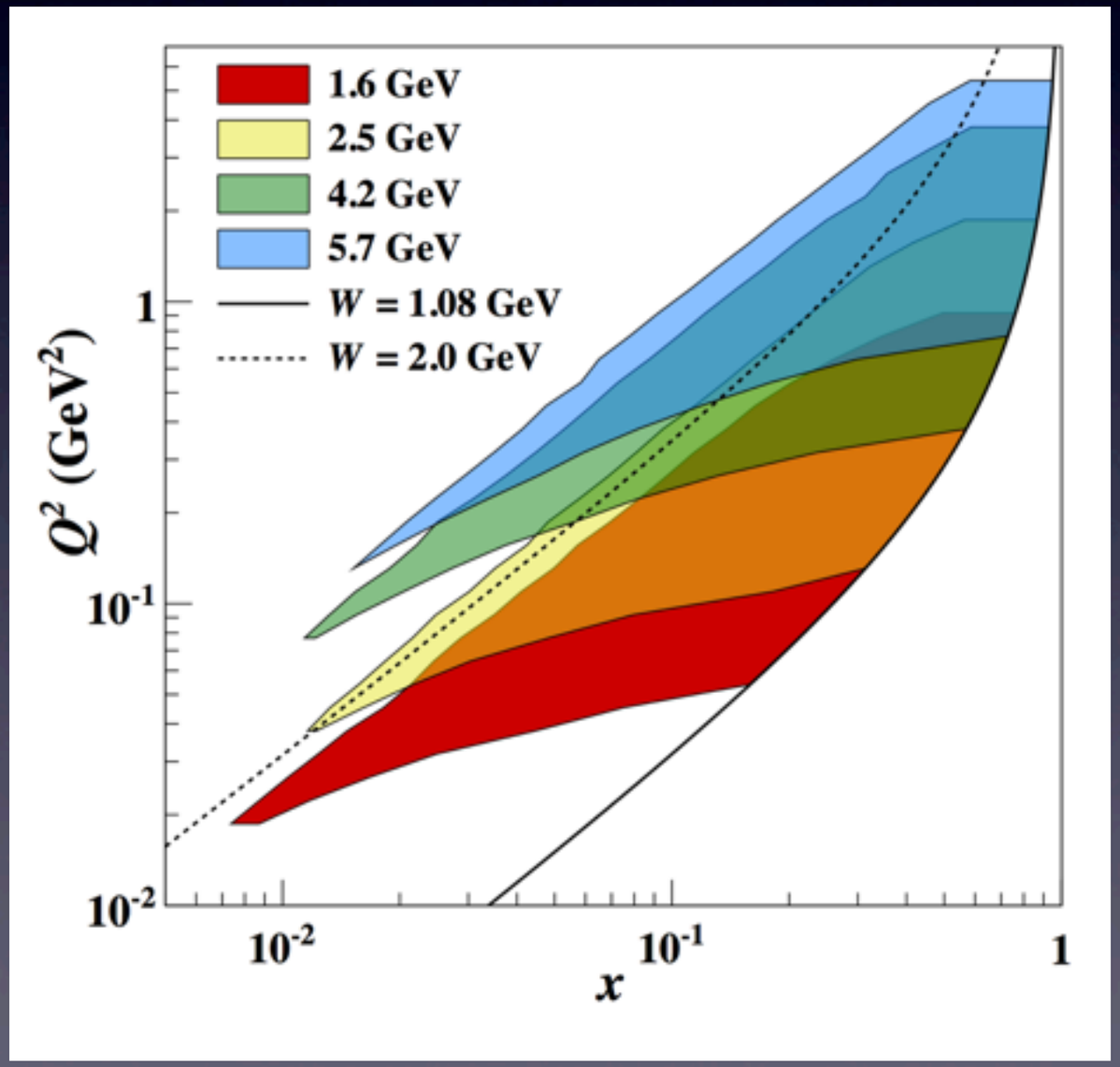


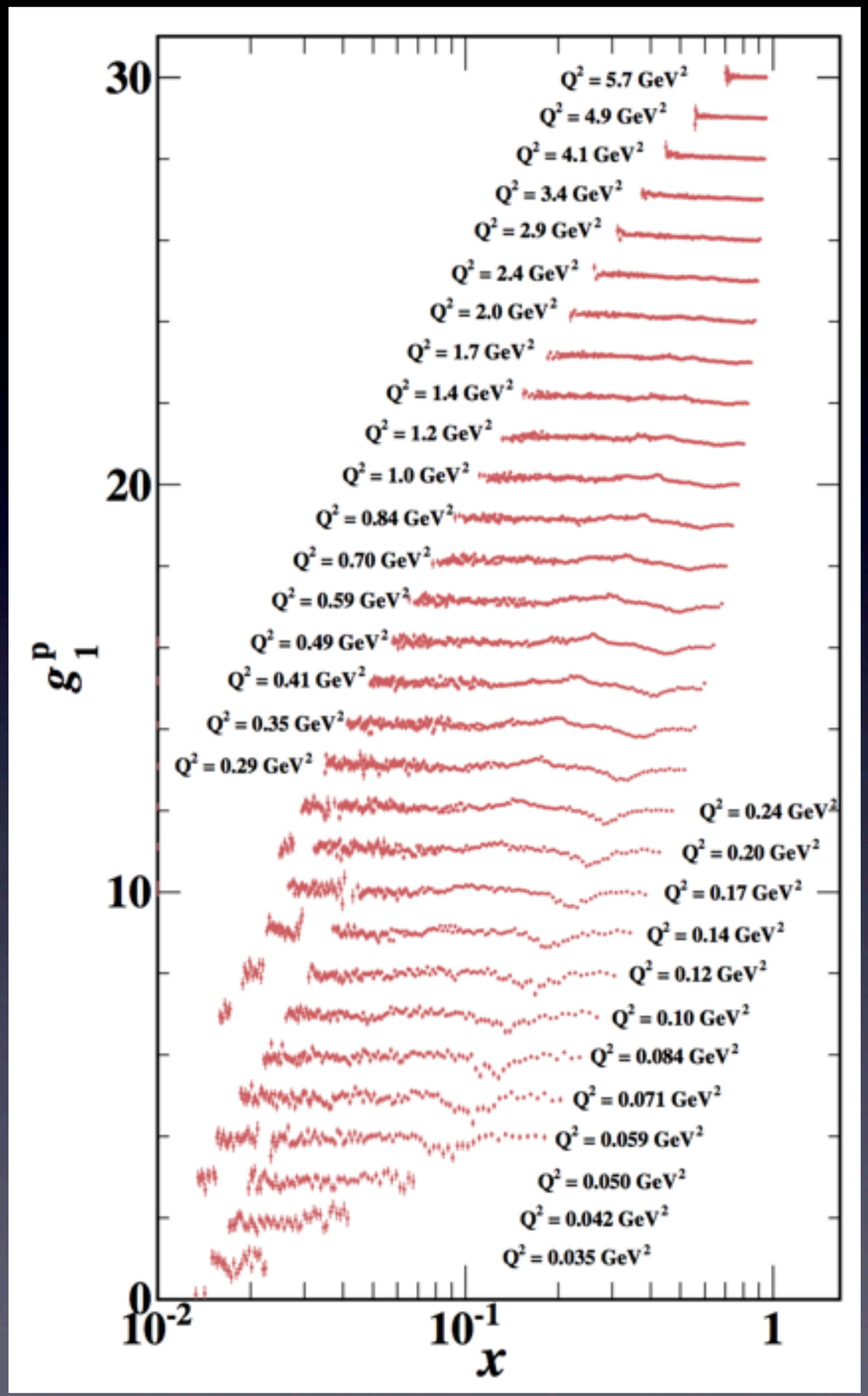
The EG1 experiment

ran in CLAS for 7 months 2000-2001

4 beam energies used
(1.6, 2.5, 4.2, 5.7 GeV)

Kinematic coverage & statistics





Many papers already published using EG1 data (including a study of Bloom-Gilman duality):

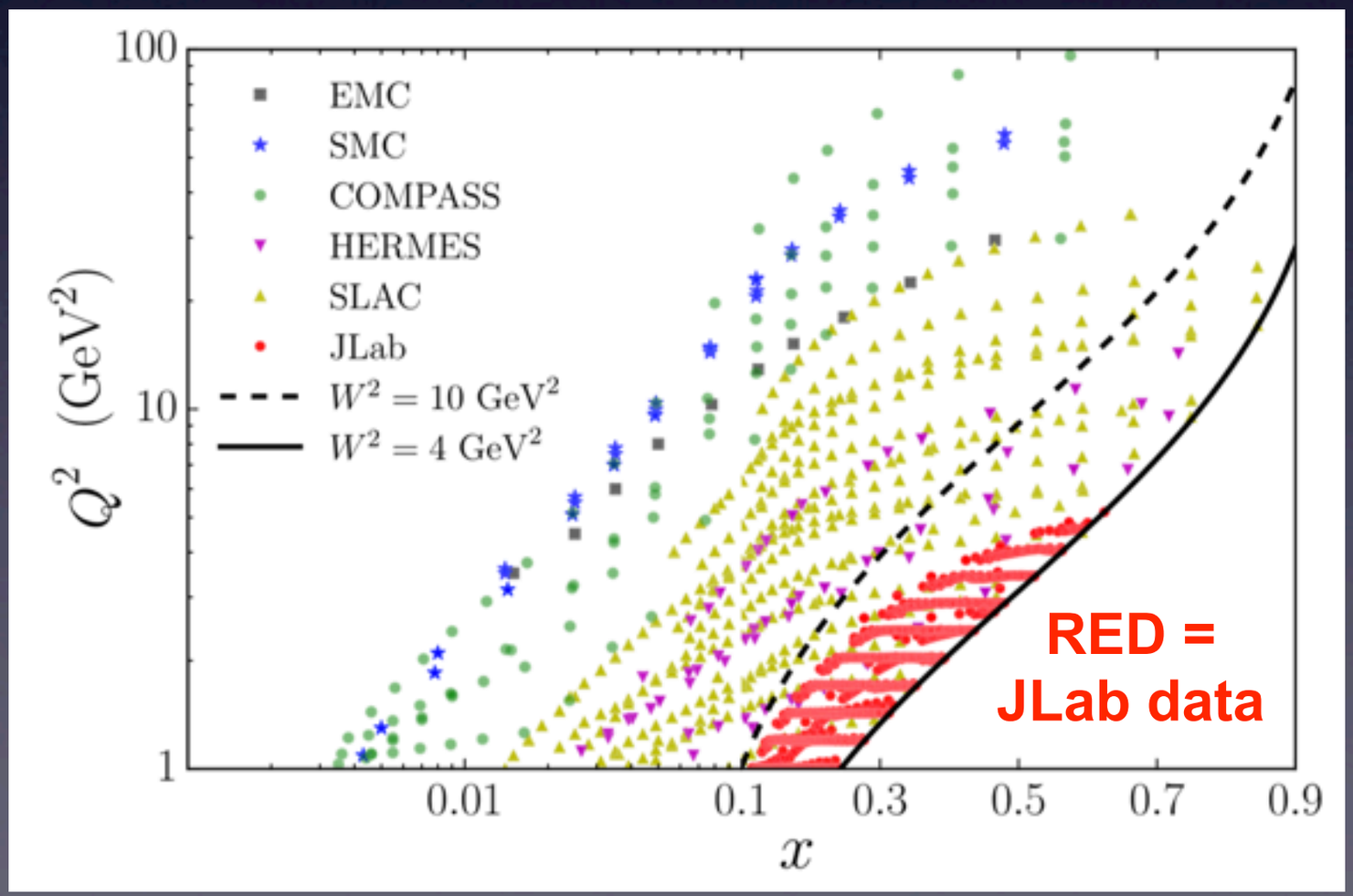
- N. Guler *et al. (CLAS Collaboration)*, “Precise Determination of the Deuteron Spin Structurevat Low to Moderate Q^2 with CLAS and Extraction of the Neutron Contribution”, Phys. Rev. C 92,v055201(2015).
- P. Bosted *et al. (CLAS Collaboration)*. “Target and Beam-Target Spin Asymmetries in Exclusive π^+ and π^- electroproduction with 1.6- to 5.7-GeV electrons”, Phys. Rev. C 94, 055201(2016)

- H. Avakian *et al. (CLAS Collaboration)*, "Measurement of Single and Double Spin Asymmetries in Deep Inelastic Pion Electroproduction with a Longitudinally Polarized Target", Phys. Rev. Lett. 105, 262002 (2010).
- Y. Prok *et al. (CLAS Collaboration)*, "Moments of the Spin Structure Functions g^p_1 and g^d_1 for $0.05 < Q^2 < 3.0$ GeV^2", Phys. Lett. B 672, 12 (2009).
- A. Biselli *et al. (CLAS Collaboration)*, "First Measurement of Target and Double Spin Asymmetries for $ep \rightarrow e'p\pi^0$ in the Nucleon Resonance Region Above the $\Delta(1232)$", Phys. Rev. C 78, 045204 (2008).
- P.E. Bosted *et al. (CLAS Collaboration)*, "Ratios of $^{15}N/^{12}C$ and $^4He/^{12}C$ Inclusive Electroproduction Cross Sections in the Nucleon Resonance Region", Phys. Rev. C 78, 015202 (2008).
- P.E. Bosted *et al. (CLAS Collaboration)*, "Quark-Hadron Duality in Spin Structure Functions g_1^p and g_1^d", Phys. Rev. C 75, 035203 (2007).
- K.V. Dharmawardane *et al. (CLAS Collaboration)*, "Measurement of the x and Q^2 Dependence of the Spin Asymmetry A_1 of the Nucleon", Phys. Lett. B. 641, 28 (2006).
- S. Chen *et al. (CLAS Collaboration)*, "Measurement of Deeply Virtual Compton Scattering with a Polarized Proton Target", Phys. Rev. Lett. 97, 072002 (2006).
- A. Biselli *et al. (CLAS Collaboration)*, "Study of $ep \rightarrow ep\pi^0$ in the $\Delta(1232)$ Mass Region Using Polarization Asymmetries", Phys. Rev. C 68, 035202 (2003).
- R. Fatemi *et al. (CLAS Collaboration)*, "Measurement of the Spin Structure Functions in the Resonance Region for Q^2 from 0.15 to 1.6 GeV^2", Phys. Rev. Lett. 91, 222002 (2003).
- J. Yun *et al. (CLAS Collaboration)*, "Measurement of Inclusive Spin Structure Functions of the Deuteron with CLAS", Phys. Rev. C 67, 055204 (2003).
- R. DeVita *et al. (CLAS Collaboration)*, "First Measurement of the Double Spin Asymmetry in $ep \rightarrow e'\pi^+n$ in the Resonance Region", Phys. Rev. Lett. 88, 082001 (2002).

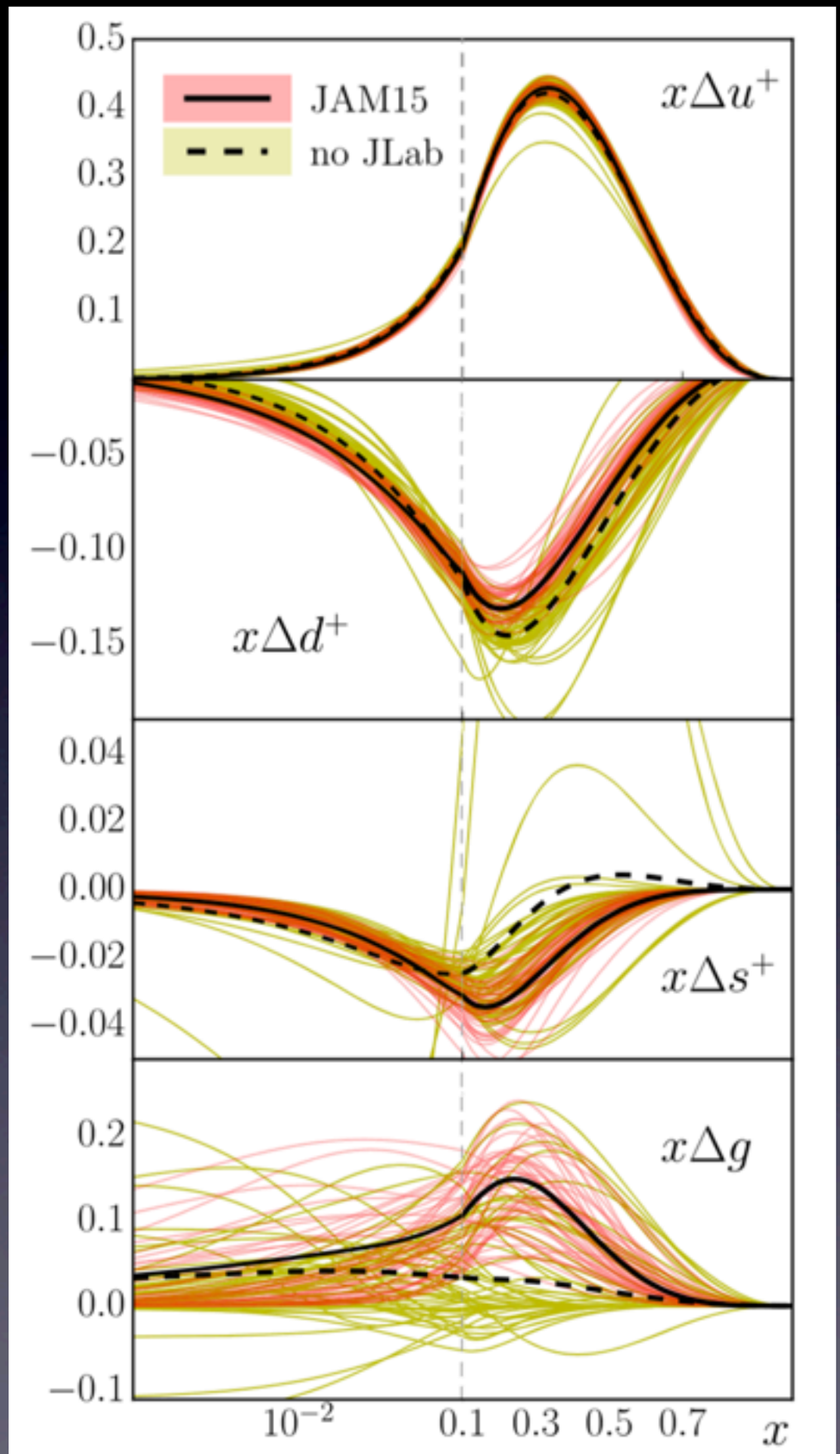
Impact of JLab / EG1 data on polarized PDFs

Global analysis by JAM (JLab Angular Momentum group)
Theory group (W. Meltinchouk ***et al.***)

Phys Rev D 93, 074005 (2016)



spin distributions within the nucleon



Final proton “long paper” is now available pending publication in Phys. Rev. C

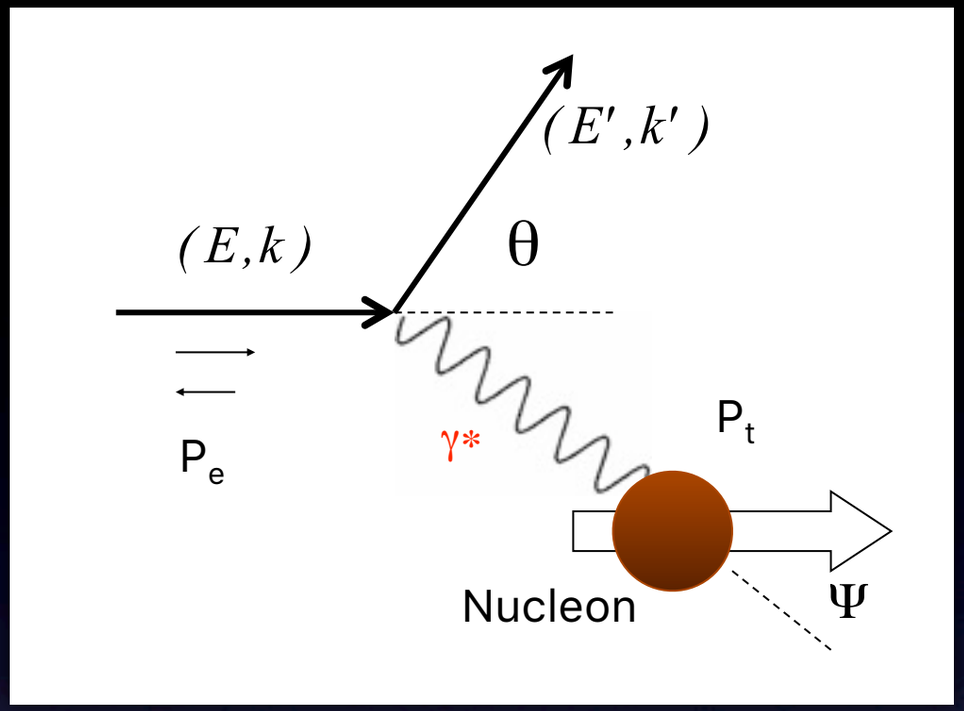
arXiv:1706.10289

Determination of the Proton Spin Structure Functions for $0.05 < Q^2 < 5$ GeV^2 using CLAS

R.G. Fersch,[7] N. Guler,[29] P. Bosted,[36] A. Deur,[36] K. Griffioen,[42] C. Keith,[36] S.E. Kuhn,[29] R. Minehart,[41] Y. Prok,[29] K.P. Adhikari,[25] Z. Akbar,[12] M.J. Amaryan,[29] S. Anefalos Pereira,[17] G. Asryan,[43] H. Avakian,[36,17] J. Ball,[6] I. Balossino,[16] N.A. Baltzell,[36] M. Battaglieri,[18] I. Bedlinskiy,[22] A.S. Biselli,[9,4] W.J. Briscoe,[14] W.K. Brooks,[37,36] S. Bültmann,[29] V.D. Burkert,[36] Frank Thanh Cao,[8] D.S. Carman,[36] A. Celentano,[18] S. Chandavar,[28] G. Charles,[29] T. Chetry,[28] G. Ciullo,[16,10] L. Clark,[39] L. Colaneri,[8] P.L. Cole,[15,36] N. Compton,[28] M. Contalbrigo,[16] O. Cortes,[15] V. Crede,[12] A. D'Angelo,[19,32] N. Dashyan,[43] R. De Vita,[18] E. De Sanctis,[17] C. Djalali,[34] G.E. Dodge,[29] R. Dupre,[21] H. Egiyan,[36,42] A. El Alaoui,[37] L. El Fassi,[25] L. Elouadrhiri,[36] P. Eugenio,[12] E. Fanchini,[18] G. Fedotov,[34,33] A. Filippi,[20] J.A. Fleming,[38] T.A. Forest,[15] M. Garc con,[6] G. Gavalian,[36,26] Y. Ghandilyan,[43] G.P. Gilfoyle,[31] K.L. Giovanetti,[23] F.X. Girod,[36,6] C. Gleason,[34] E. Golovatch,[33] R.W. Gothe,[34] M. Guidal,[21] L. Guo,[11,36] K. Hafidi,[1] H. Hakobyan,[37,43] C. Hanretty,[36] N. Harrison,[36] D. Heddle,[7,36] K. Hicks,[28] M. Holtrop,[26] S.M. Hughes,[38] Y. Ilieva,[34,14] D.G. Ireland,[39] B.S. Ishkhanov,[33] E.L. Isupov,[33] D. Jenkins,[40] D. Keller,[41] G. Khachatryan,[43] M. Khachatryan,[29] M. Khandaker,[27,*] A. Kim,[8] W. Kim,[24] A. Klein,[29] F.J. Klein,[5] V. Kubarovsky,[36,30] V.G. Lagerquist,[29] L. Lanza,[19] P. Lenisa,[16] K. Livingston,[39] H.Y. Lu,[34] B. McKinnon,[39] C.A. Meyer,[4] M. Mirazita,[17] V. Mokeev,[36,33] R.A. Montgomery,[39] A Movsisyan,[16] C. Munoz Camacho,[21] G. Murdoch,[39] P. Nadel-Turonski,[36] S. Niccolai,[21] G. Niculescu,[23] I. Niculescu,[23] M. Osipenko,[18] A.I. Ostrovidov,[12] M. Paolone,[35] R. Paremuzyan,[26] K. Park,[36,24] E. Pasyuk,[36,2] W. Phelps,[11] S. Pisano,[17] O. Pogorelko,[22] J.W. Price,[3] D. Protopopescu,[26,†] B.A. Raue,[11,36] M. Ripani,[18] D. Riser,[8] A. Rizzo,[19,32] G. Rosner,[39] P. Rossi,[36,17] P. Roy,[12] F. Sabatié,[6] C. Salgado,[27] R.A. Schumacher,[4] Y.G. Sharabian,[36] A. Simonyan,[43] Iu. Skorodumina,[34,33] G.D. Smith,[38] D. Sokhan,[39] N. Sparveris,[35] I. Stankovic,[38] S. Stepanyan,[36] I.I. Strakovsky,[14] S. Strauch,[34] M. Taiuti,[13,‡] Ye Tian,[34] B. Torayev,[29] M. Ungaro,[36,30] H. Voskanyan,[43] E. Voutier,[21] N.K. Walford,[5] X. Wei,[36] L.B. Weinstein,[29] N. Zachariou,[38] and J. Zhang[36,29]

(The CLAS Collaboration)

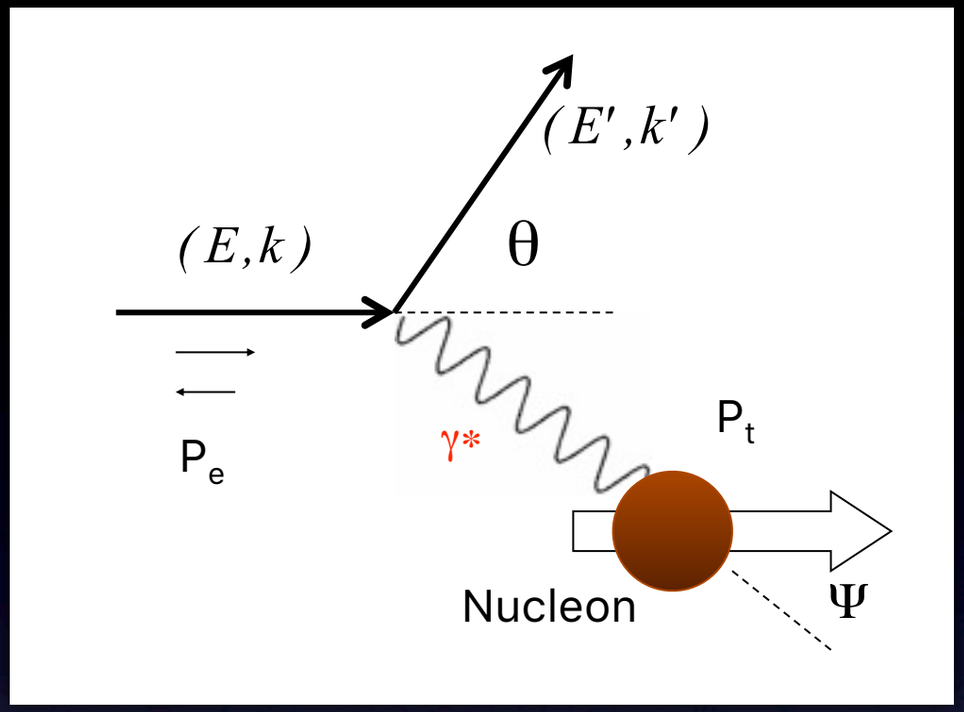
Analysis of Polarized Inclusive *ep* scattering



Double spin asymmetry
between + (↑↑,↓↓) and – (↑↓,↓↑)
beam and target polarizations

$$A_{\parallel} = \frac{1}{P_b P_t F_{DF}} \frac{n^+ - n^-}{n^+ + n^-}$$

Analysis of Polarized Inclusive *ep* scattering

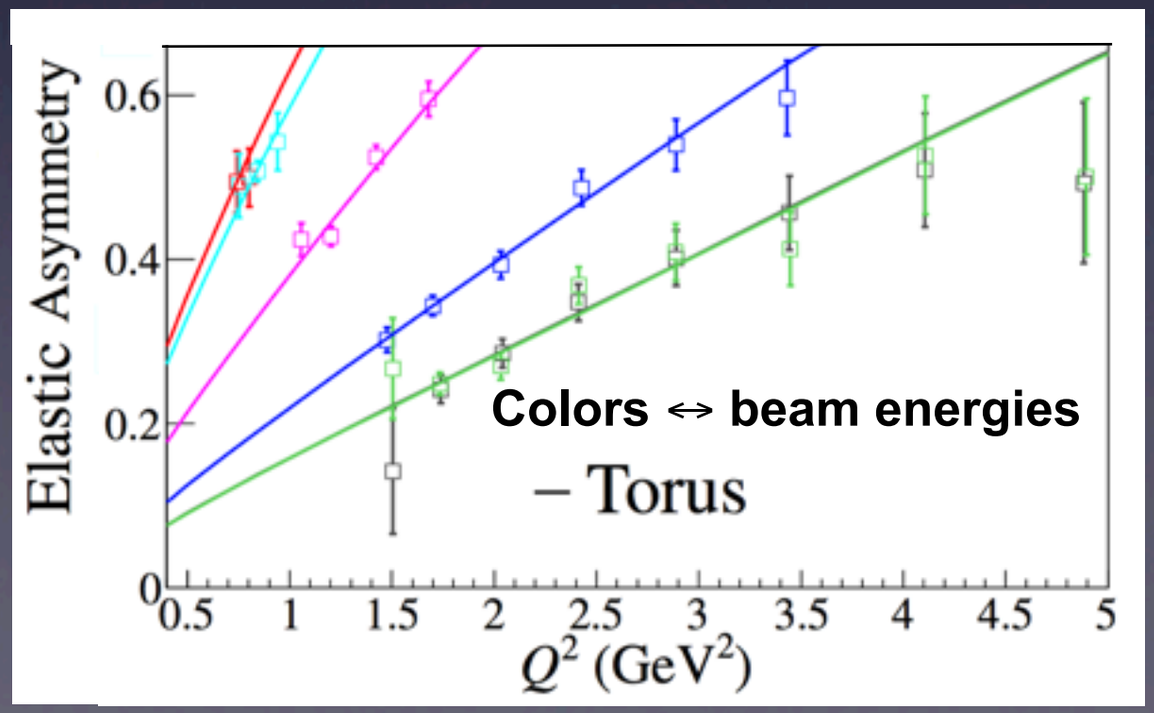


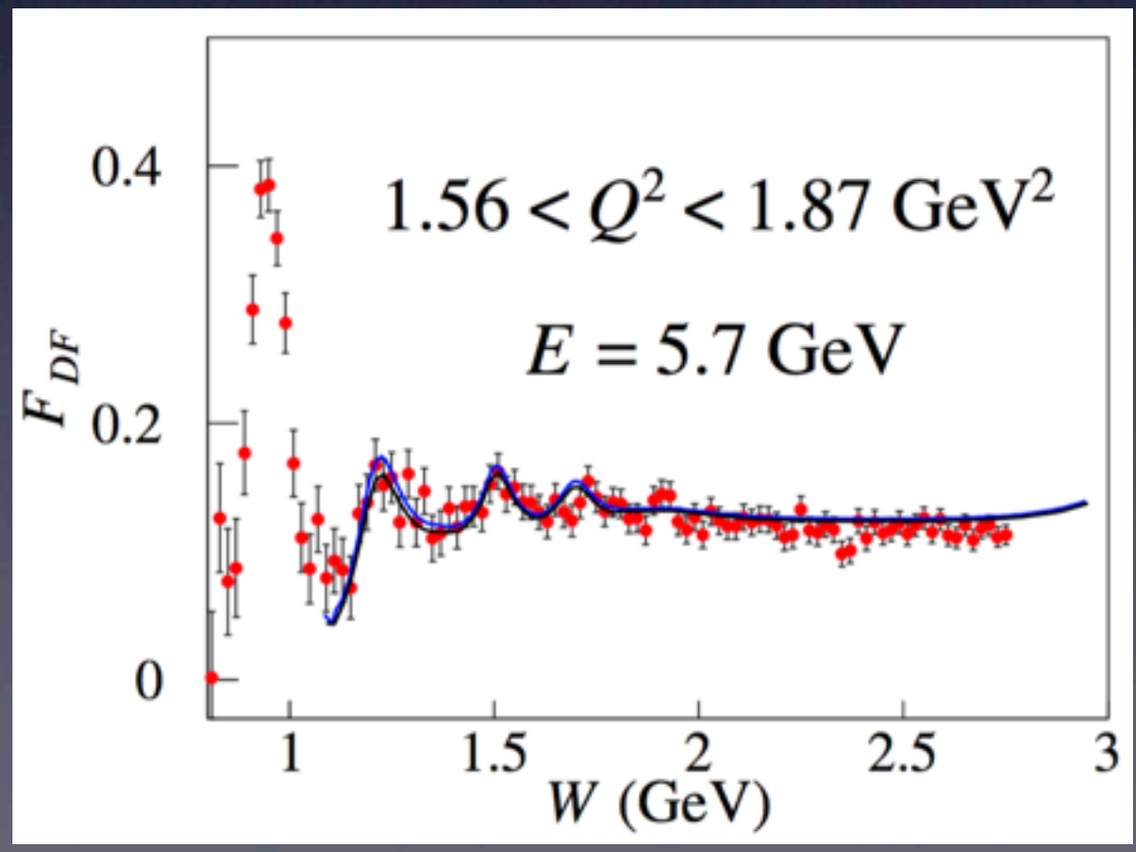
Double spin asymmetry between + (↑↑,↓↓) and – (↑↓,↓↑) beam and target polarizations

$$A_{\parallel} = \frac{1}{P_b P_t F_{DF}} \frac{n^+ - n^-}{n^+ + n^-}$$

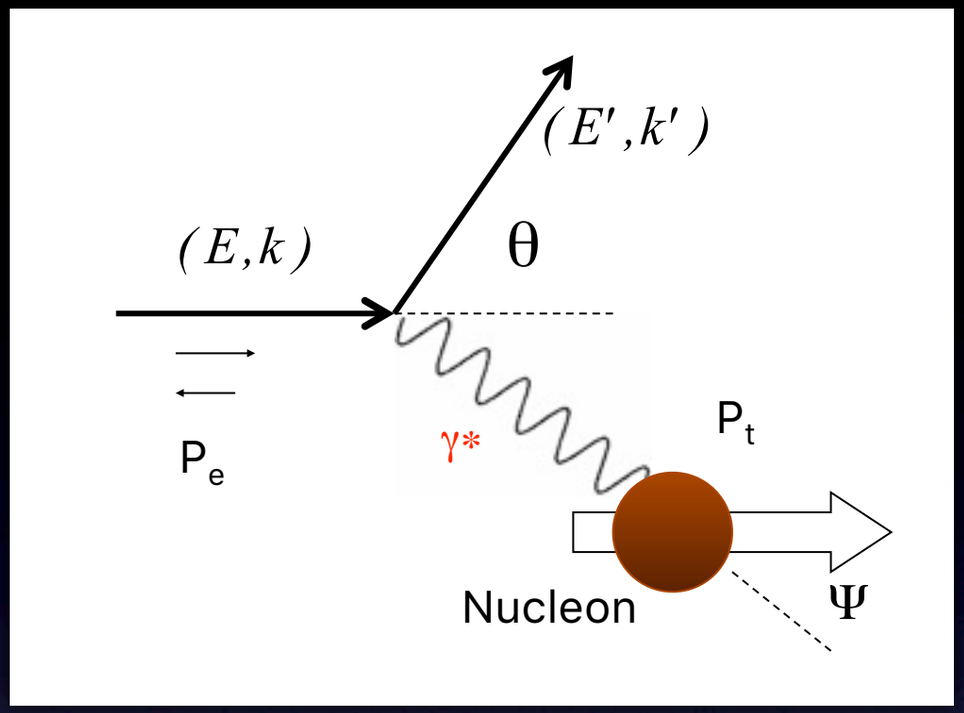
Polarization product from elastic asymmetry normalization to global data (polarized background)

Dilution factor from 12C, LHe runs and radiated cross section model (unpolarized background)





Analysis of Polarized Inclusive *ep* scattering



Double spin asymmetry
between + (↑↑,↓↓) and – (↑↓,↓↑)
beam and target polarizations

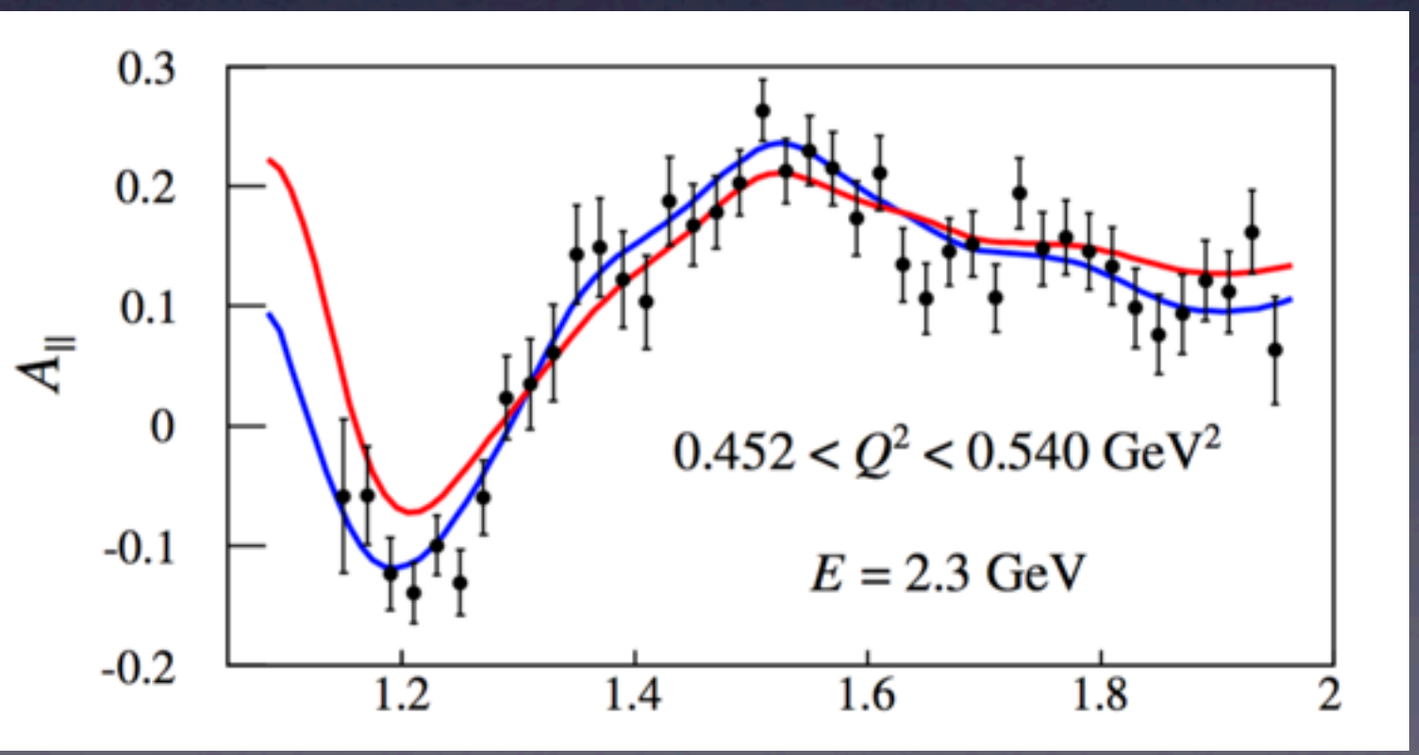
$$A_{\parallel} = \frac{1}{P_b P_t F_{DF}} \frac{n^+ - n^-}{n^+ + n^-}$$

Physics quantities

virtual photon asymmetries A_1 and A_2

$$A_{||}(\nu, Q^2) = D[A_1(\nu, Q^2) + \eta A_2(\nu, Q^2)]$$

Radiative corrections **(difference between red, blue lines)** (also nuclear polarization and e^+e^- corrections)



spin structure functions g_1 and g_2

$$\frac{A_{||}}{D} = (1 + \eta\gamma)\frac{g_1}{F_1} + \gamma(\eta - \gamma)\frac{g_2}{F_1}$$

(kinematics/models)

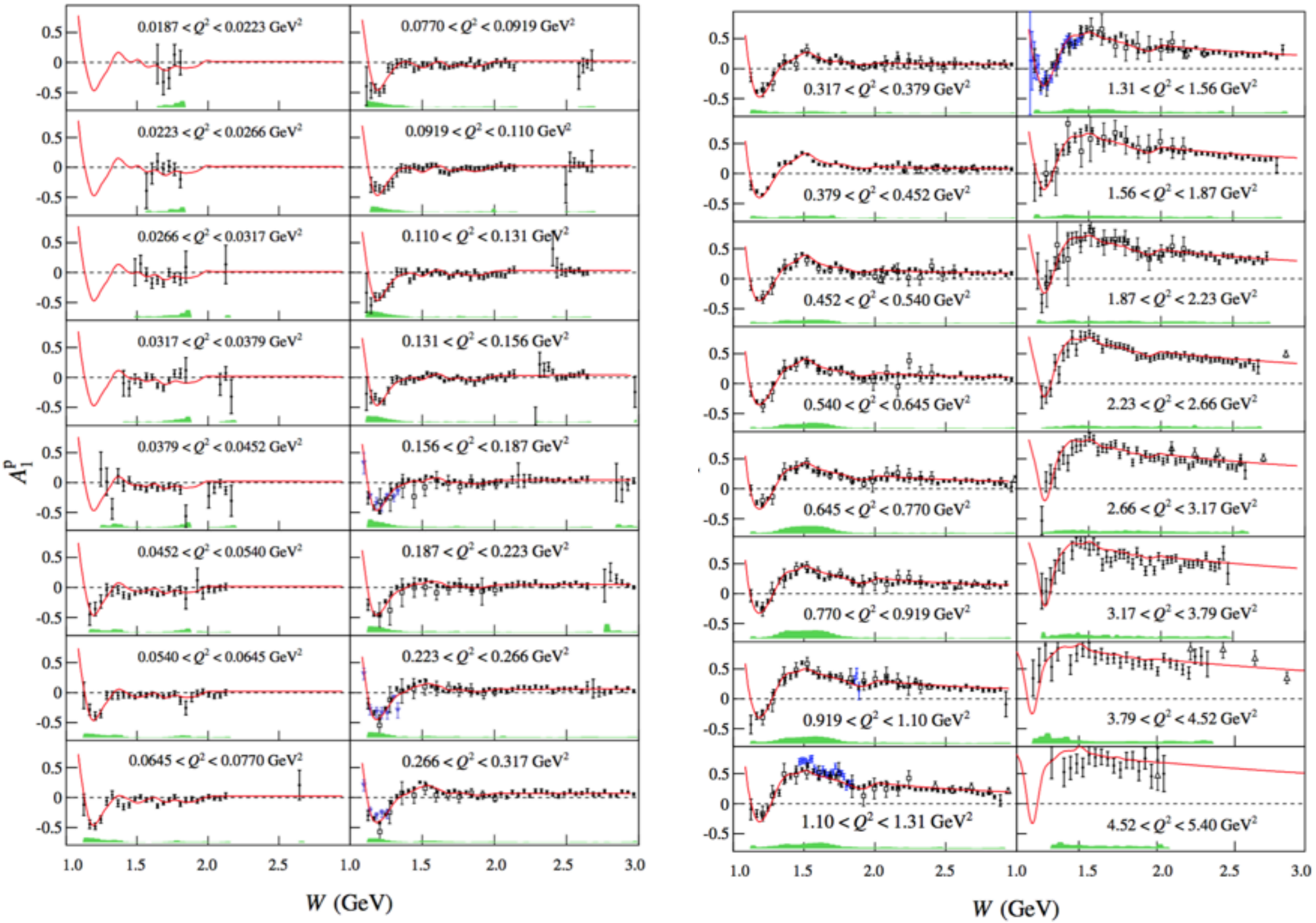
$$D = \frac{1 - E'\varepsilon / E}{1 + \varepsilon R}; \quad \eta = \frac{\varepsilon\sqrt{Q^2}}{E - E'\varepsilon} \qquad R = \frac{\sigma_L}{\sigma_T}$$

$$\gamma = \frac{2Mx}{\sqrt{Q^2}}$$

$$A_{||}(\nu, Q^2) = D[A_1(\nu, Q^2) + \eta A_2(\nu, Q^2)]$$

A_1 for the proton shown against world data

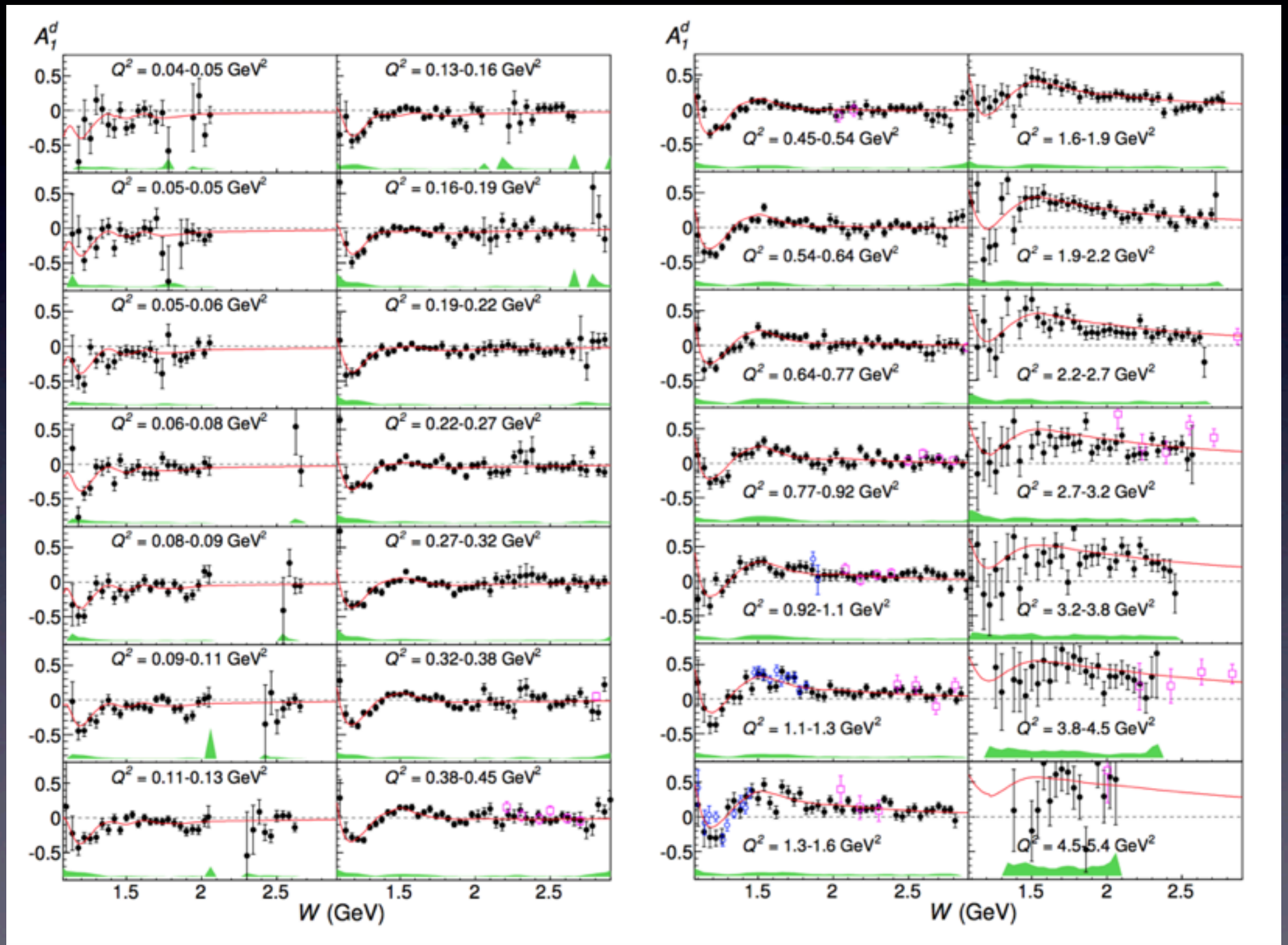
Note coverage in resonance region over wide Q^2



$$A_{||}(\nu, Q^2) = D[A_1(\nu, Q^2) + \eta A_2(\nu, Q^2)]$$

A_1 for the deuteron shown against world data

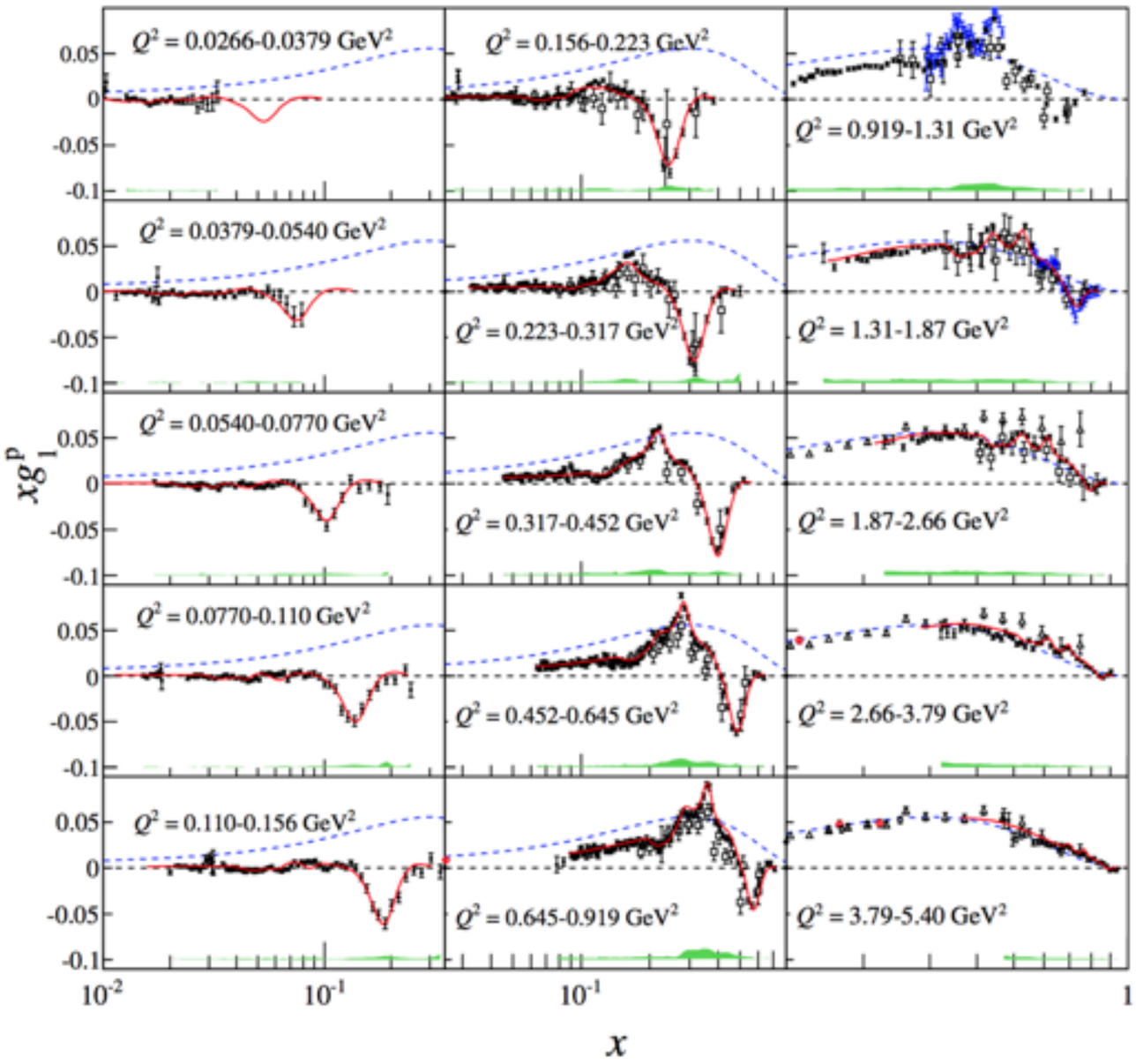
Coverage comparable to that of proton



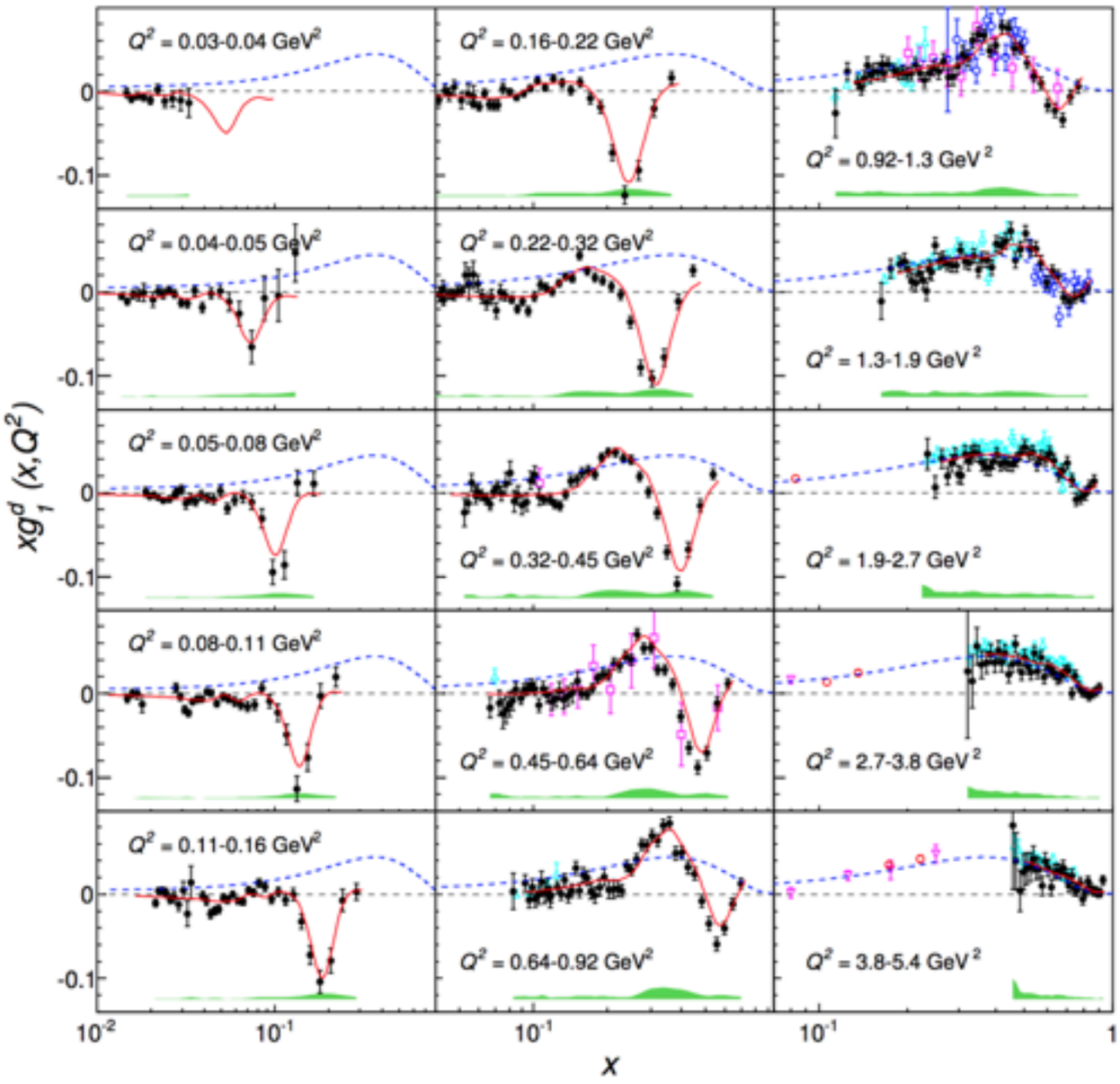
g_1 shown against world data

$$\frac{A_{\parallel}}{D} = (1+\eta\gamma)\frac{g_1}{F_1} + \gamma(\eta-\gamma)\frac{g_2}{F_1}$$

Proton



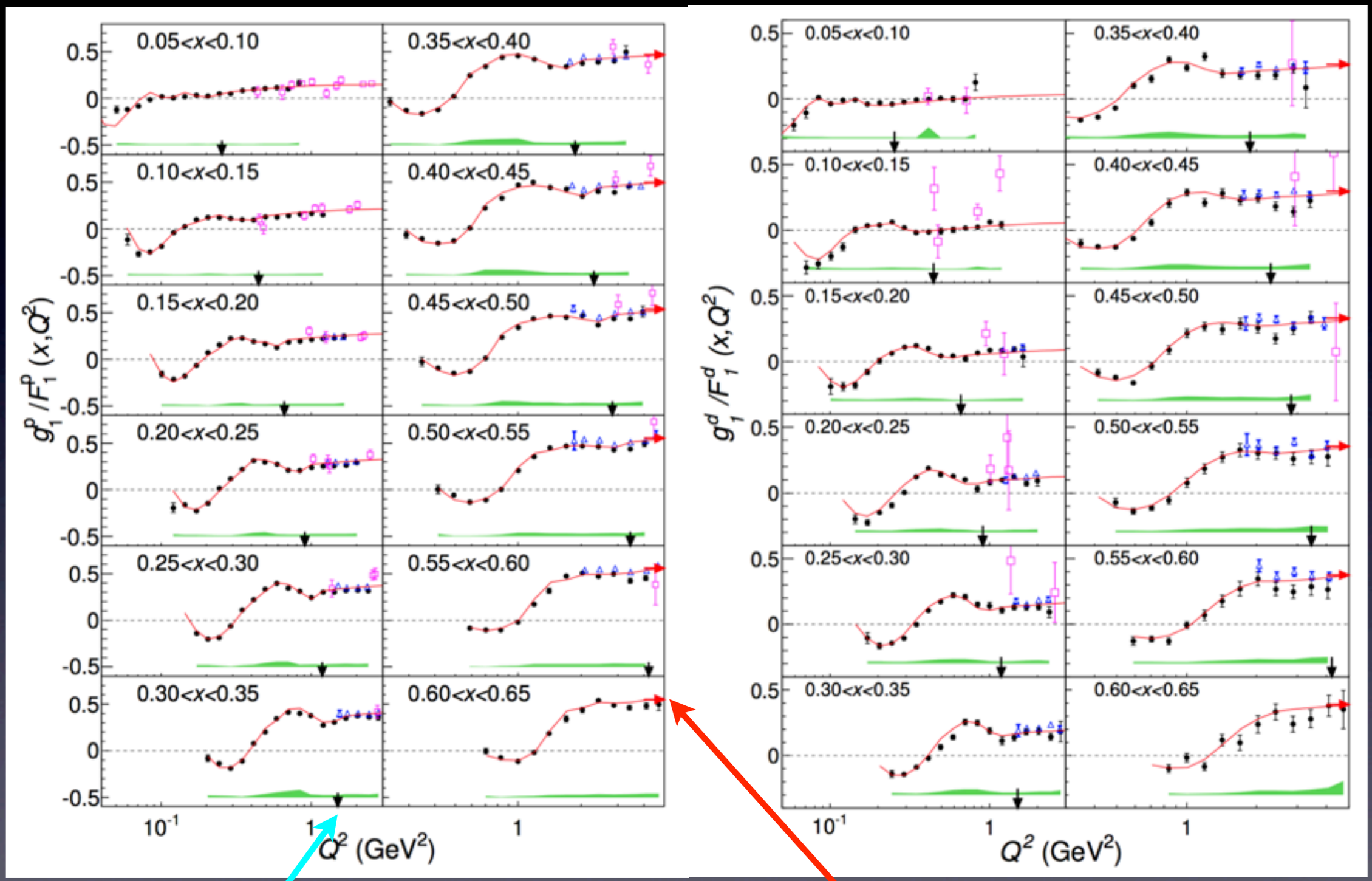
Deuteron



g_1/F_1 vs. Q^2

(shown with E143, EG1-DVCS data)

$$\frac{A_{||}}{D} = (1 + \eta\gamma)\frac{g_1}{F_1} + \gamma(\eta - \gamma)\frac{g_2}{F_1}$$



DIS limit
(W = 2 GeV)

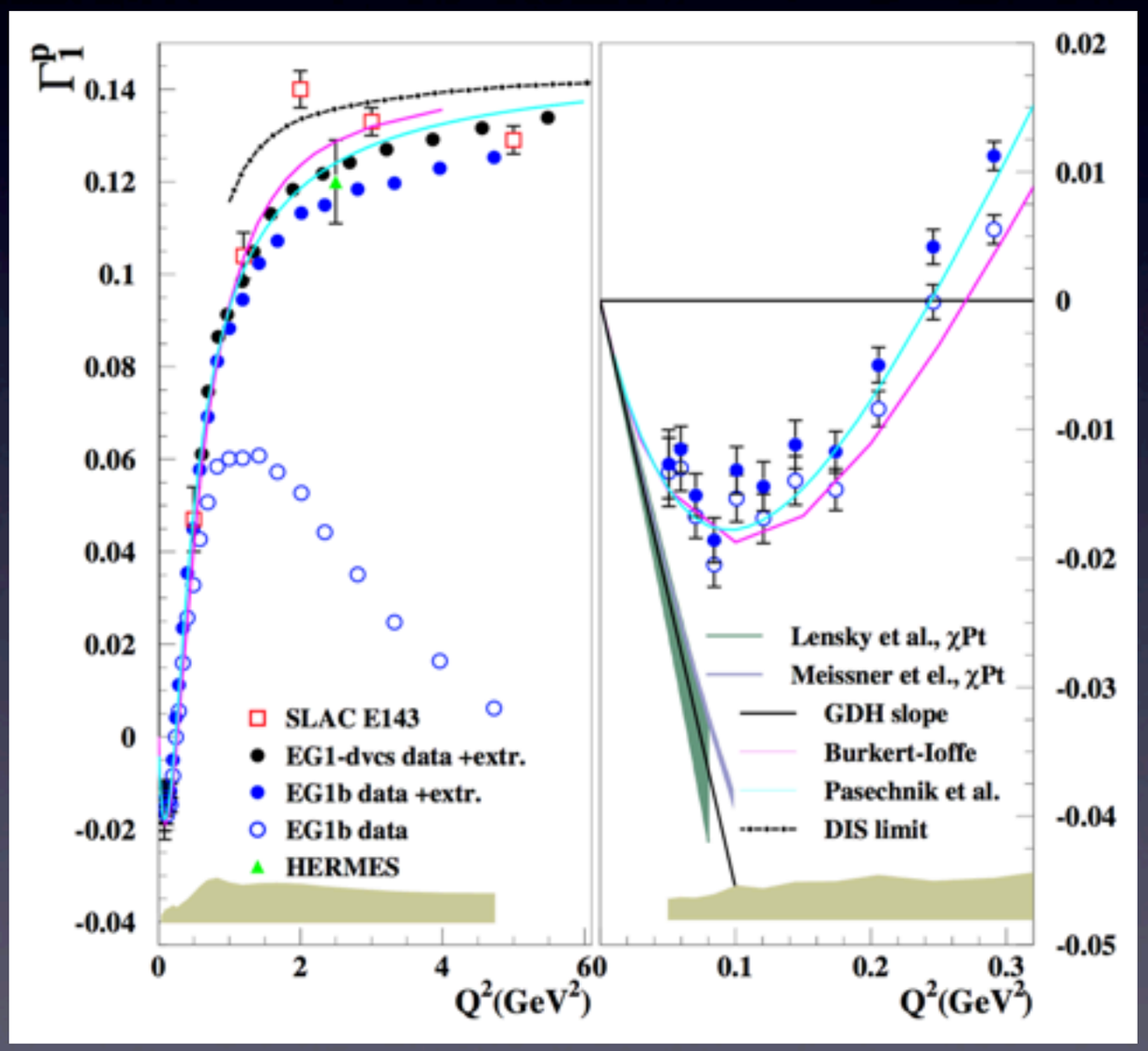
NLO PDF
fit at Q^2 = 5 GeV^2

Moments of g_1

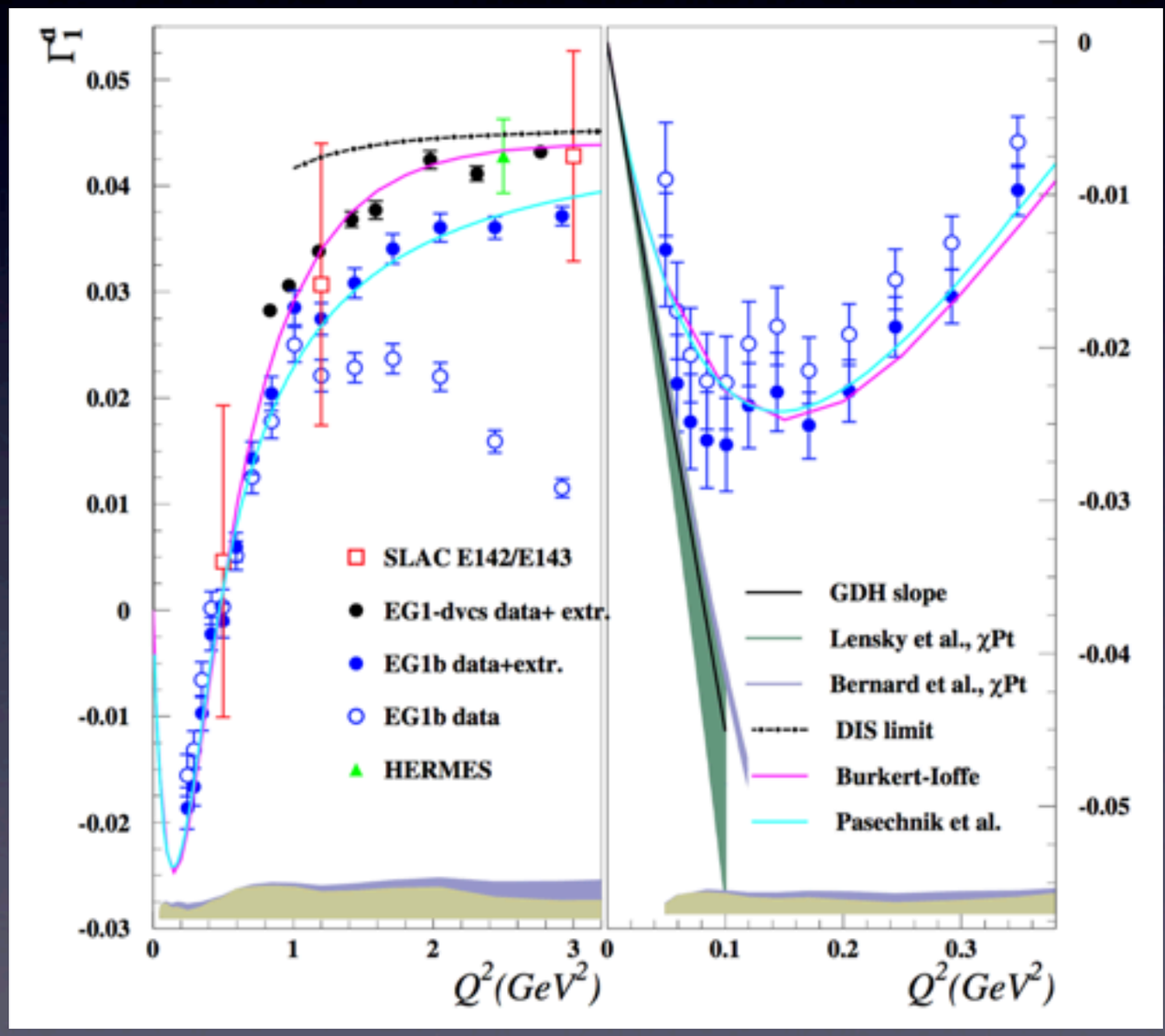
Needed to test *sum rules* and determine matrix elements in the OPE (Operator Product Expansion)

$$\Gamma_1 = \int g_1 \, dx$$ (integrated over x from x=0.001 to elastic threshold)

Proton



Deuteron



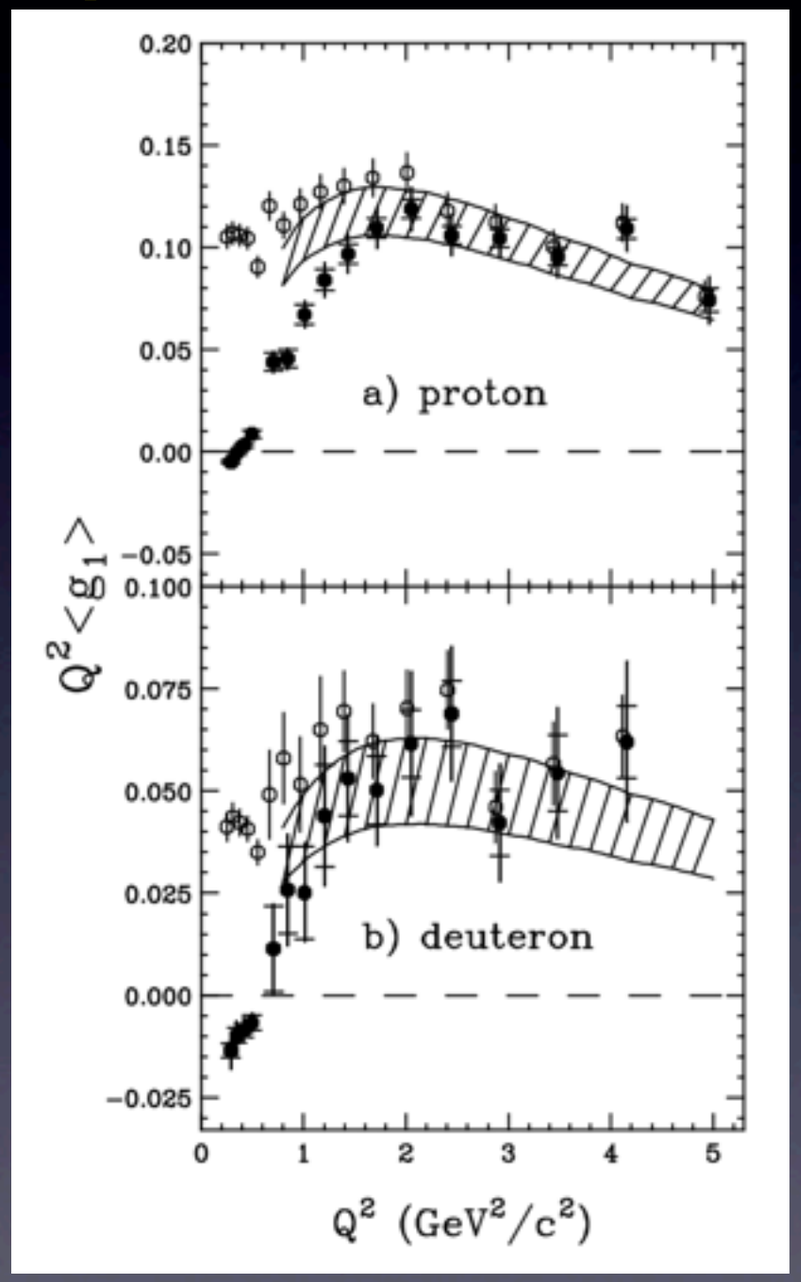
(…"truncated moments" used to test local duality…)

Tests of Bloom-Gillman Duality

Averaging over resonances - comparing to extrapolated NLO PDFs

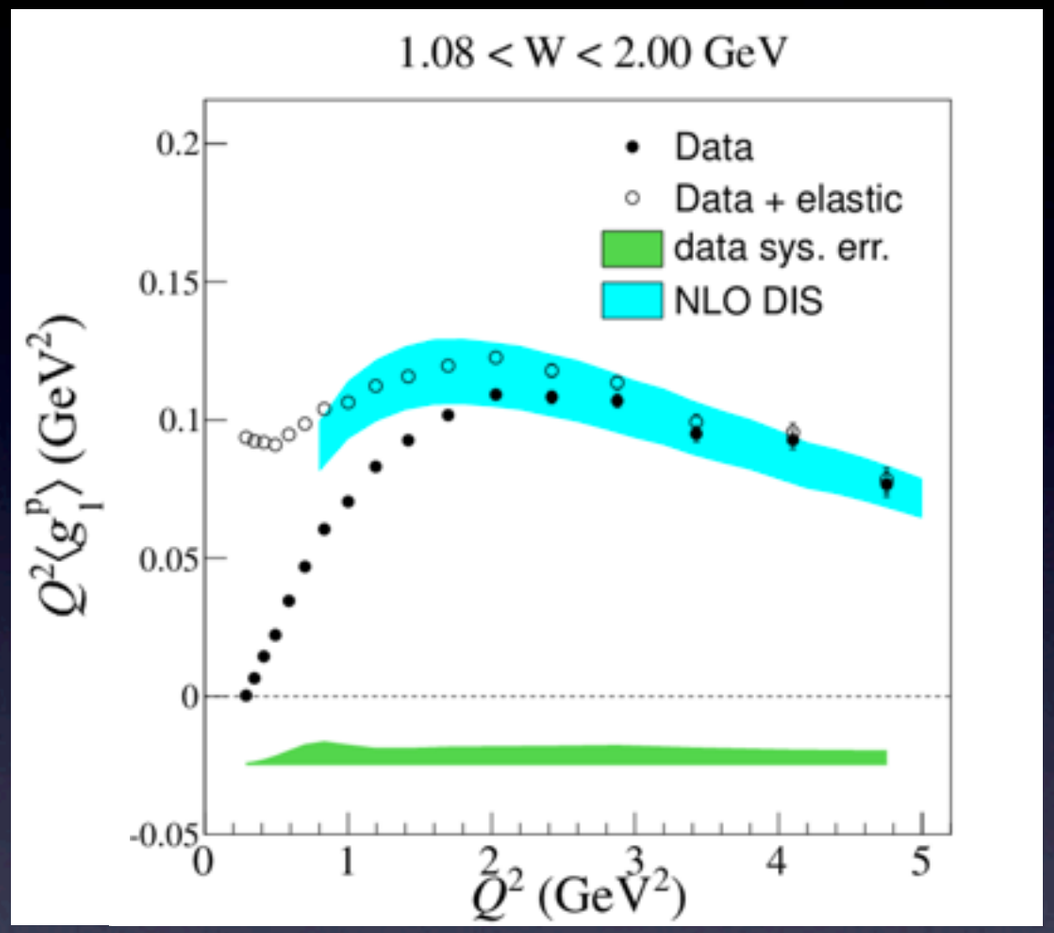
$$< g_1(Q^2) >= \frac{\int_{x_l}^{x_h} g_1(x,Q^2)dx}{x_h - x_l}$$

previous results



1.6, 5.7 GeV results only
(Bosted, *et al.* Phys. Rev. C 75, 035203 (2007))

new proton results



extended analysis including
all 4 beam energies (1.6, 2.5, 4.2, 5.7 GeV)

Parton Distribution Functions:
Determined to NLO, fit to g_{1QCD} above resonance region
Target mass corrections included (Blümlein and Tkbladzke)
10(20)% error for proton(deuteron)
(estimate of high-*x* resummation error)

Tests of Bloom-Gillman Duality

Averaging over resonances - comparing to extrapolated NLO PDFs

(see also Bosted, *et al.* Phys. Rev. C 75, 035203 (2007))

"local" duality results for the proton

Dominating resonances:

$\Delta(1232)$ $\sigma_{3/2}$

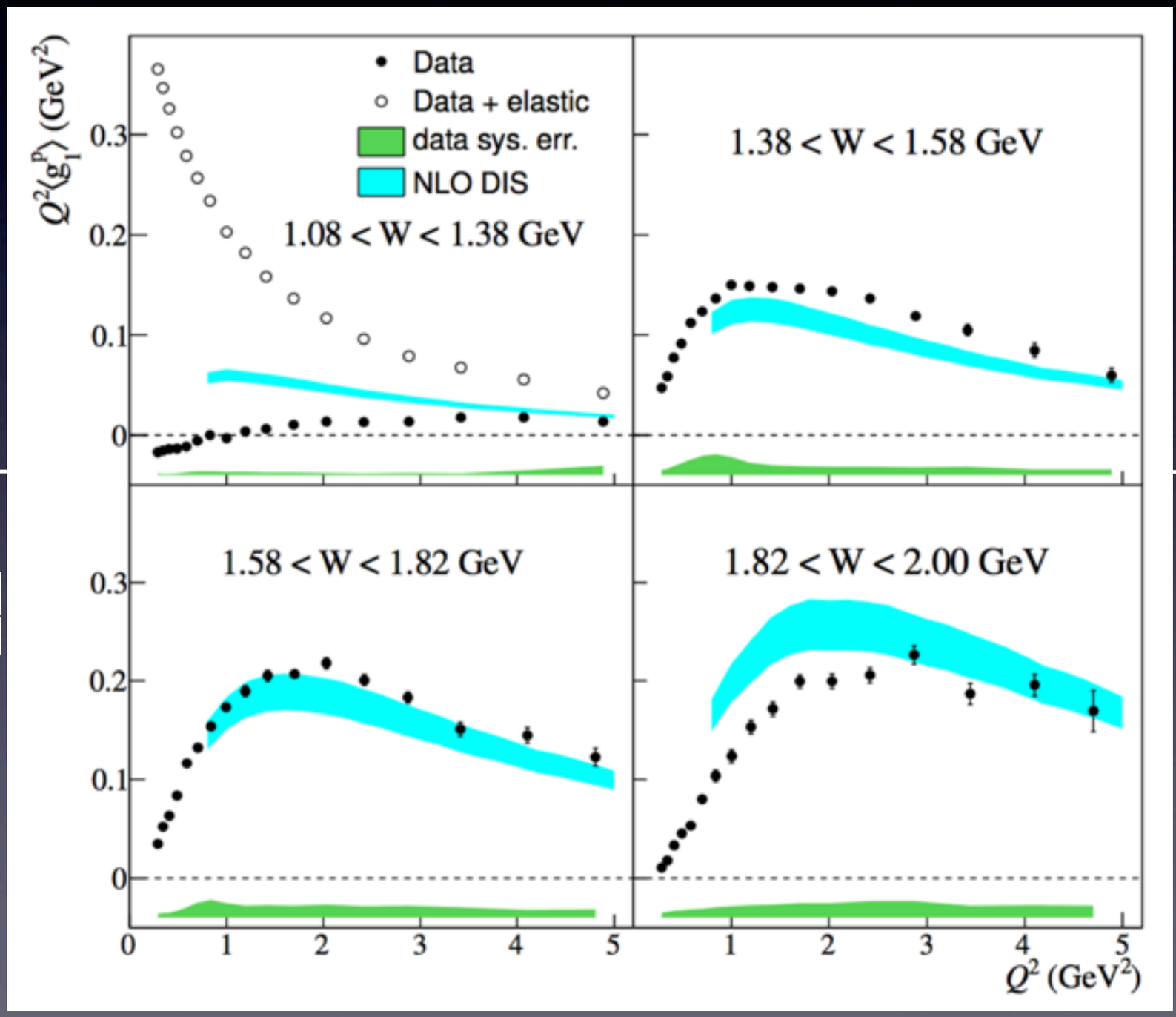
elastic $\sigma_{1/2}$

dominant at low Q^2:

$F_{15}(1680)$ $\sigma_{3/2}$ $\sigma_{1/2}$

at larger Q^2

$S_{11}(1650)$
$S_{31}(1620)$
$D_{33}(1700)$



$P_{11}(1440)$
$S_{11}(1535)$ $\sigma_{1/2}$

$D_{13}(1520)$ $\sigma_{3/2}$ $\sigma_{1/2}$

dominates above Q^2>1

Large number of less well-established resonances

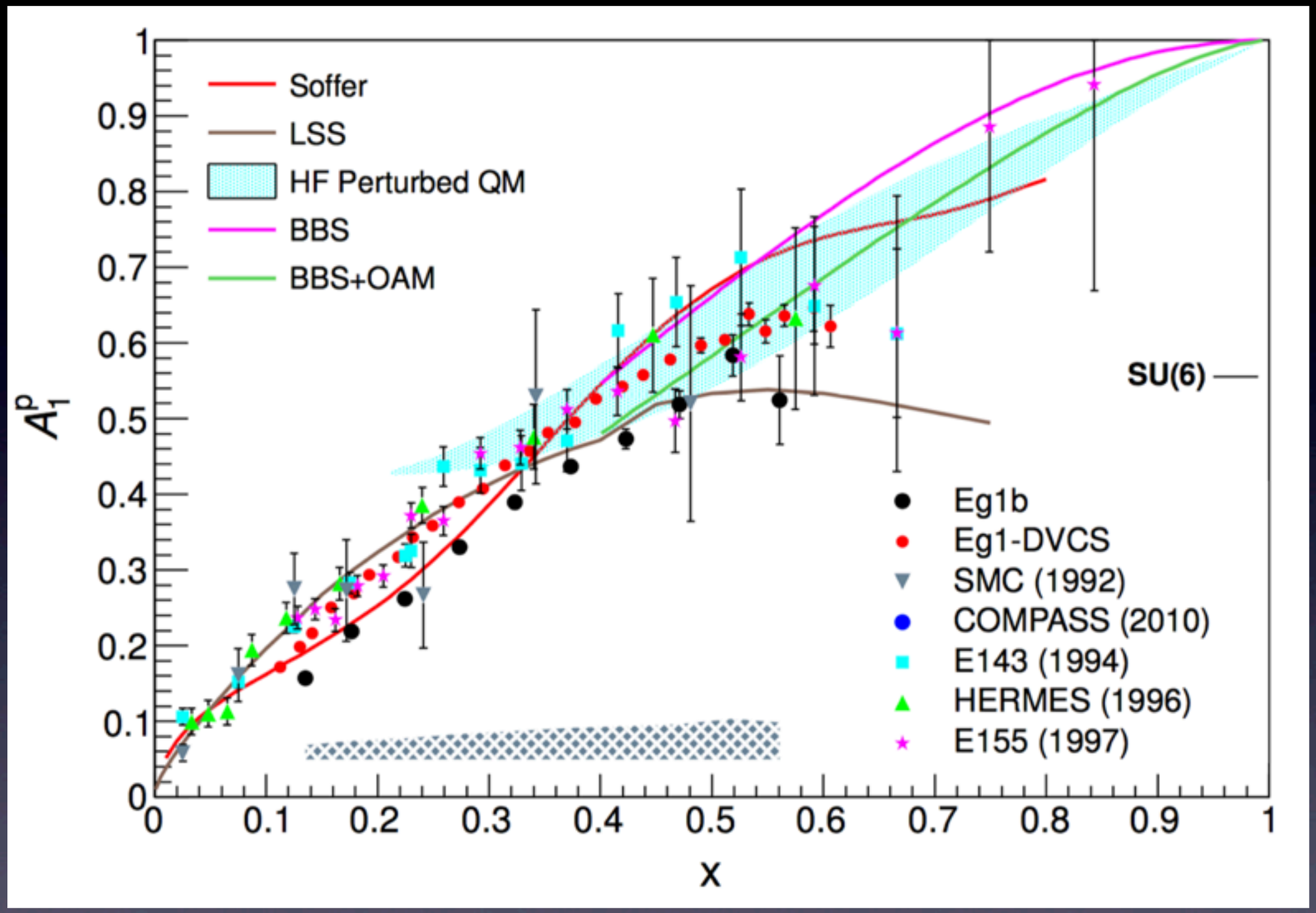
Summary:

The EG1 data set (from Jefferson Laboratory Hall-B) offers by far the most comprehensive data coverage of the g_1 polarized structure function available in the resonance region for the study of quark-hadron duality.

Analyzed data tables from this experiment are now available and pending final publication in Phys. Rev. C.

EXTRA SLIDES

A_1 Deep Inelastic Scattering ($Q^2 > 1$ GeV^2, $W > 2$ GeV)



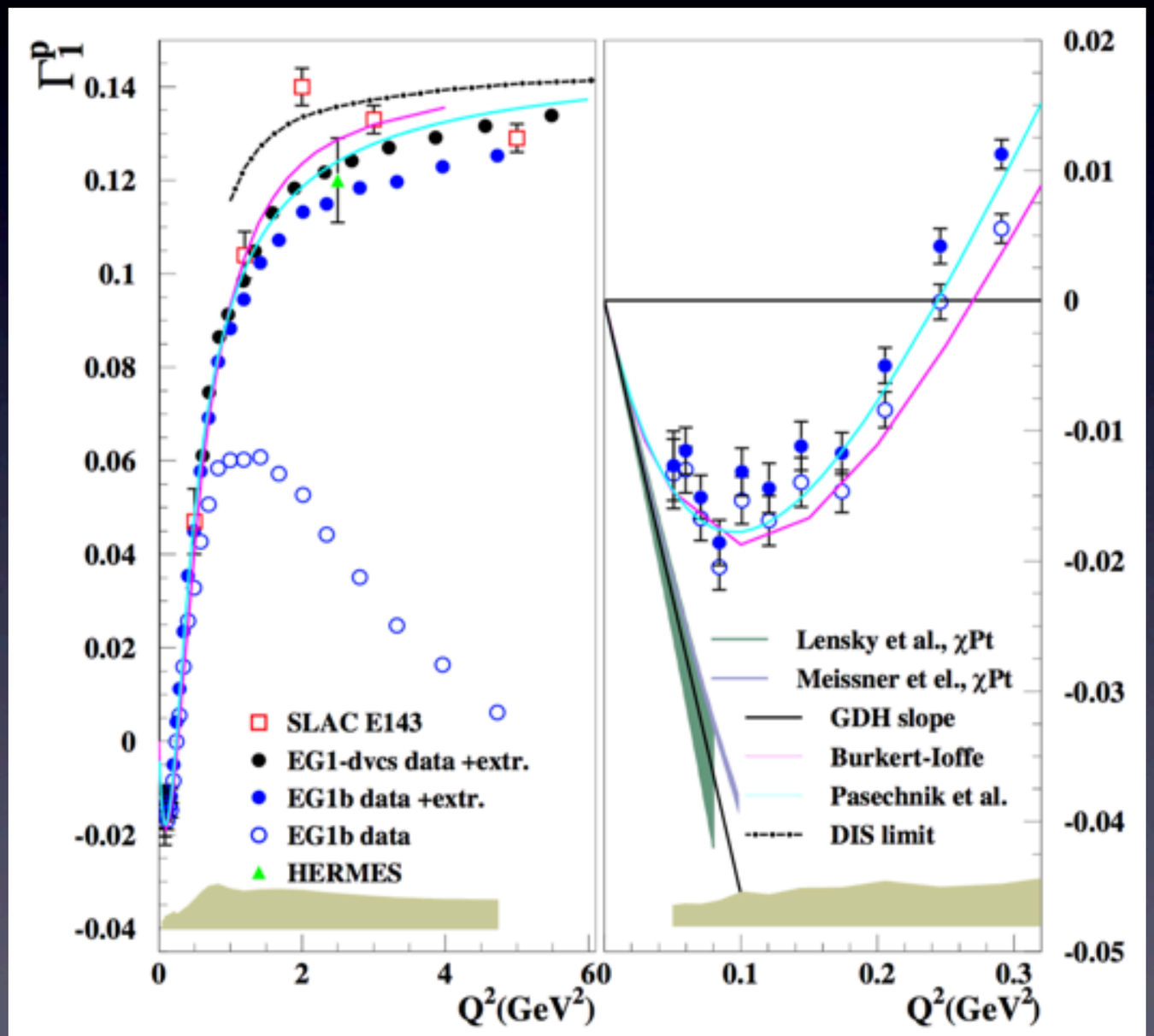
DIS results at high *x* provide insights into QCD models of the nucleon

Moments of g_1

Needed to test *sum rules* and determine matrix elements in the OPE (Operator Product Expansion)

$$\Gamma_1 = \int g_1 \, dx$$ **(integrated over *x* from *x*=0.001 to elastic threshold)**

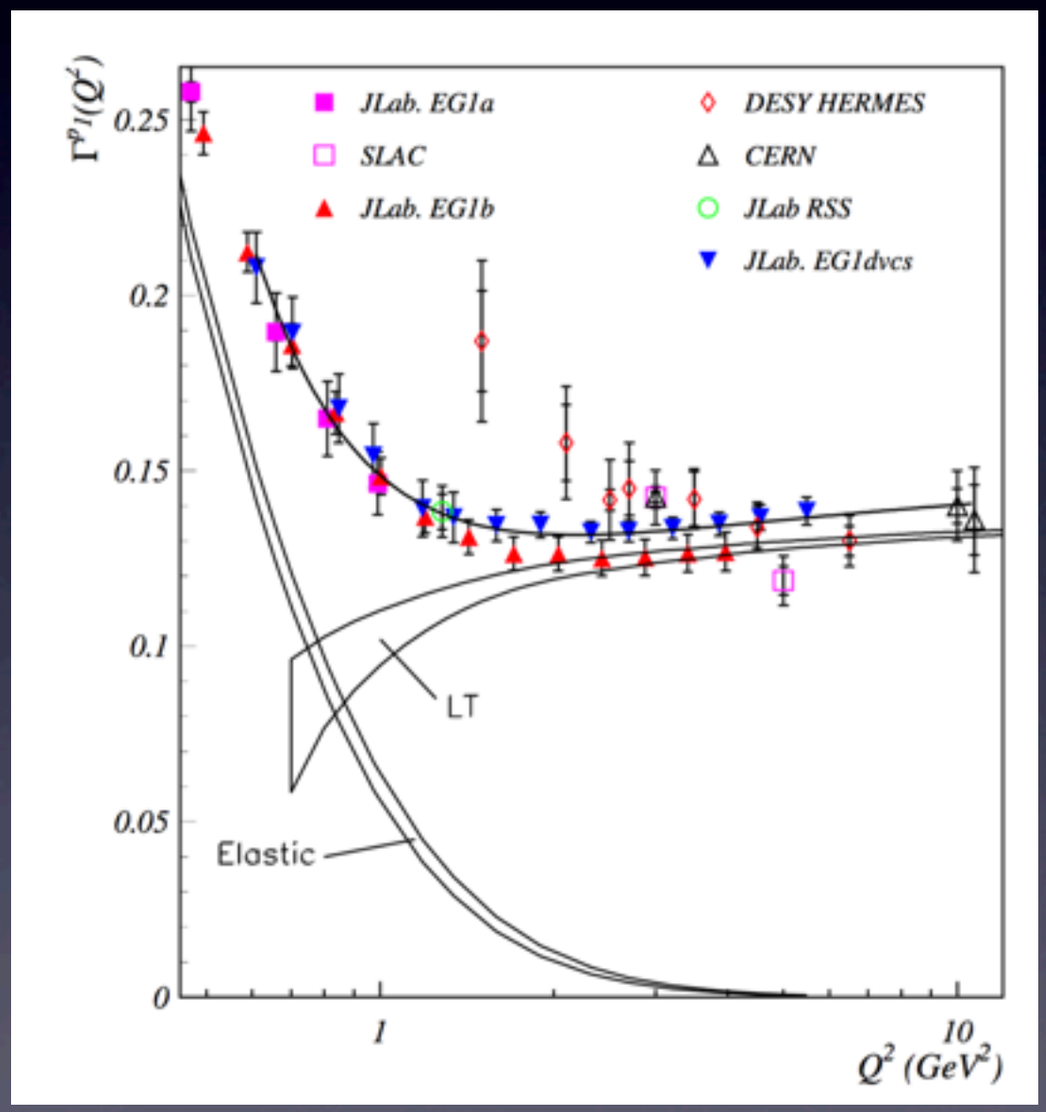
("first moment" of g_1)



see also Prok, *et al.* Phys. Rev. B 672, 12 (2009)

Higher Twist analysis of Γ_1

(includes elastic contribution)



Extraction of higher twist elements through a fit by A. Deur

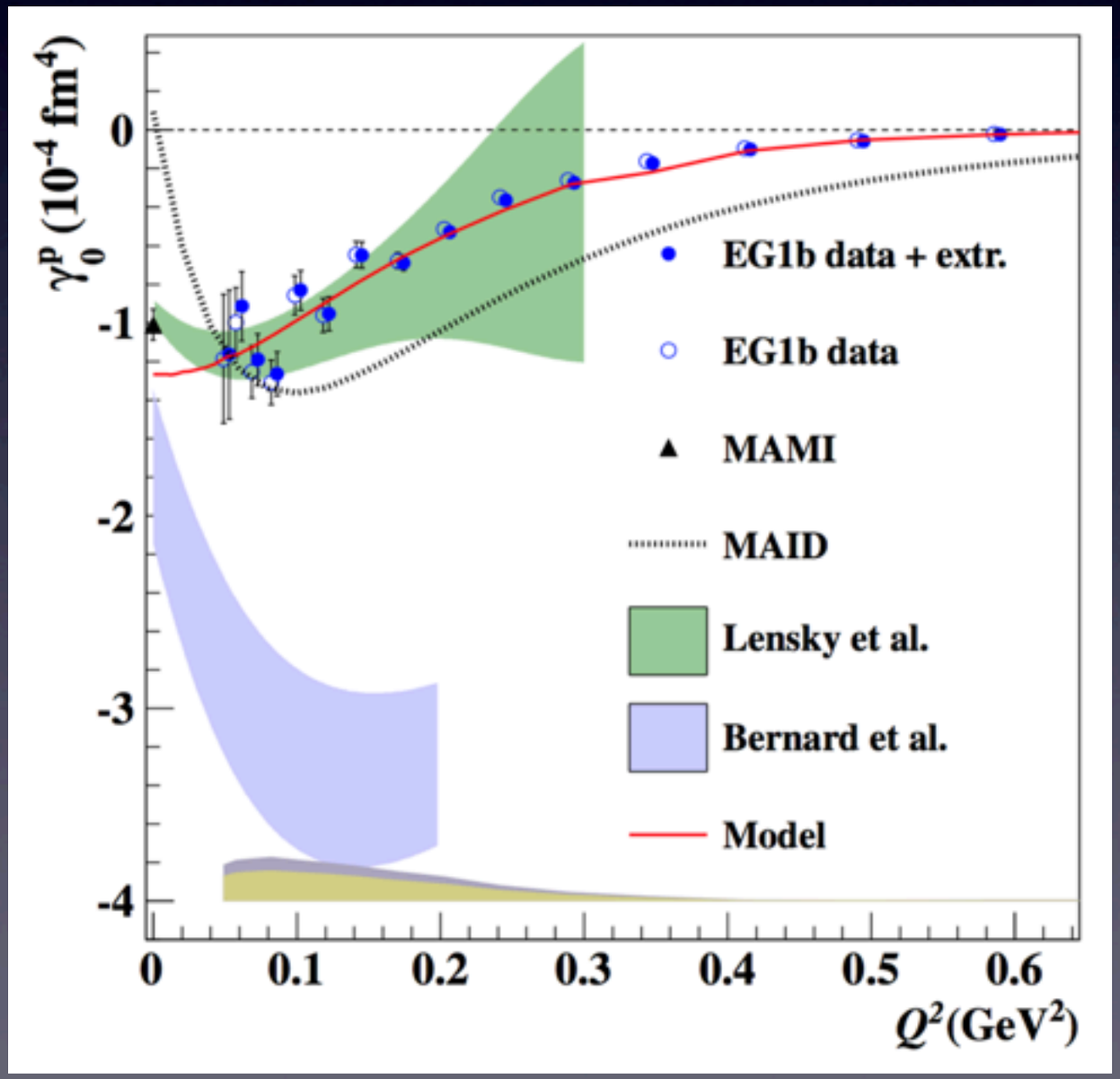
Forward Spin Polarizability

see also Prok, *et al.* Phys. Rev. B 672, 12 (2009)

For scattering cross-sections in terms of Compton amplitudes

$$\gamma_0 = \frac{1}{4\pi}\int_{\nu_{th}}^{\infty}\frac{\sigma_{3/2}-\sigma_{1/2}}{\nu'^3}\,d\nu'$$

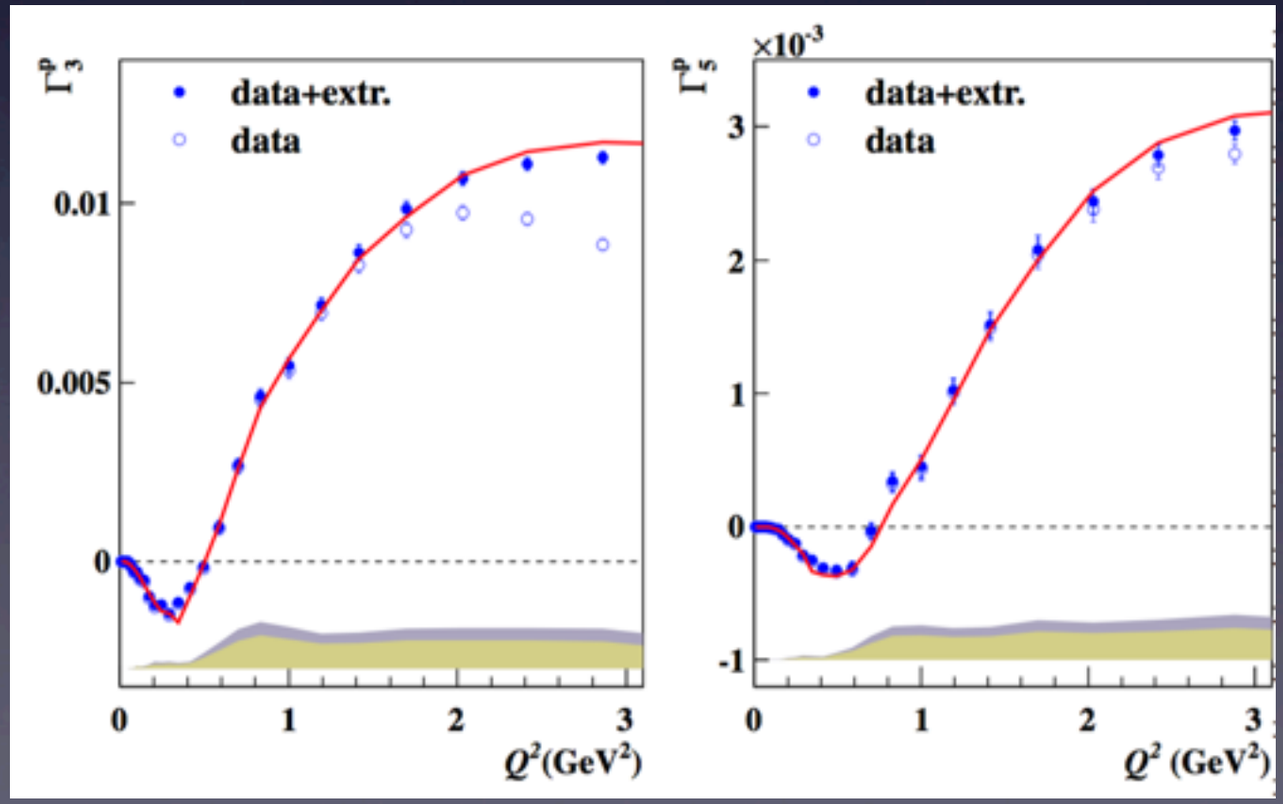
$$= \frac{16M^2\alpha}{Q^6}\int_0^{x_{th}} x^2 A_1(x,Q^2)F_1(x,Q^2)dx$$



Higher Moments

Large *x*-range provided opportunity to measure these

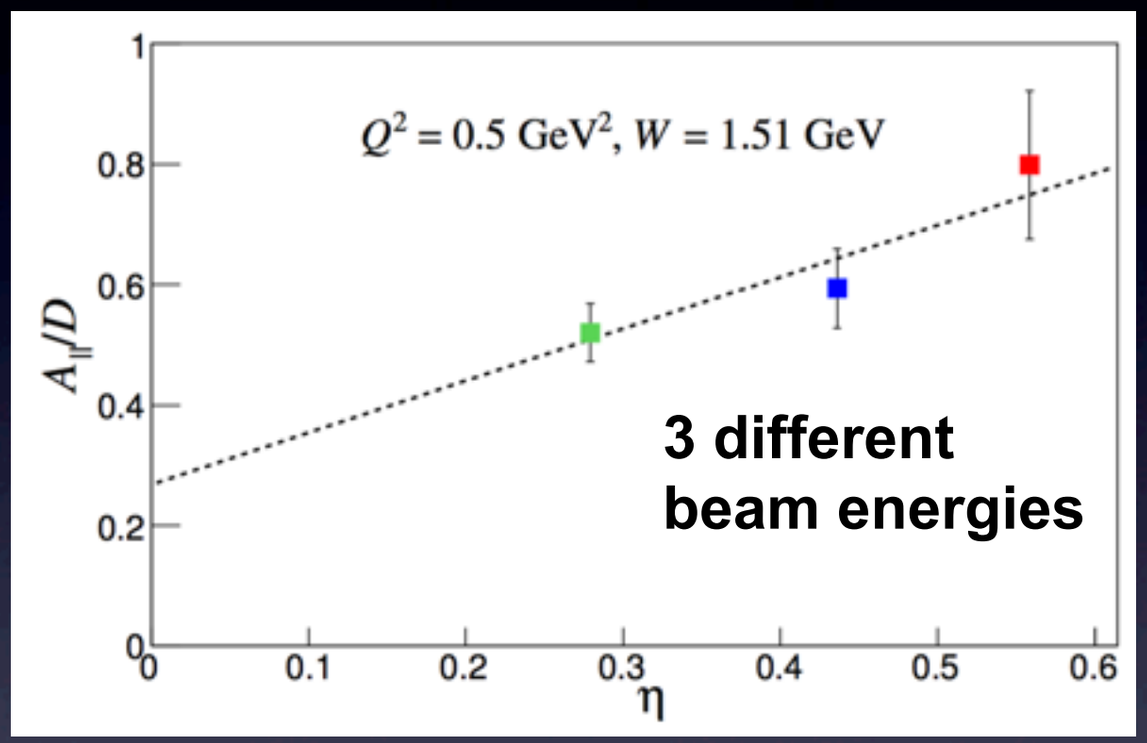
$$\Gamma_1^n = \int x^{n-1} g_1(x,Q^2)dx$$



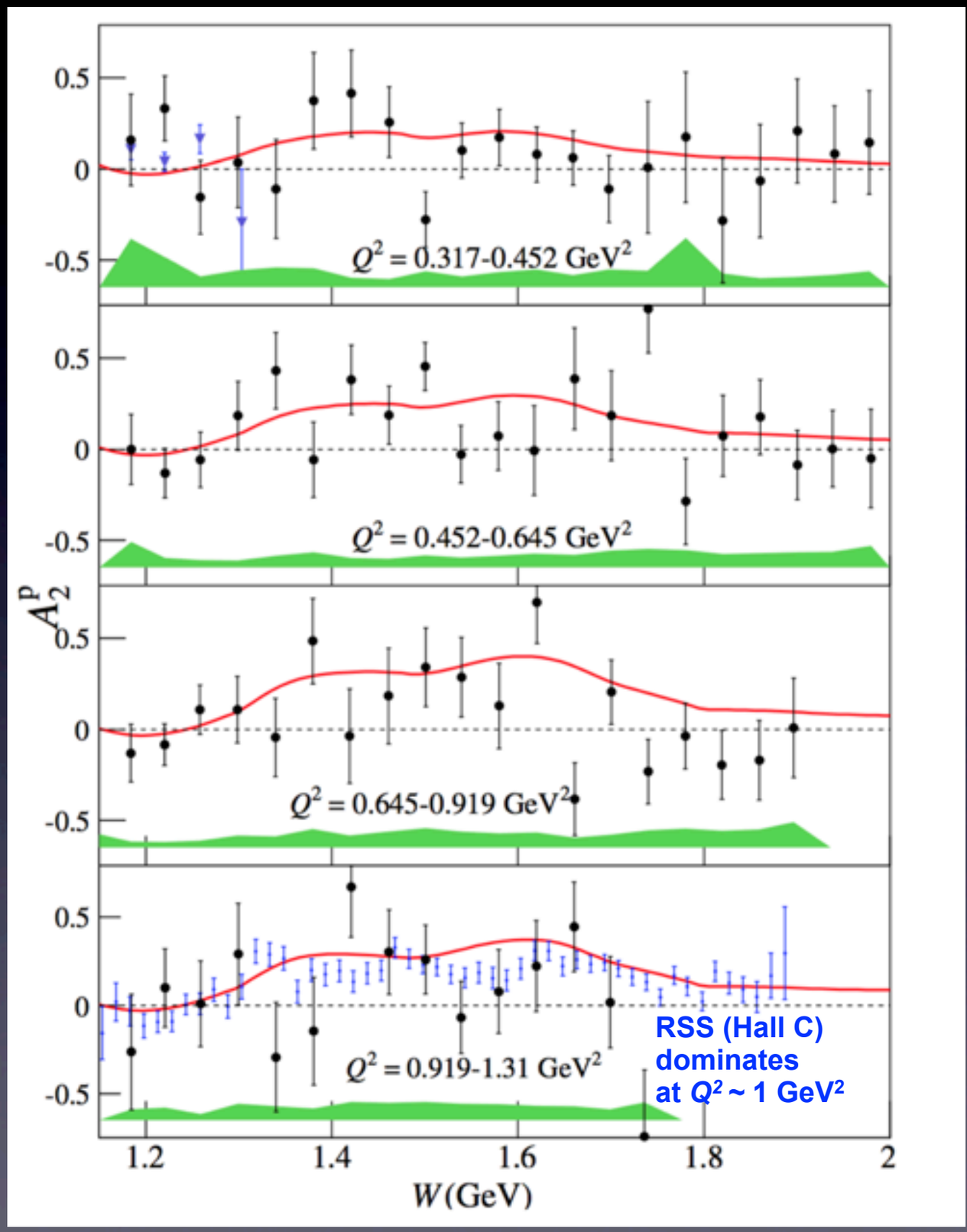
First extraction of A_2 and g_2 from EG1 data

$$A_1 + \eta A_2 = \frac{A_{//}}{D}$$

A_1 = y-intercept,
A_2 = slope



little world data available!

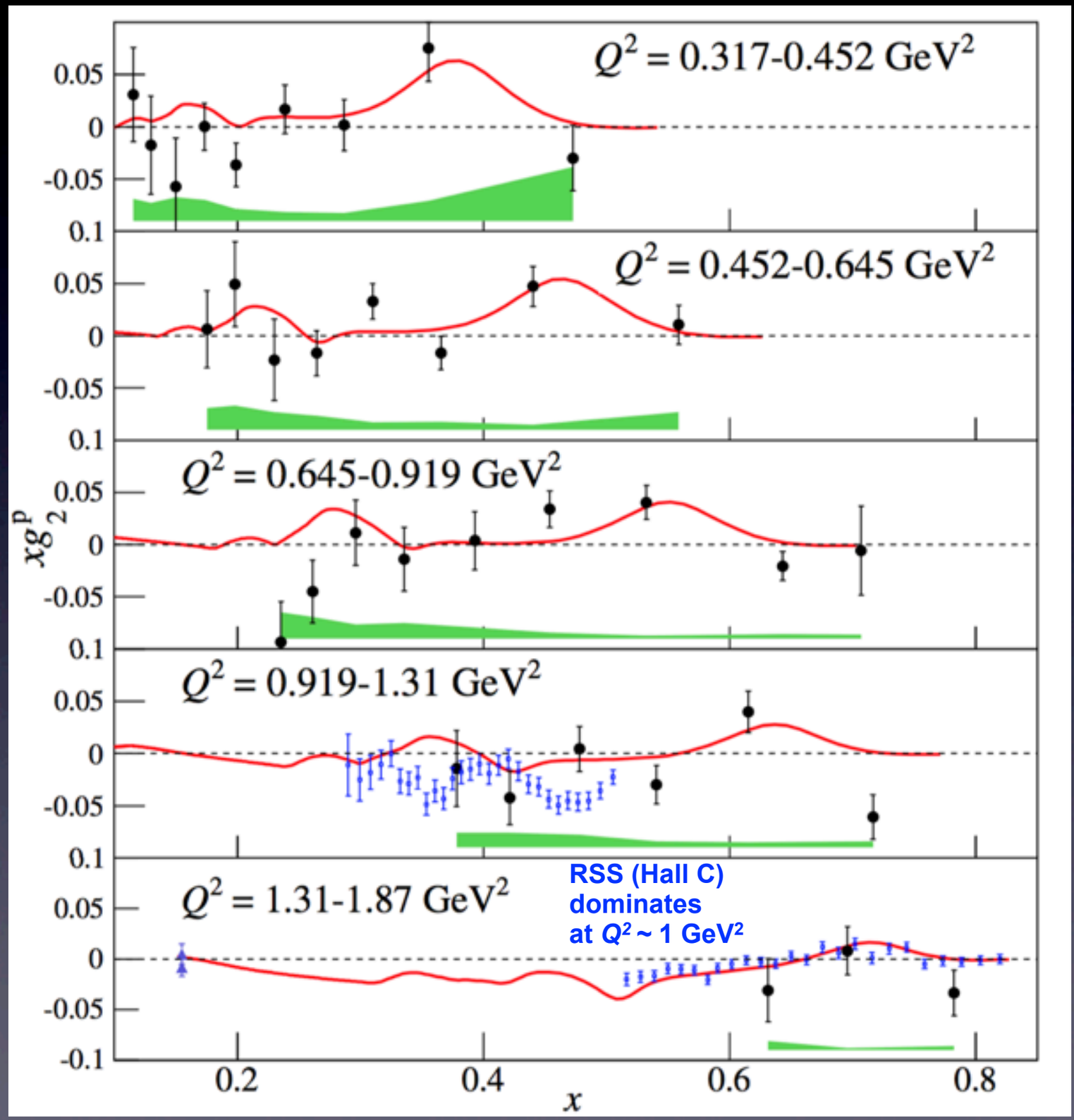


First extraction of A_2 and g_2 from EG1 data

g_2 extracted similarly

$$\frac{A_{||}}{D} = (1+\eta\gamma)\frac{g_1^p}{F_1^p} + \gamma(\eta-\gamma)\frac{g_2^p}{F_1^p}$$

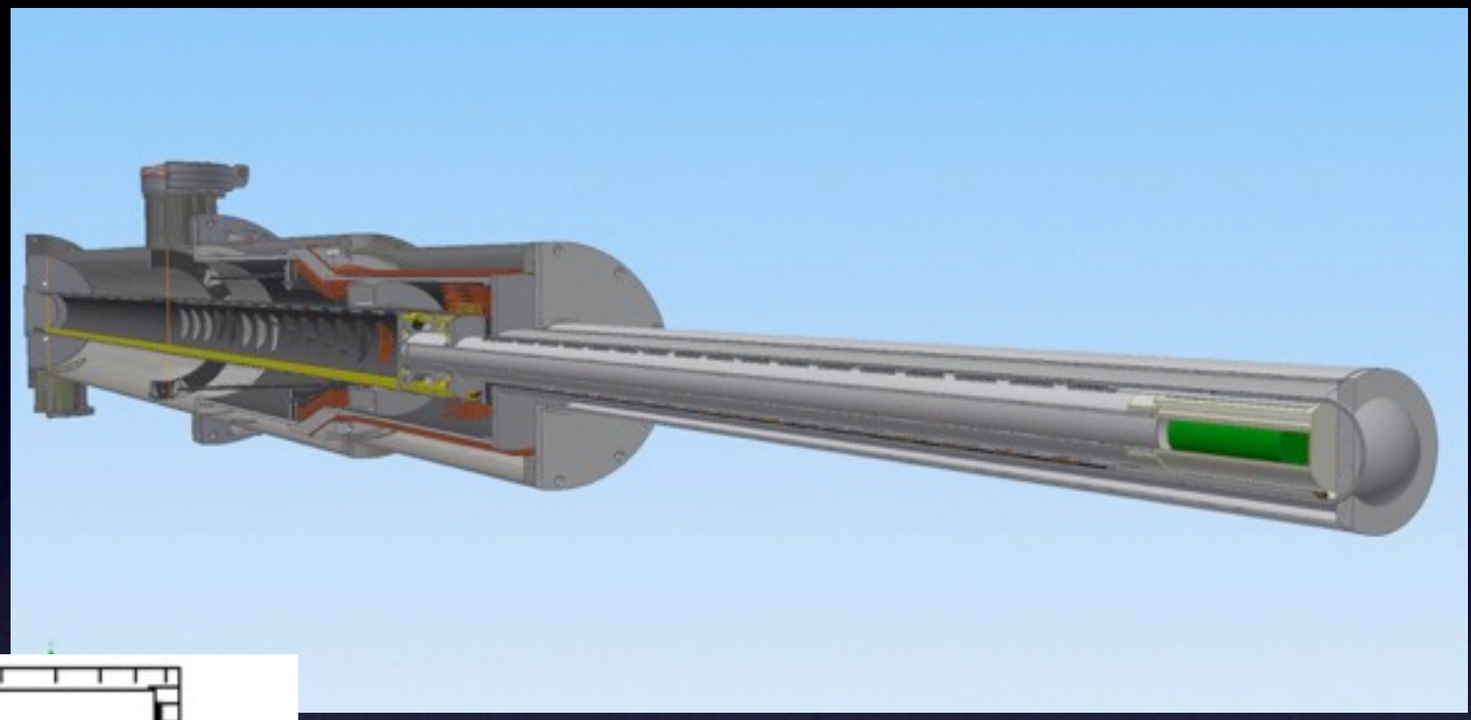
little world data available!

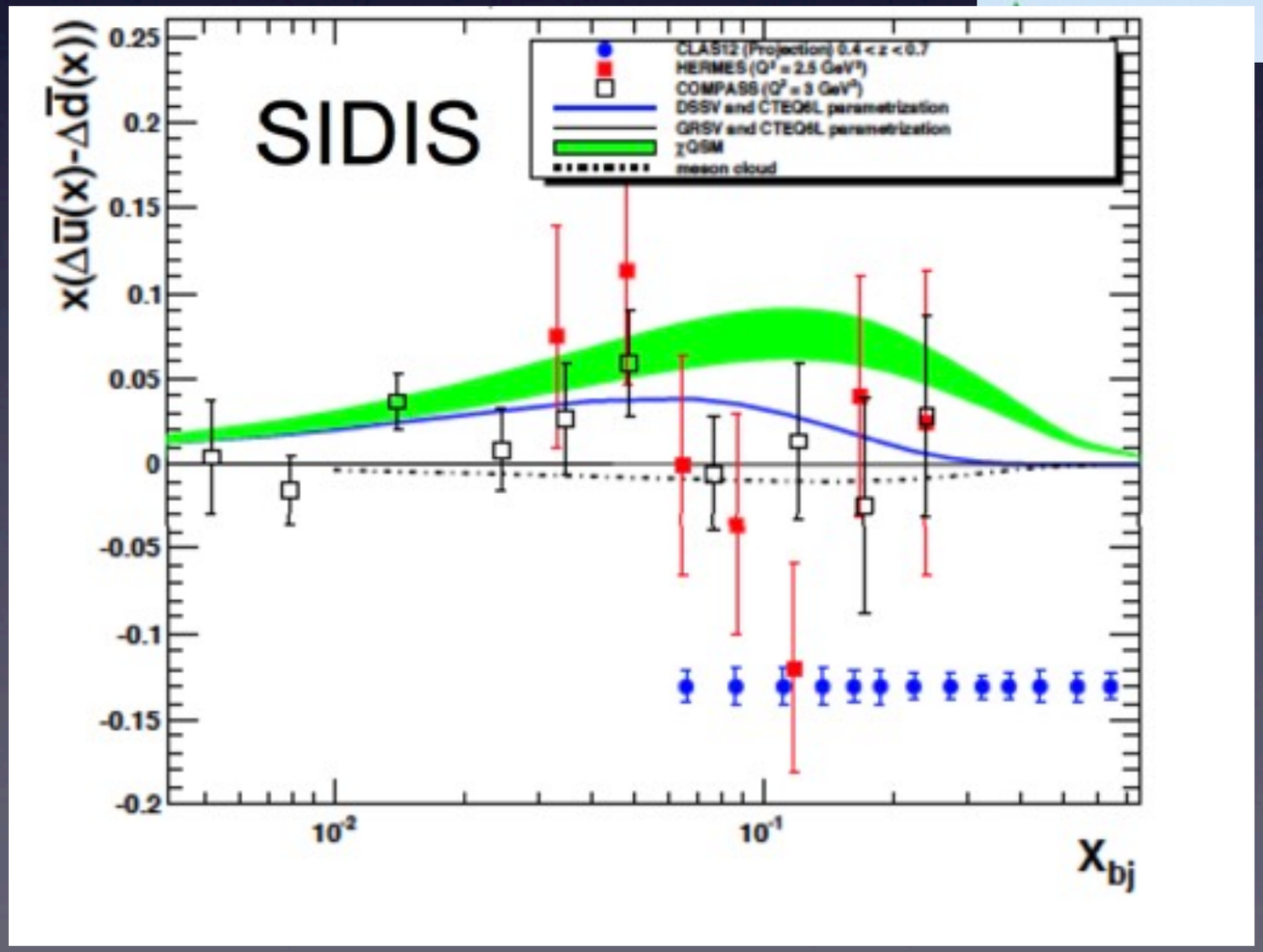


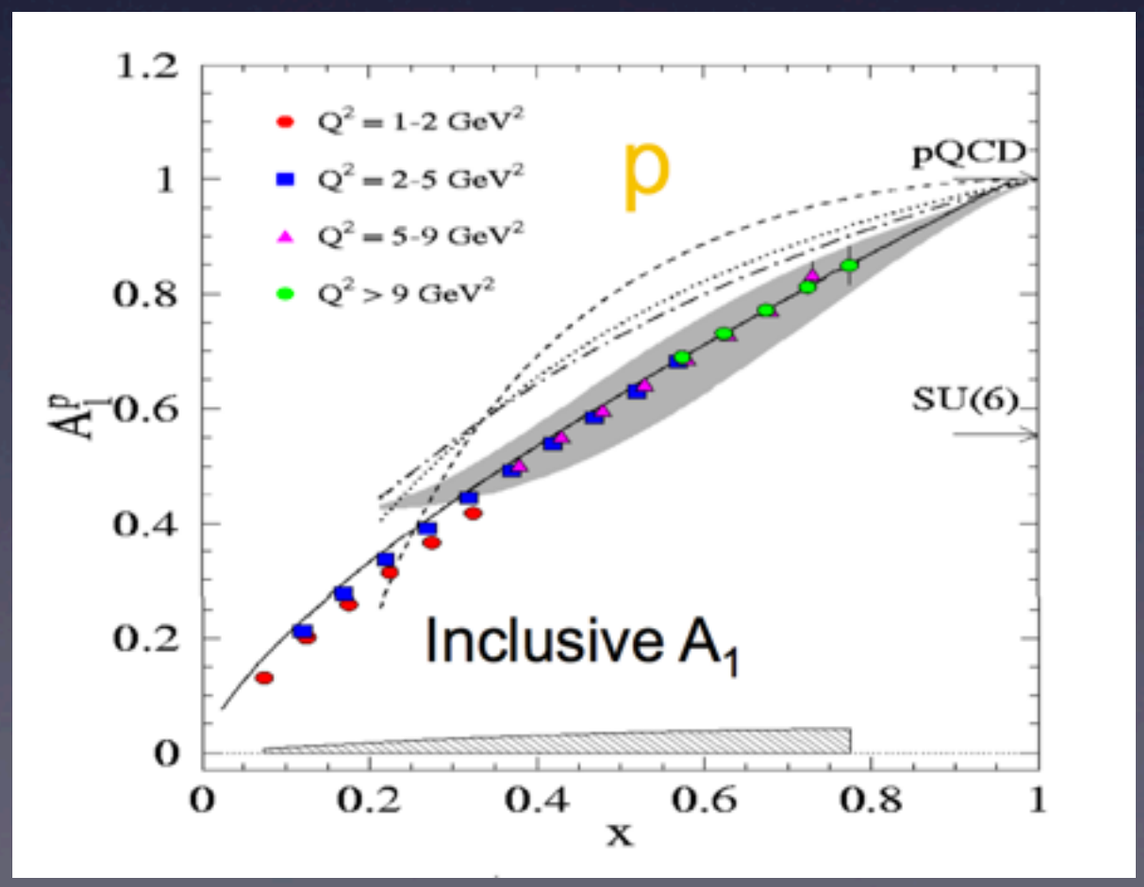
-Many EG1 publications helped build global models of nucleon spin structure!

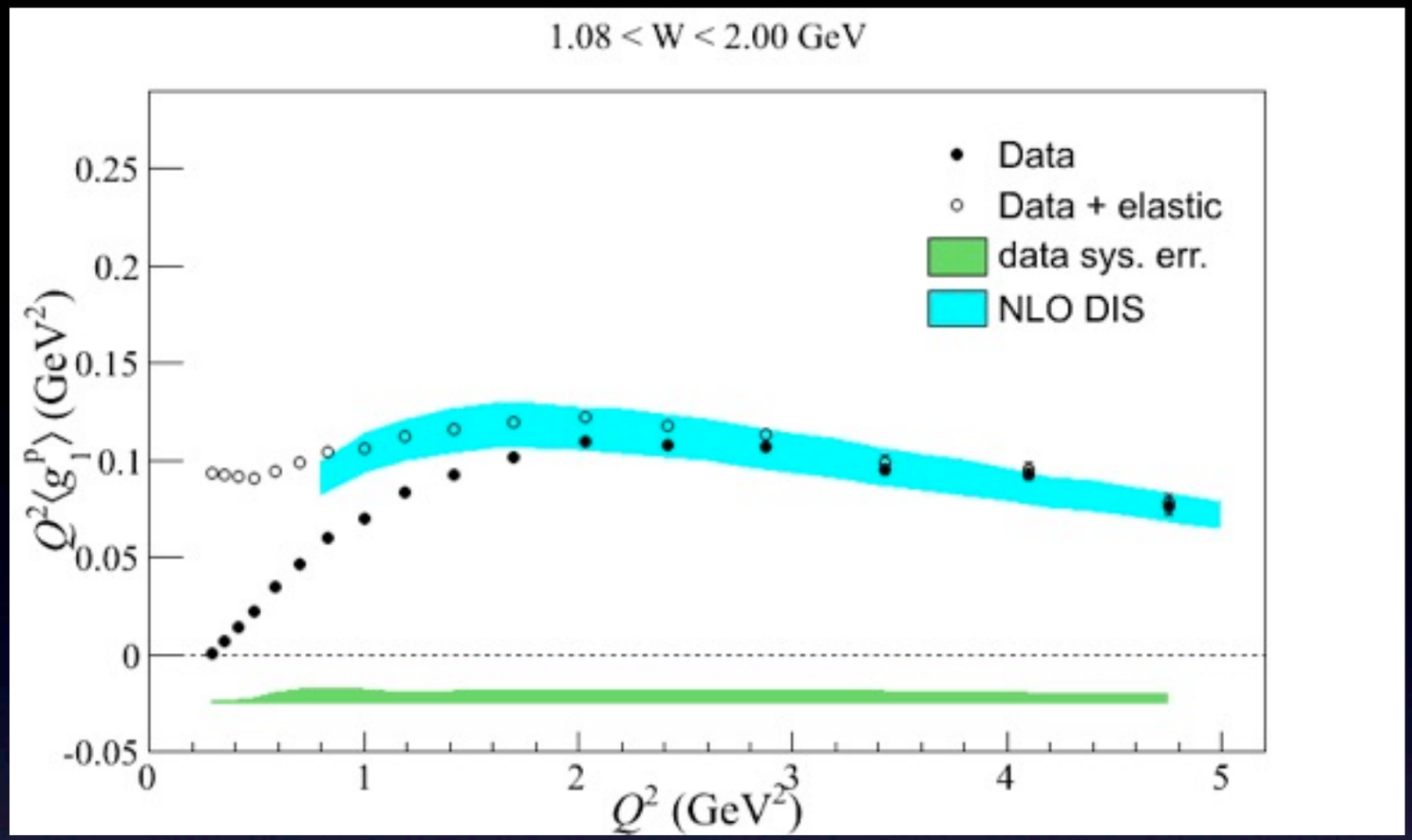
-The 12 GeV longitudinally polarized target: higher *x* means better testing of QCD models

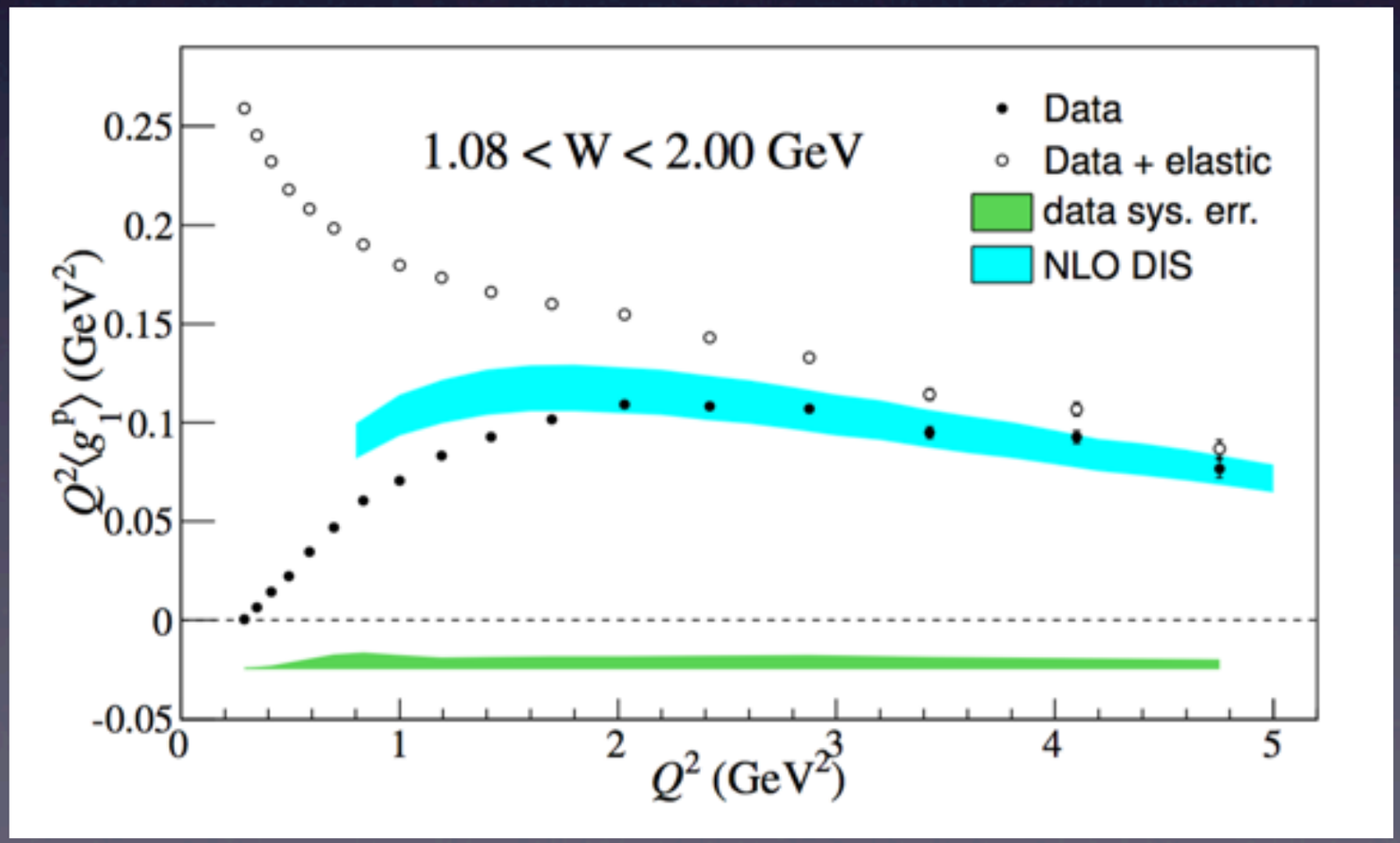
CLAS12 longitudinally polarized target design








1.08 < W < 2.00 GeV
Data
Data + elastic
data sys. err.
NLO DIS
$Q^2\langle g_1^p\rangle$ (GeV^2)
Q^2 (GeV^2)
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
1
2
3
4
5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$Q^2\langle g_1^p\rangle$ (GeV^2)
Q^2 (GeV^2)
0.25
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0.15
0.1
0.05
0
-0.05
0
1
2
3
4
5

Blümlein and Tkbladzke Target Mass Corrections

$$g_1^{TM}(x,Q^2) = \frac{x}{\xi(1+\gamma)^{3/2}} g_1^{QCD}(\xi,Q^2) + \frac{(x+\xi)\gamma}{\xi(1+\gamma)^2}\int_\xi^1 \frac{du}{u} g_1^{QCD}(u,Q^2) - \frac{\gamma(2-\gamma)}{2(1+\gamma)^{5/2}}\int_\xi^1 \frac{du}{u}\int_u^1 \frac{dv}{v} g_1^{QCD}(v,Q^2)$$

Blümlein and Takbladzke, Nucl. Phys. B553, 427 (1999)

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

Errors due to high-x resummation:

Bianchi, Fantoni, Liuti, Phys. Rev. D 69, 014505 (2004)