Nucleon Spin Structure at Large Distances

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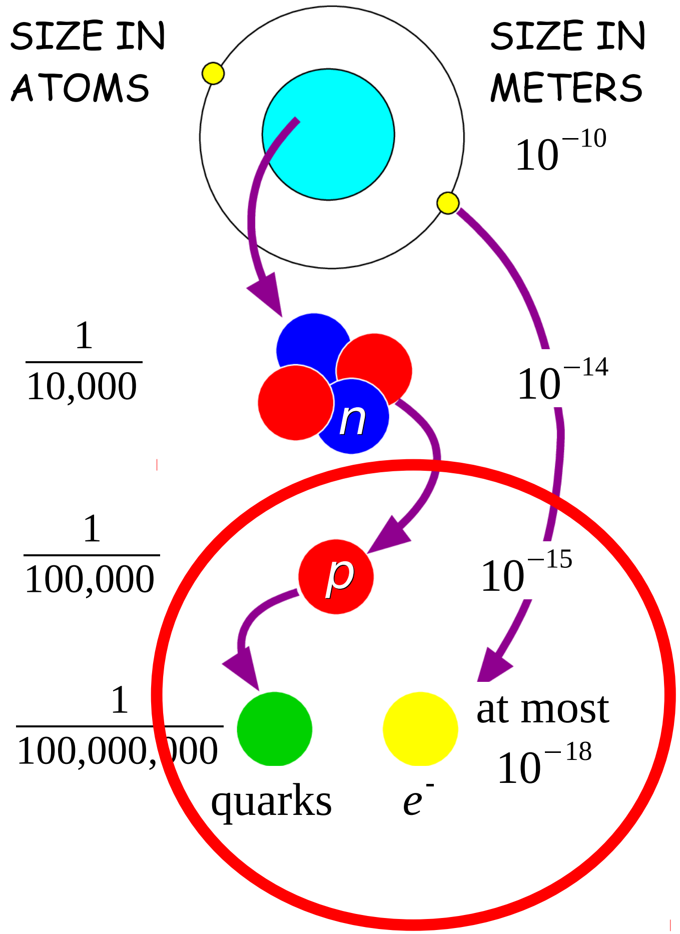
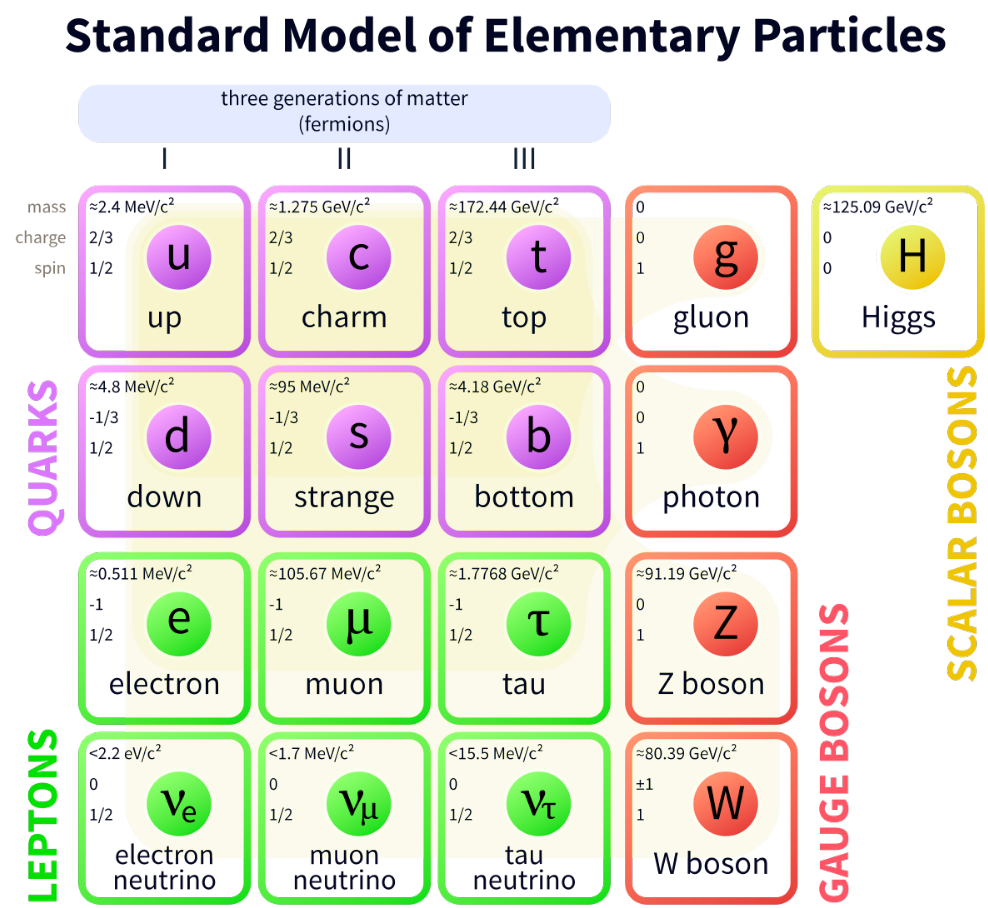
4/21/2020

- The Standard Model of subatomic physics
- Strong interaction at large distances and the nucleon spin
- Recent progress in inclusive spin physics program at JLab
  - low Q^2 spin physics and new results
  - high x spin physics and upcoming/ongoing experiments
- Summary and outlook

The Standard Model



(1) the elementary fermions – quarks and leptons
(2) the symmetries + gauge invariance → interactions
(3) mass of most elementary particles



$$D^\mu = \partial^\mu - i g_1 \frac{Y}{2} B^\mu - i g_2 \frac{\tau_i}{2} W_i^\mu - i g_3 \frac{\lambda_\alpha}{2} G_\alpha^\mu$$

Success and Challenges of the Standard Model

The Standard Model is “an effective theory at the electroweak scale”

– QED: tested to 9 orders of magnitude

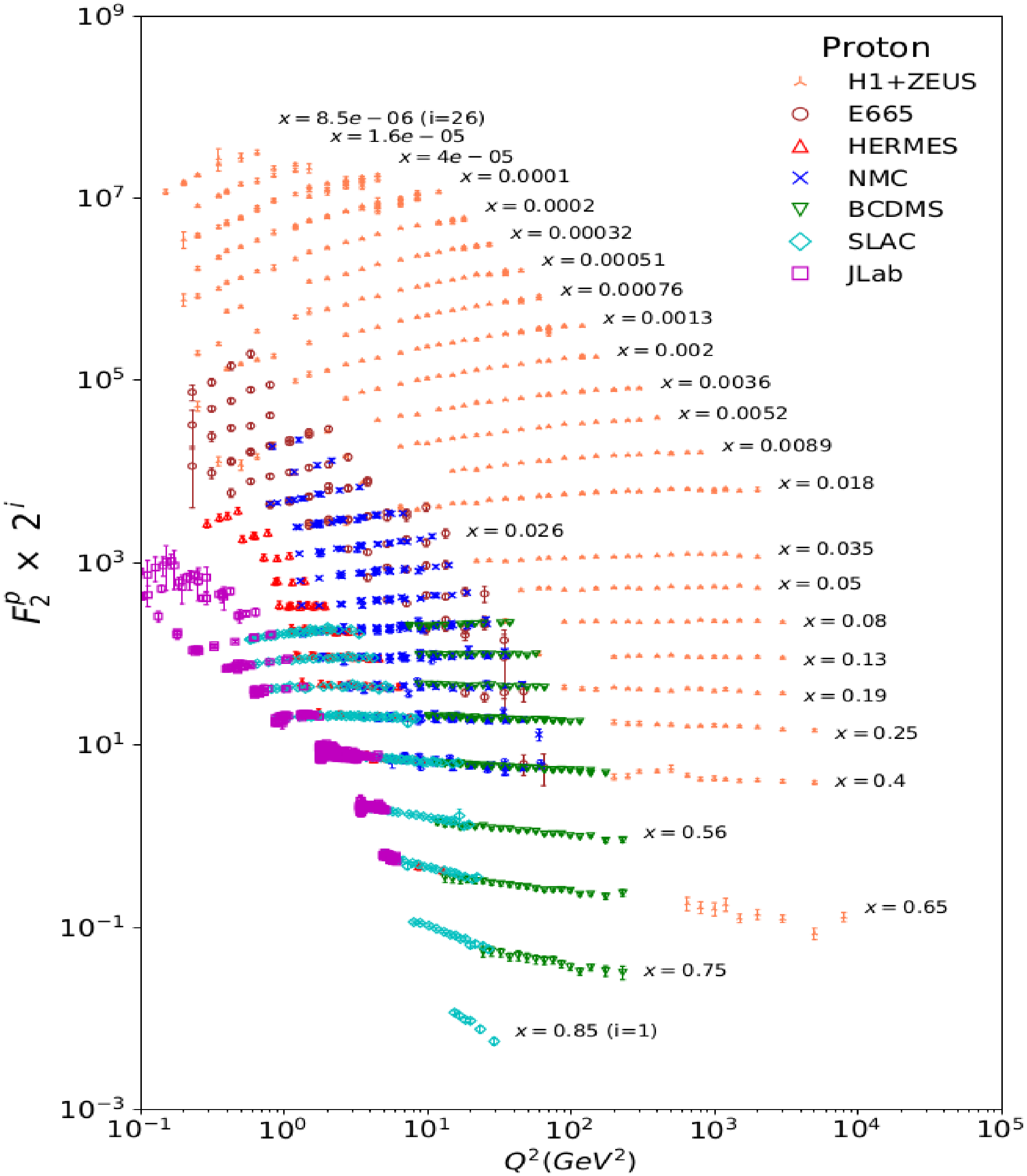
– Electroweak unification has been tested rigorously and so far data do not (yet) indicate any new physics

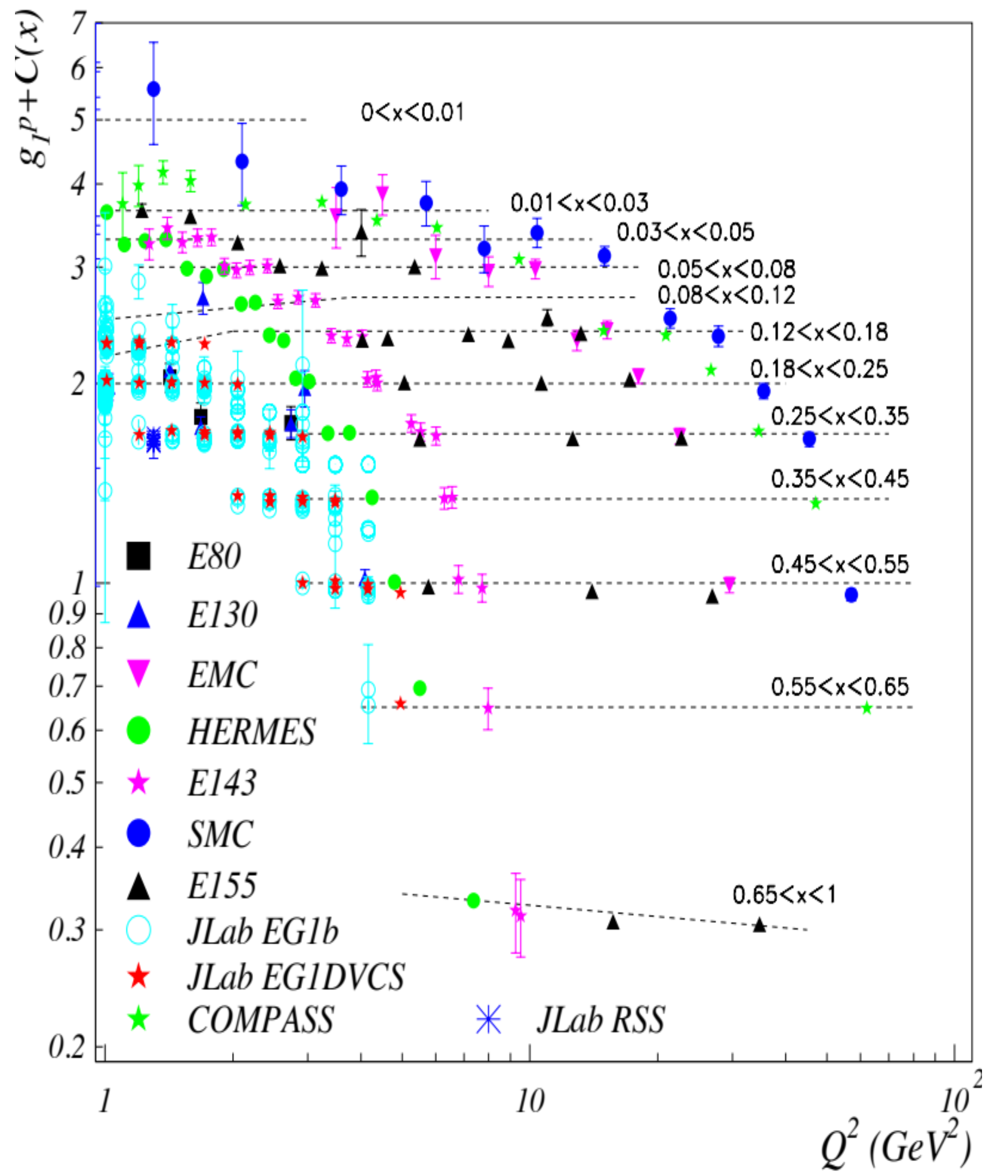
– Strong interaction: asymptotic freedom vs. confinement

Success of QCD (in the perturbative regime)

Most of progress was made between 1933 and 1973, ending with

$$\alpha_s(Q^2) = \frac{4\pi}{(11 - 2n_f/3)\ln(Q^2/\Lambda^2)}$$





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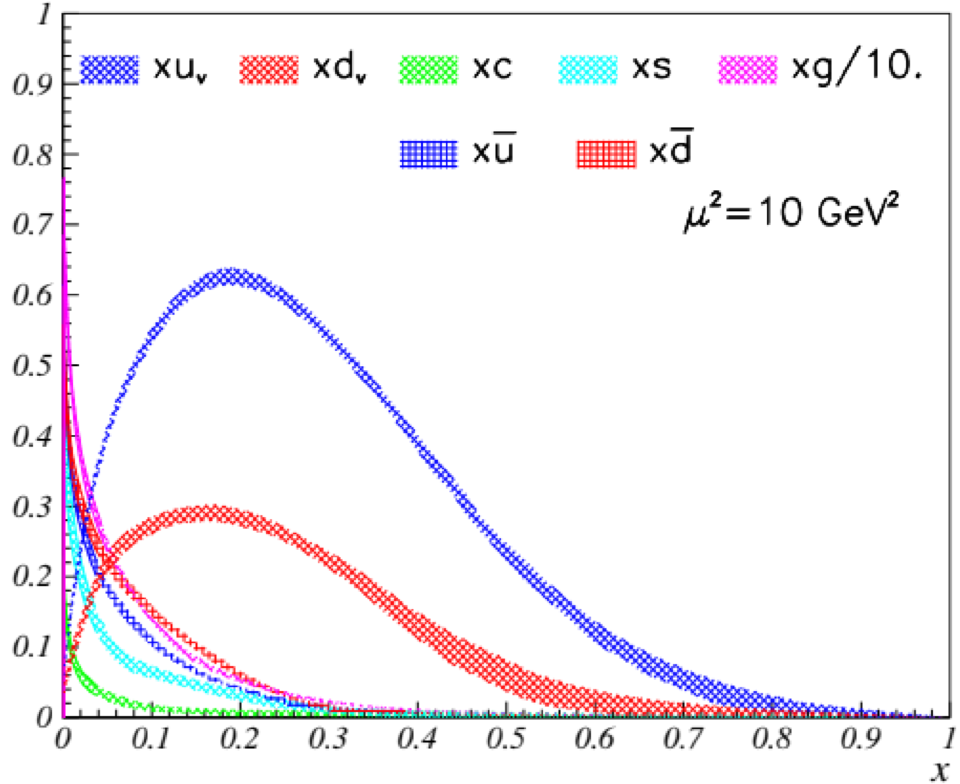
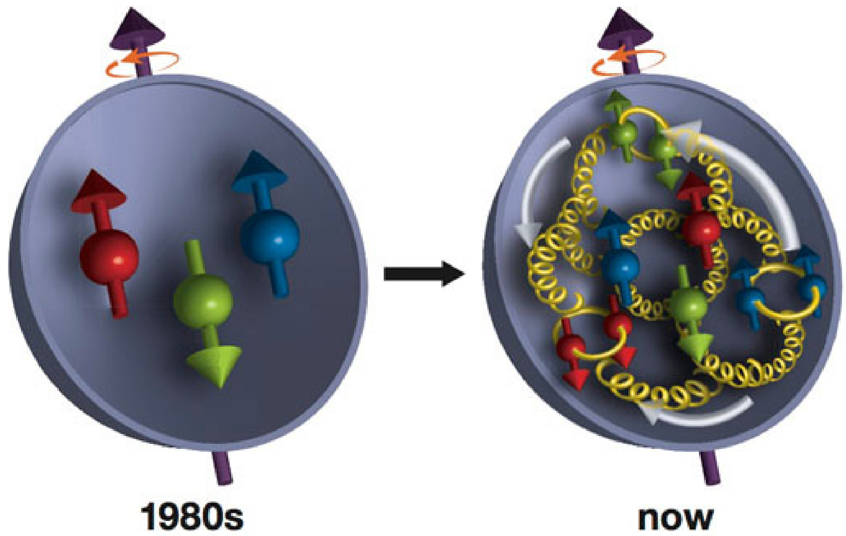
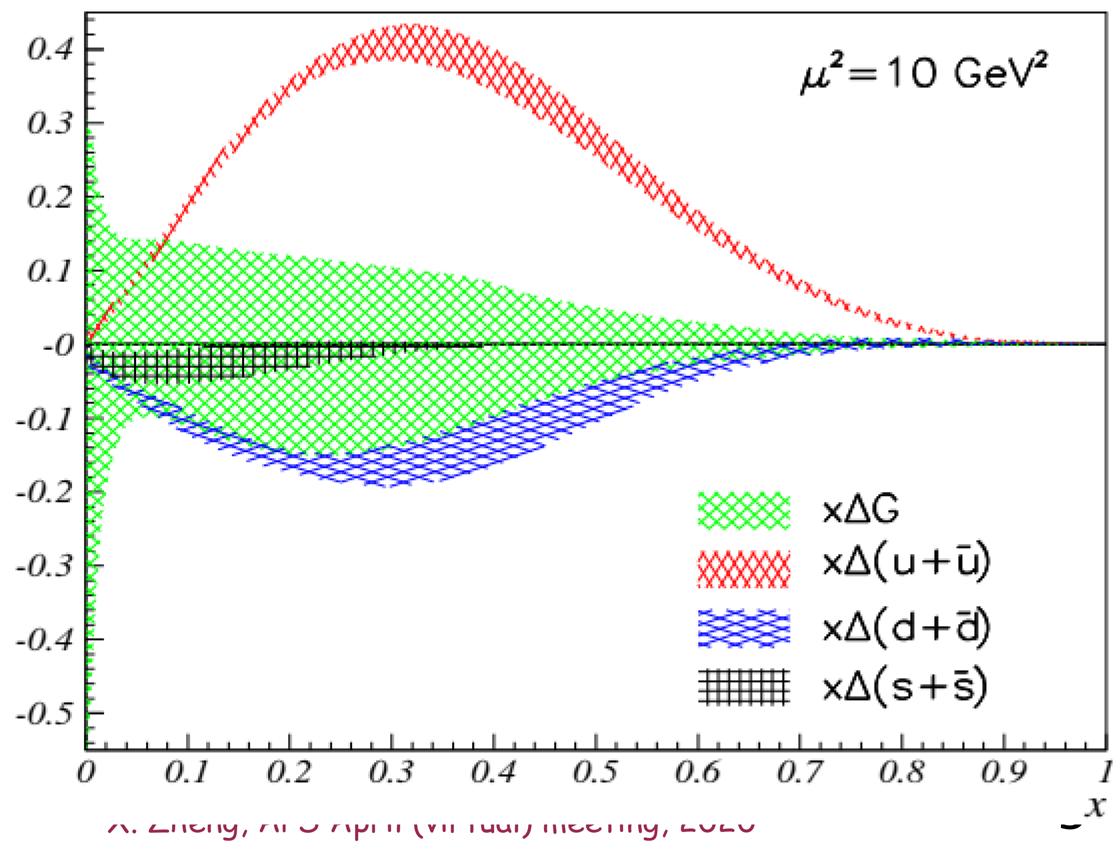
X. Zheng, APS April (virtual) meeting, 2020

Success of our Understanding of the Nucleon Structure





The nucleon structure itself is non-perturbative in nature.



Success and Challenges of the Standard Model

After decades of studying pQCD and the “high-energy end” of the nucleon structure, we must now face the need of understanding the non-perturbative nature of strong interaction: strong interaction at large distances and color confinement.

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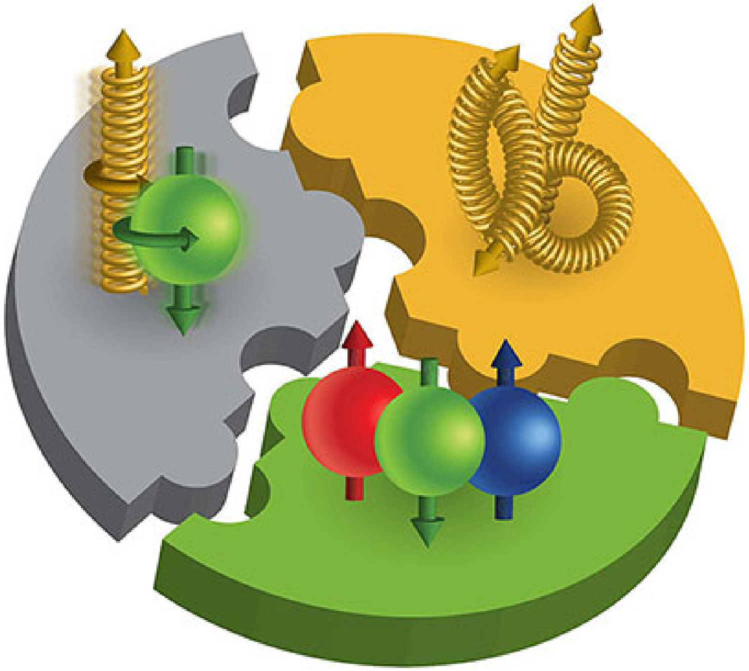
After decades of studying pQCD and the "high-energy end" of the nucleon structure, we must now face the need of understanding the non-perturbative nature of strong interaction: strong interaction at large distances and color confinement.

For many decades we have been talking about the equation:

$$J=\frac{1}{2}=\frac{1}{2}\Delta\Sigma+L_q+\Delta G+L_G$$



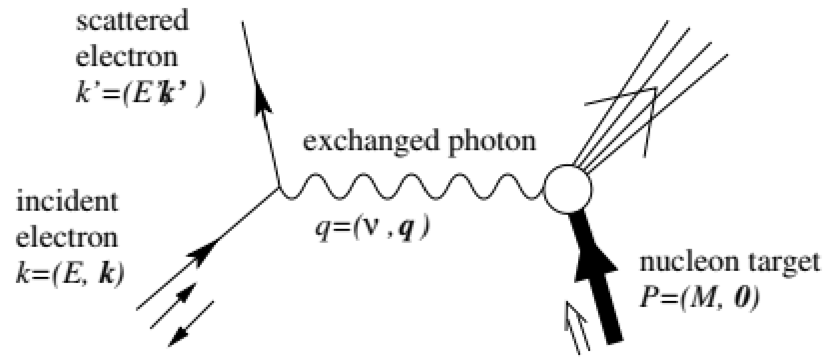
However the main purpose of studying the proton spin puzzle is beyond understanding the different contributions of the pie chart. More importantly we need to check consistency of QCD and to understand complex and important phenomena such as quark/color confinement

The Observables

$$\frac{d^2\sigma^{\uparrow\downarrow}}{d\Omega\, dE'} - \frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega\, dE'} \propto \sigma_{point-like}\left[\alpha' g_1(x,Q^2) + \beta' g_2(x,Q^2)\right]$$

$$g_1(x) = \frac{1}{2}\Sigma e_i^2\left[q_i^{\uparrow}(x) - q_i^{\downarrow}(x)\right] = \frac{1}{2}\Sigma e_i^2\left[\Delta q_i(x)\right]$$

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \qquad \frac{\Delta u}{u}, \frac{\Delta d}{d}$$



- To understand compositeness – how do partons form the nucleon spin? – the proton spin puzzle – moments (of polarized structure functions)
- to understand non-perturbative regime: to test effective field theories that use the hadronic degrees of freedom, which may in turn help us to understand the underlying principles and nature of QCD

  – moments at low Q^2/long distances
- to test predictions for structure functions – structure functions at large x
- how hadrons arise from quark and gluon degrees of freedom? – lattice QCD – Q^2 dependence of moments

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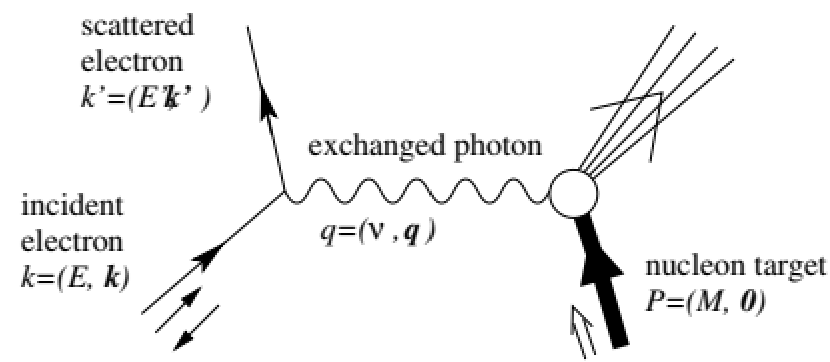

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focus of this talk

(Some) Moments and Sum Rules

- Quark spin contribution to the nucleon spin: $\sum_f \Delta q_f$

- Bjorken Sum Rule: (current algebra, isospin symmetry)

$$\int (g_1^p - g_1^n)\, dx = \frac{1}{6} g_A \left(1 + \frac{\alpha_S(Q^2)}{\pi} + \ldots\right) + \text{non-pertubative corrections (higher twists)}$$

axial charge

- GDH Sum Rule (real photon):

(unitarity)

anomalous magnetic moment

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

- GDH Sum Rule (virtual photon): spin dependent DDVCS amplitude

$$\frac{16\alpha\pi^2}{Q^2} \int_0^1 g_1\, dx = 2\alpha\pi^2 S_1 \xrightarrow[Q^2 \to 0]{} -\frac{2\alpha\pi^2\kappa^2}{M^2} \quad \text{or} \quad I_{TT} \sim \int (A_1 F_1)\, dx$$

low-to-intermediate Q²: chiral PT, OPE

- Burkhardt-CottinghamSum Rule: $\Gamma_2 = \int_0^1 g_2(x, Q^2)\, dx = 0$

Higher Moments – Spin Polarizabilities

- Generalized forward spin polarizability:

$$\gamma_0 = \frac{16\alpha M^2}{\pi Q^6} \int_0^{x_0} x^2 \left[g_1 - \frac{4M^2}{Q^2} x^2 g_2 \right] dx$$

- Longitudinal-Transverse polarizability:

$$\delta_{LT} = \frac{16\alpha M^2}{\pi Q^6} \int_0^{x_0} x^2 [g_1 + g_2] dx$$

- Twist-3 term d_2:

$$d_2(Q^2) = \int_0^1 x^2 \left[2g_1(x,Q^2) + 3g_2(x,Q^2) \right] dx = 3\int_0^1 x^2 \left[g_2(x,Q^2) - g_2^{WW}(x,Q^2) \right] dx$$

Calculations exist or possible from lattice QCD, Dyson-Schwinger Equations, or Chiral PT

Lepton scattering spin structure experiments (mostly inclusive):

Experiment	Ref.	Target	Analysis	W (GeV)	x_{Bj}	Q^2 (GeV^2)
E80 (SLAC)	[101]	p	A_1	2.1 to 2.6	0.2 to 0.33	1.4 to 2.7
E130 (SLAC)	[102]	p	A_1	2.1 to 4.0	0.1 to 0.5	1.0 to 4.1
EMC (CERN)	[103]	p	A_1	5.9 to 15.2	1.5×10^{-2} to 0.47	3.5 to 29.5
SMC (CERN)	[250]	p, d	A_1	7.7 to 16.1	10^{-4} to 0.482	0.02 to 57
E142 (SLAC)	[244]	^{3}He	A_1, A_2	2.7 to 5.5	3.6×10^{-2} to 0.47	1.1 to 5.5
E143 (SLAC)	[245]	p, d	A_1, A_2	1.1 to 6.4	3.1×10^{-2} to 0.75	0.45 to 9.5
E154 (SLAC)	[246, 247]	^{3}He	A_1, A_2	3.5 to 8.4	1.7×10^{-2} to 0.57	1.2 to 15.0
E155/x (SLAC)	[248, 249]	p, d	A_1, A_2	3.5 to 9.0	1.5×10^{-2} to 0.75	1.2 to 34.7
HERMES (DESY)	[253, 254]	p, ^{3}He	A_1	2.1 to 6.2	2.1×10^{-2} to 0.85	0.8 to 20
E94010 (JLab)	[256]	^{3}He	g_1, g_2	1.0 to 2.4	1.9×10^{-2} to 1.0	0.019 to 1.2
EG1a (JLab)	[257]	p, d	A_1	1.0 to 2.1	5.9×10^{-2} to 1.0	0.15 to 1.8
RSS (JLab)	[258, 259]	p, d	A_1, A_2	1.0 to 1.9	0.3 to 1.0	0.8 to 1.4
COMPASS (CERN) DIS	[251]	p, d	A_1	7.0 to 15.5	4.6×10^{-3} to 0.6	1.1 to 62.1
COMPASS (CERN) low-Q^2	[280]	p, d	A_1	5.2 to 19.1	4×10^{-5} to 4×10^{-2}	0.001 to 1.
EG1b (JLab)	[260, 261, 262, 263]	p, d	A_1	1.0 to 3.1	2.5×10^{-2} to 1.0	0.05 to 4.2
E99-117 (JLab)	[264]	^{3}He	A_1, A_2	2.0 to 2.5	0.33 to 0.60	2.7 to 4.8
E99-107 (JLab)	[265]	^{3}He	g_1, g_2	2.0 to 2.5	0.16 to 0.20	0.57 to 1.34
E01-012 (JLab)	[266, 267]	^{3}He	g_1, g_2	1.0 to 1.8	0.33 to 1.0	1.2 to 3.3
E97-110 (JLab)	[268]	^{3}He	g_1, g_2	1.0 to 2.6	2.8×10^{-3} to 1.0	0.006 to 0.3
EG4 (JLab)	[269]	p, n	g_1	1.0 to 2.4	7.0×10^{-3} to 1.0	0.003 to 0.84
SANE (JLab)	[271]	p	A_1, A_2	1.4 to 2.8	0.3 to 0.85	2.5 to 6.5
EG1dvcs (JLab)	[270]	p	A_1	1.0 to 3.1	6.9×10^{-2} to 0.63	0.61 to 5.8
E06-014 (JLab)	[272, 273]	^{3}He	g_1, g_2	1.0 to 2.9	0.25 to 1.0	1.9 to 6.9
E06-010/011 (JLab)	[278]	^{3}He	single spin asy.	2.4 to 2.9	0.16 to 0.35	1.4 to 2.7
E07-013 (JLab)	[72]	^{3}He	single spin asy.	1.7 to 2.9	0.16 to 0.65	1.1 to 4.0
E08-027 (JLab)	[309]	p	g_1, g_2	1. to 2.1	3.0×10^{-3} to 1.0	0.02 to 0.4

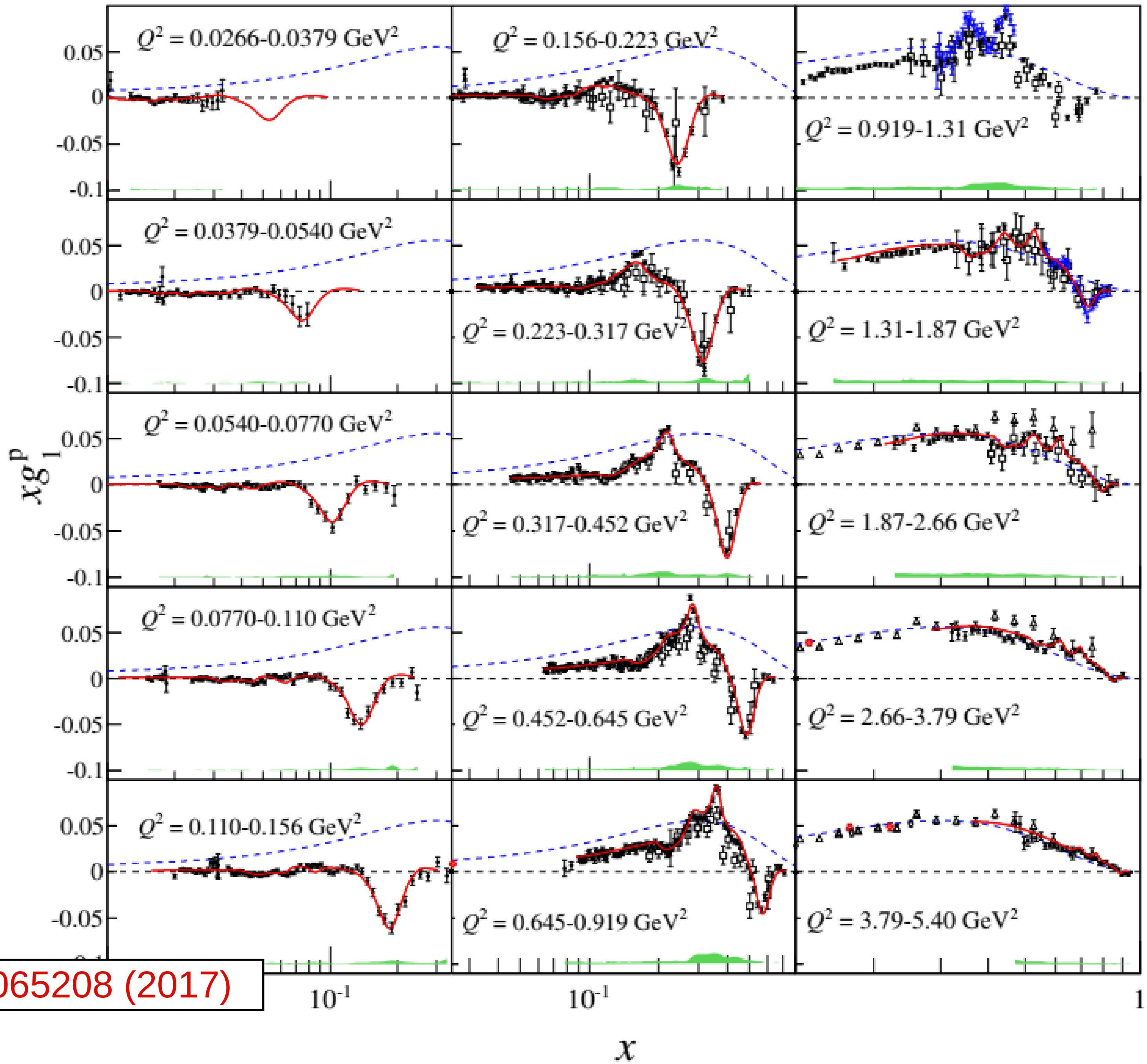
Jefferson Lab's focus is high precision, low to intermediate Q^2 values, and high x

Deur, Brodsky, de Teramond

Rept.Prog.Phys. 82 (2019) 076201

(Recently Published and Preliminary) Results on Moments of Structure Functions in the low to intermediate Q^2 region

Proton Spin Structure Data (up to 2017)



Fersch et al. PRC 96 065208 (2017)

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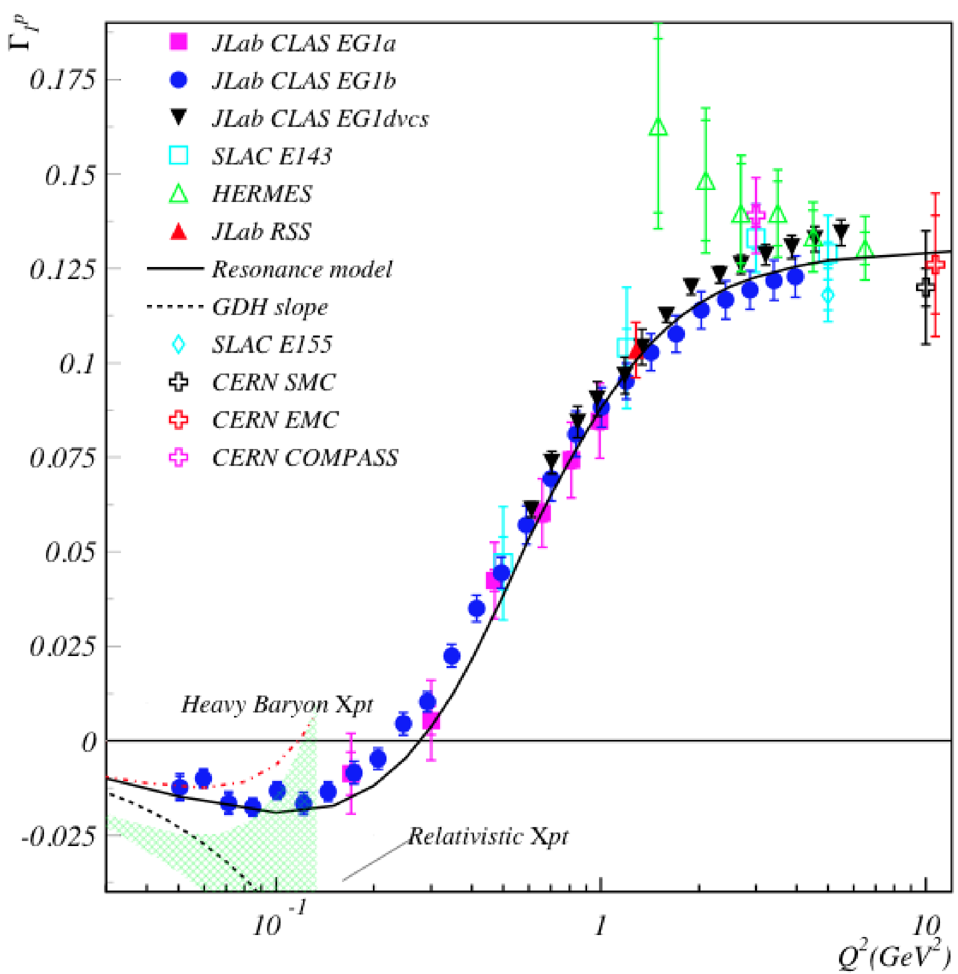
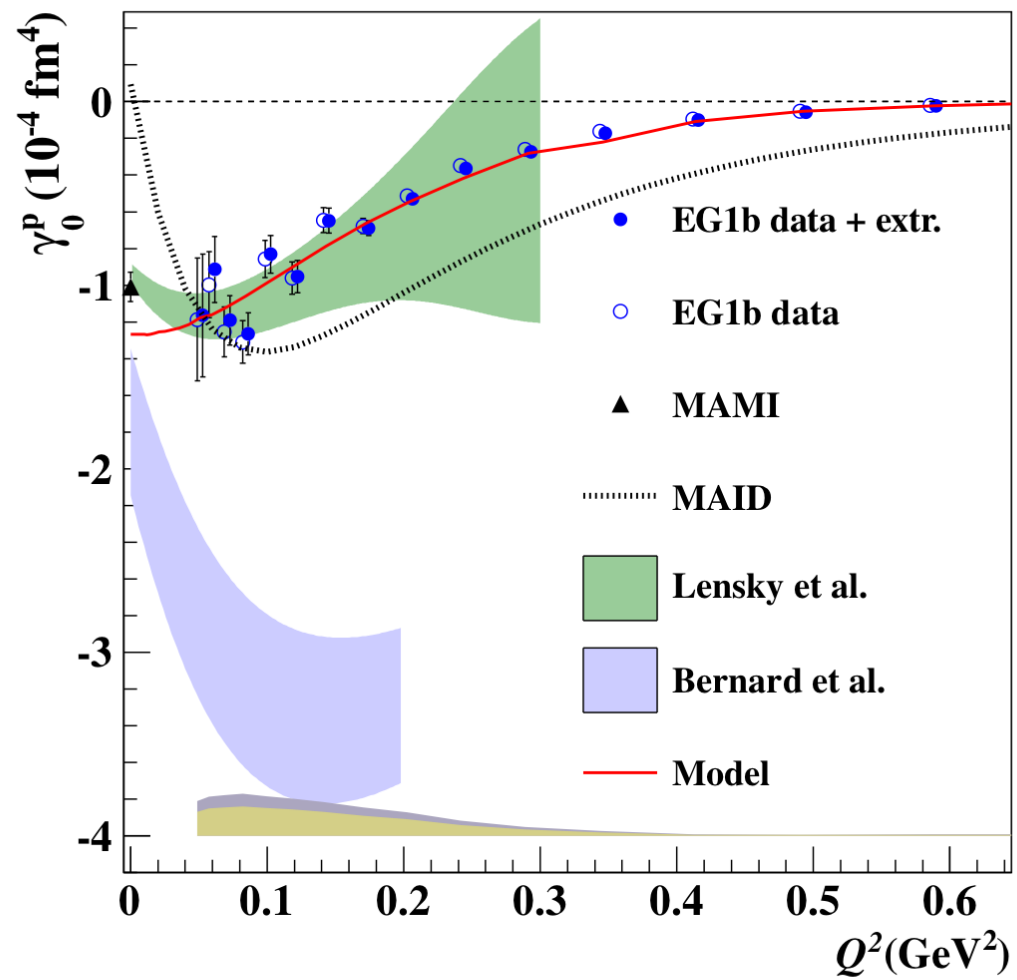
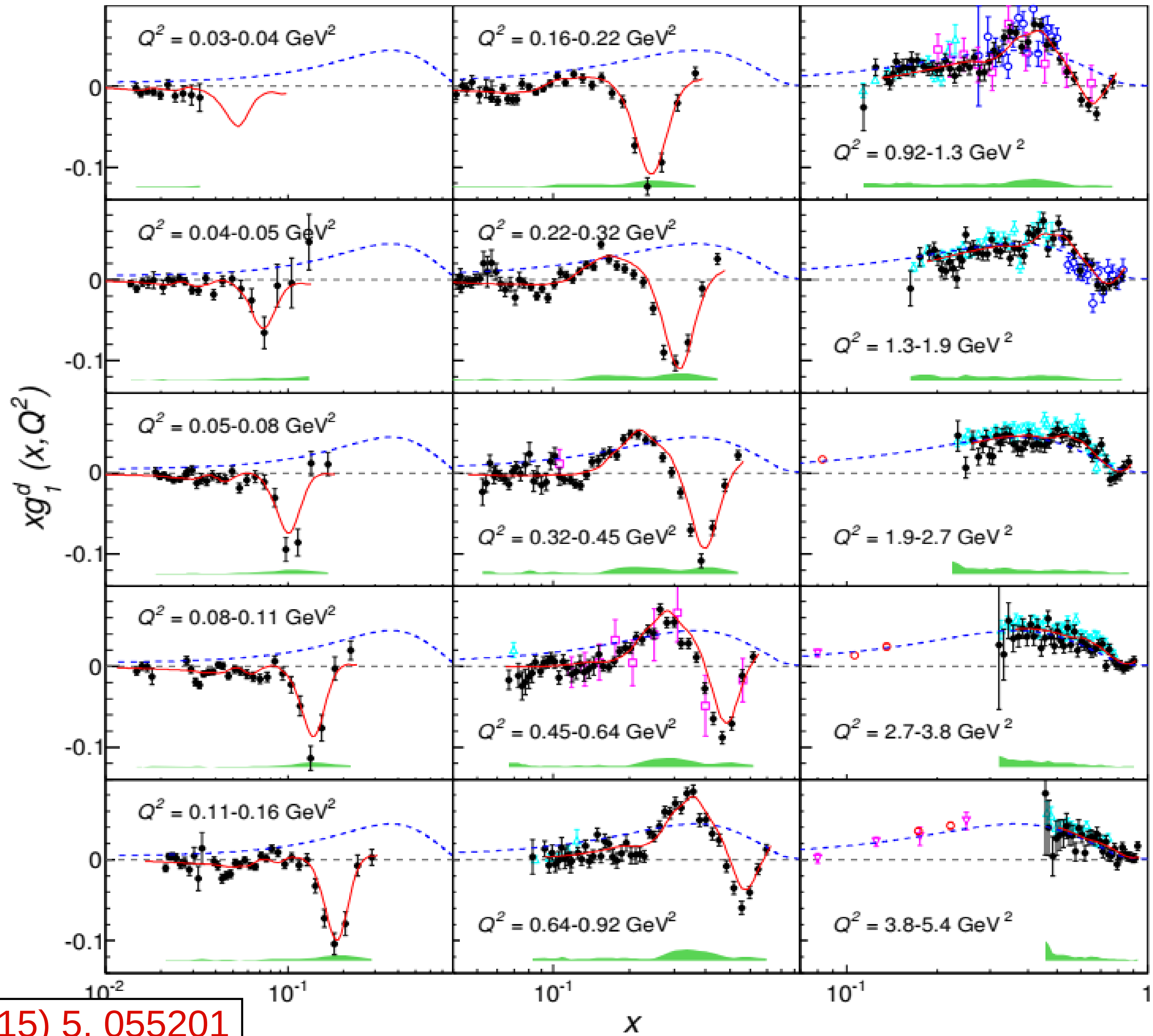




$$\gamma_0 = \frac{16\alpha M^2}{\pi Q^6}\int_0^{x_0} x^2\left[g_1 - \frac{4M^2}{Q^2}x^2 g_2\right]dx$$

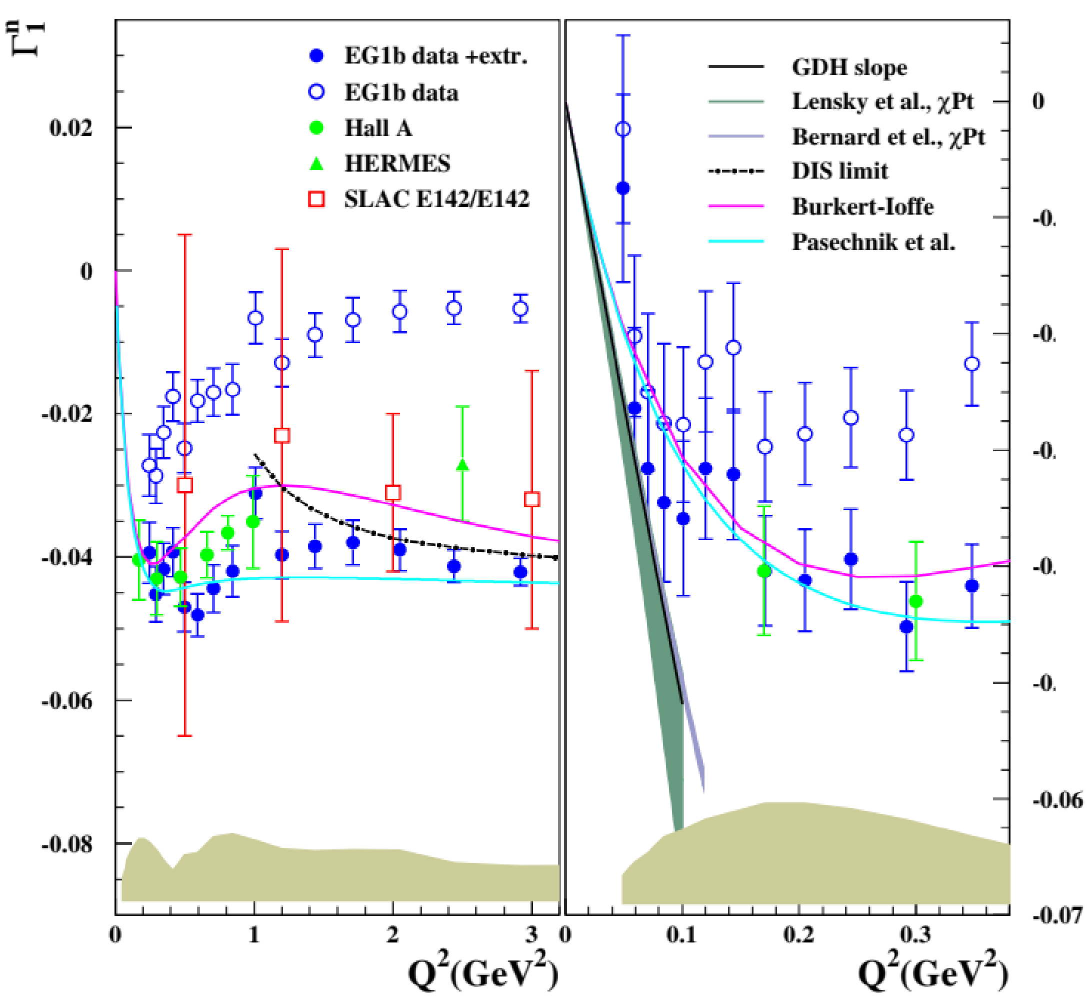
Fersch et al. PRC 96 065208 (2017)

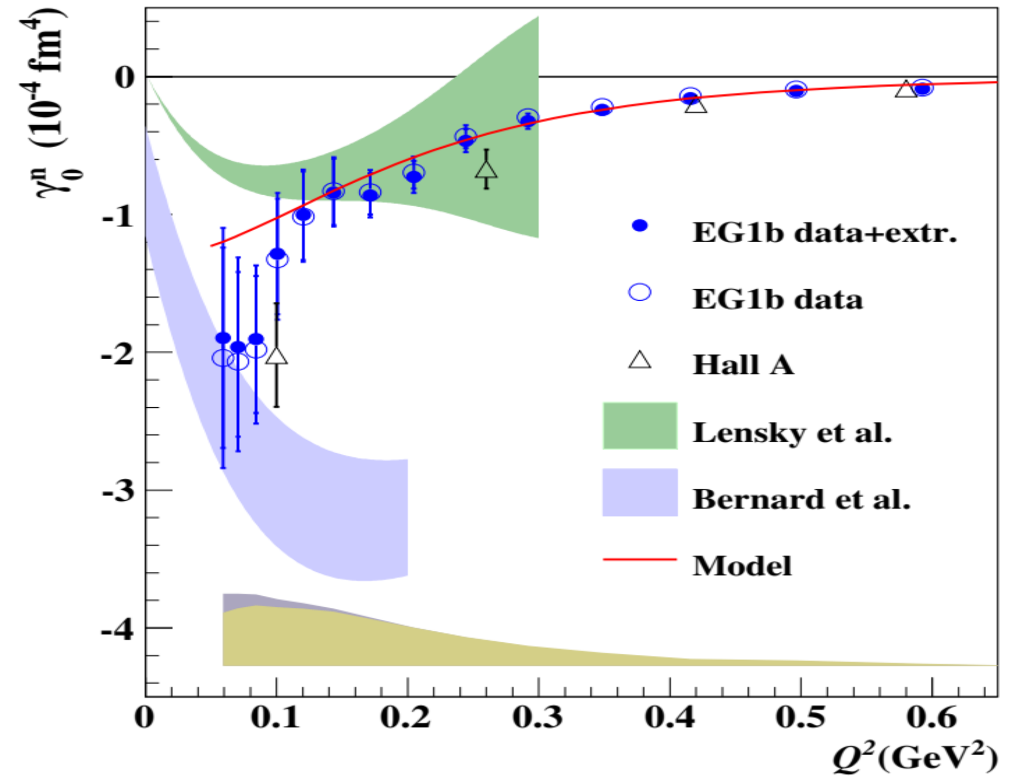
Deuteron Spin Structure Data (up to 2017)



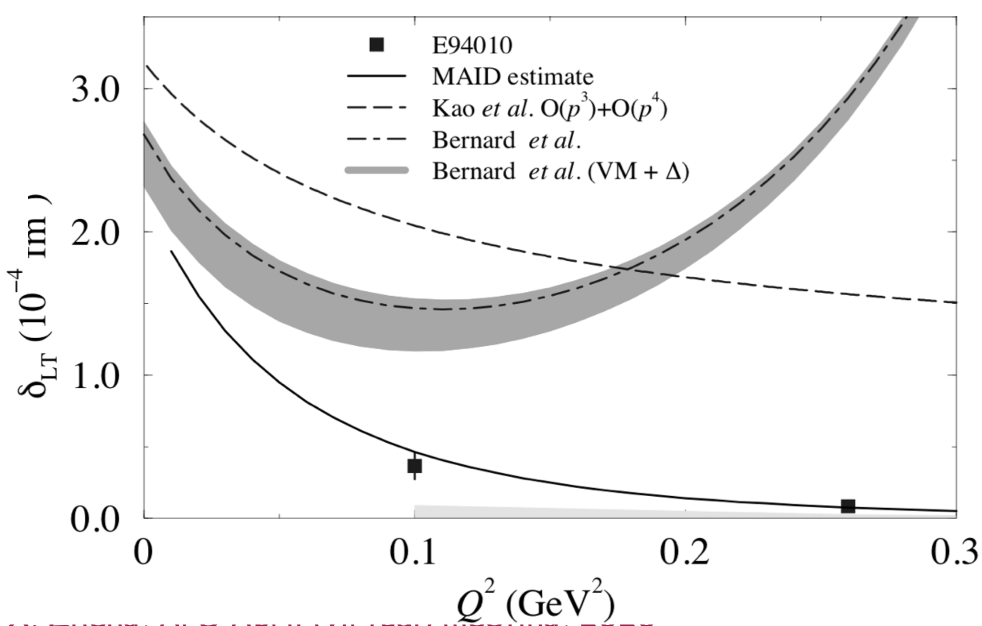
Guler et al. PRC 92 (2015) 5, 055201

Neutron (both D and 3He) Spin Structure Data (up to 2017)





Guler et al. PRC 92 (2015) 5, 055201



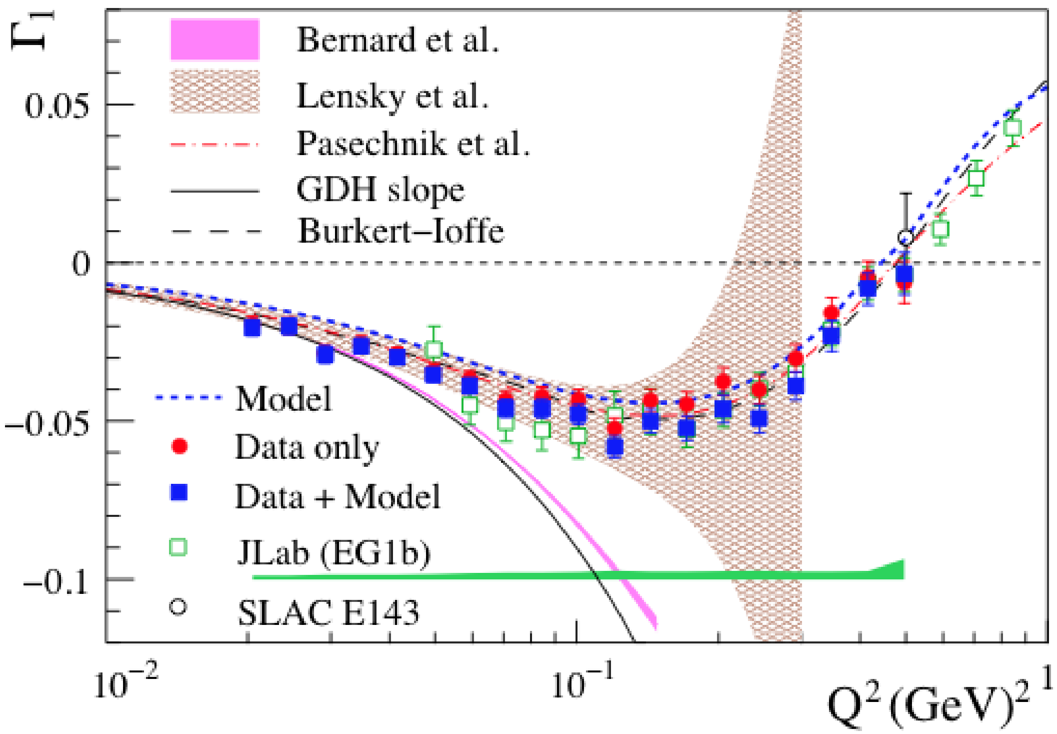
Amarian et al

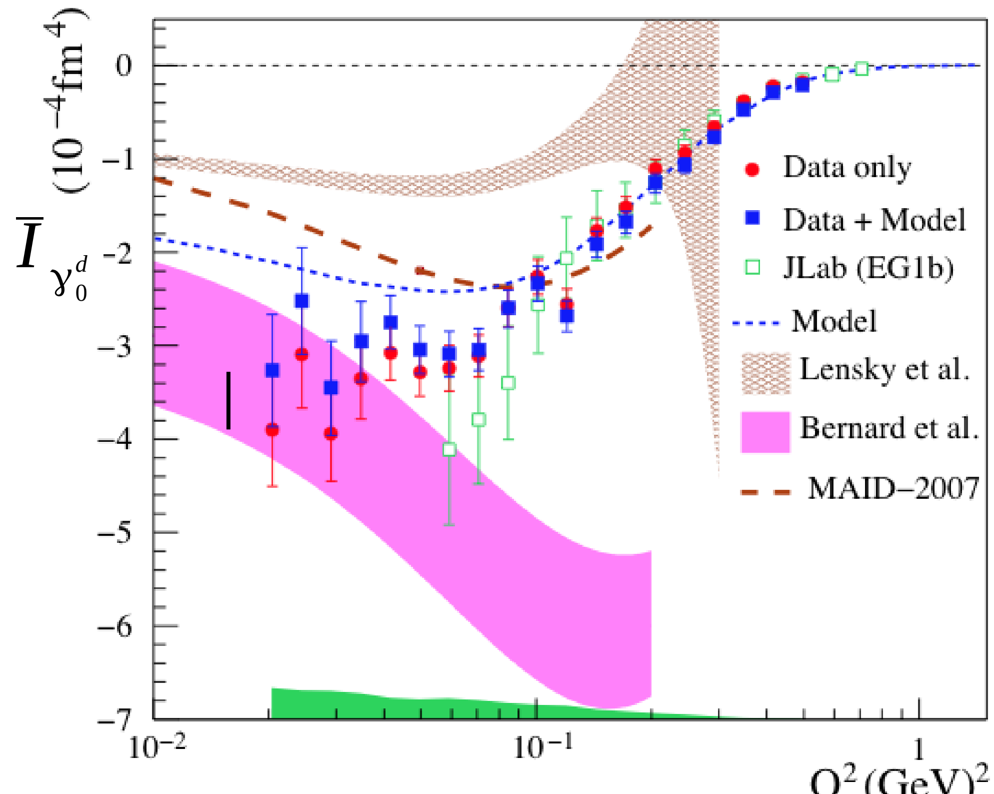
Phys. Rev. Lett. 89 242301

Phys. Rev. Lett. 92 022301

Phys. Rev. Lett. 93 152301

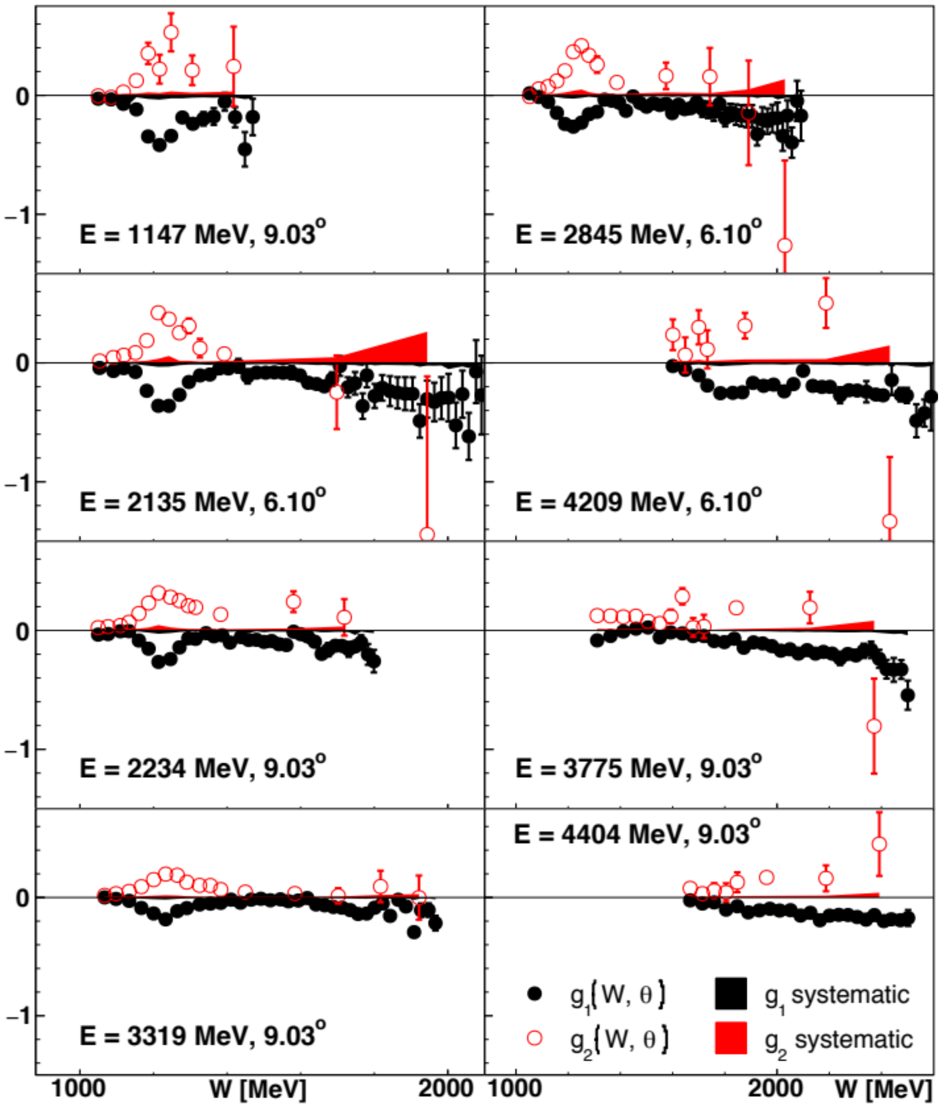
Deuteron results from EG4 (Hall B)

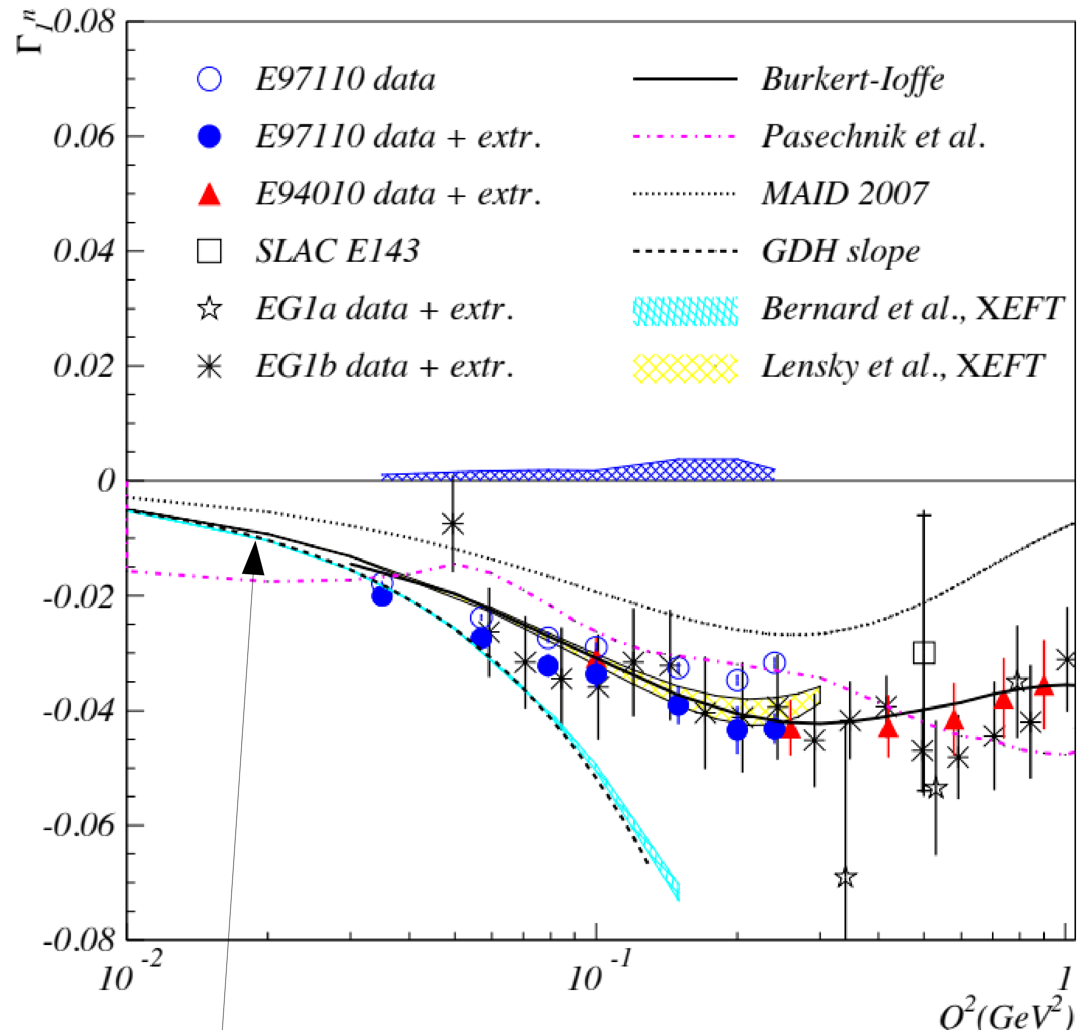




Adhikari et al., PRL 120, 062501 (2018)

New Neutron (3He) Spin Structure Data from E97-110

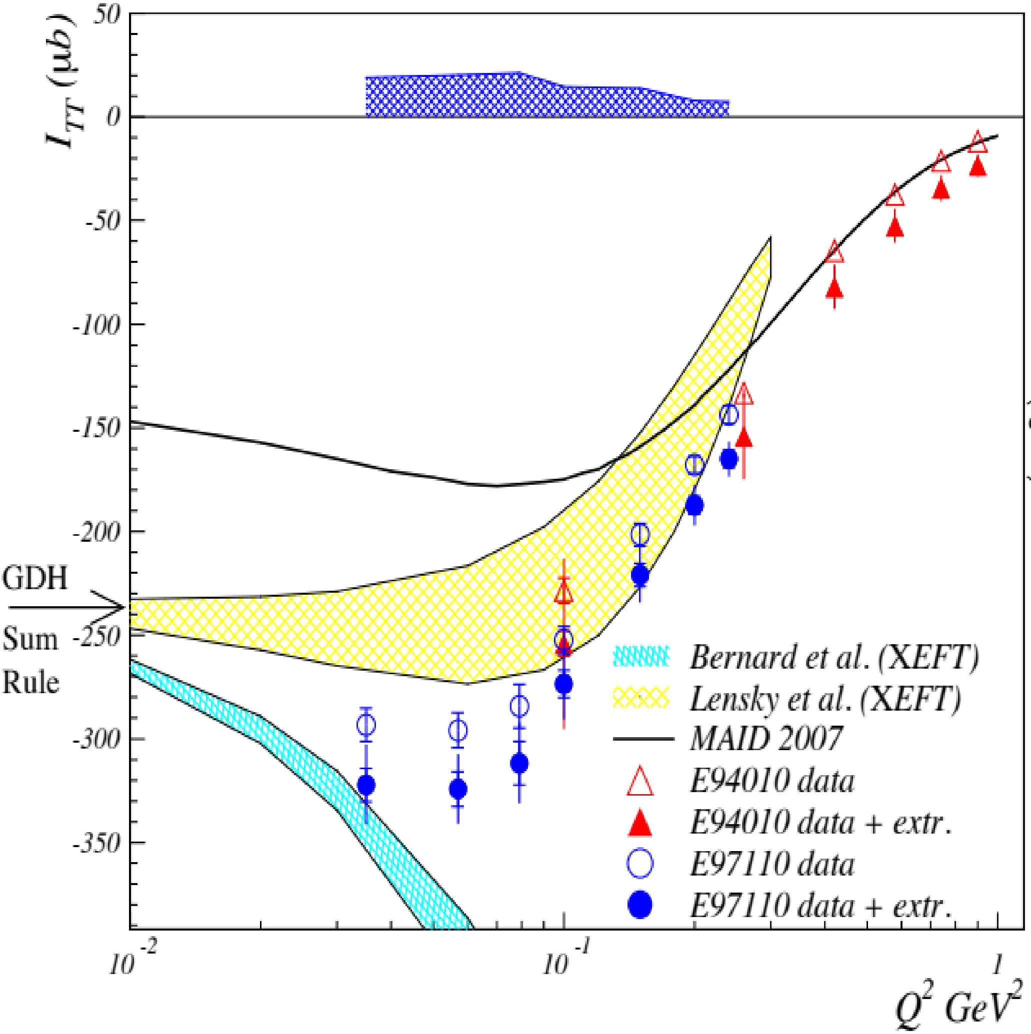


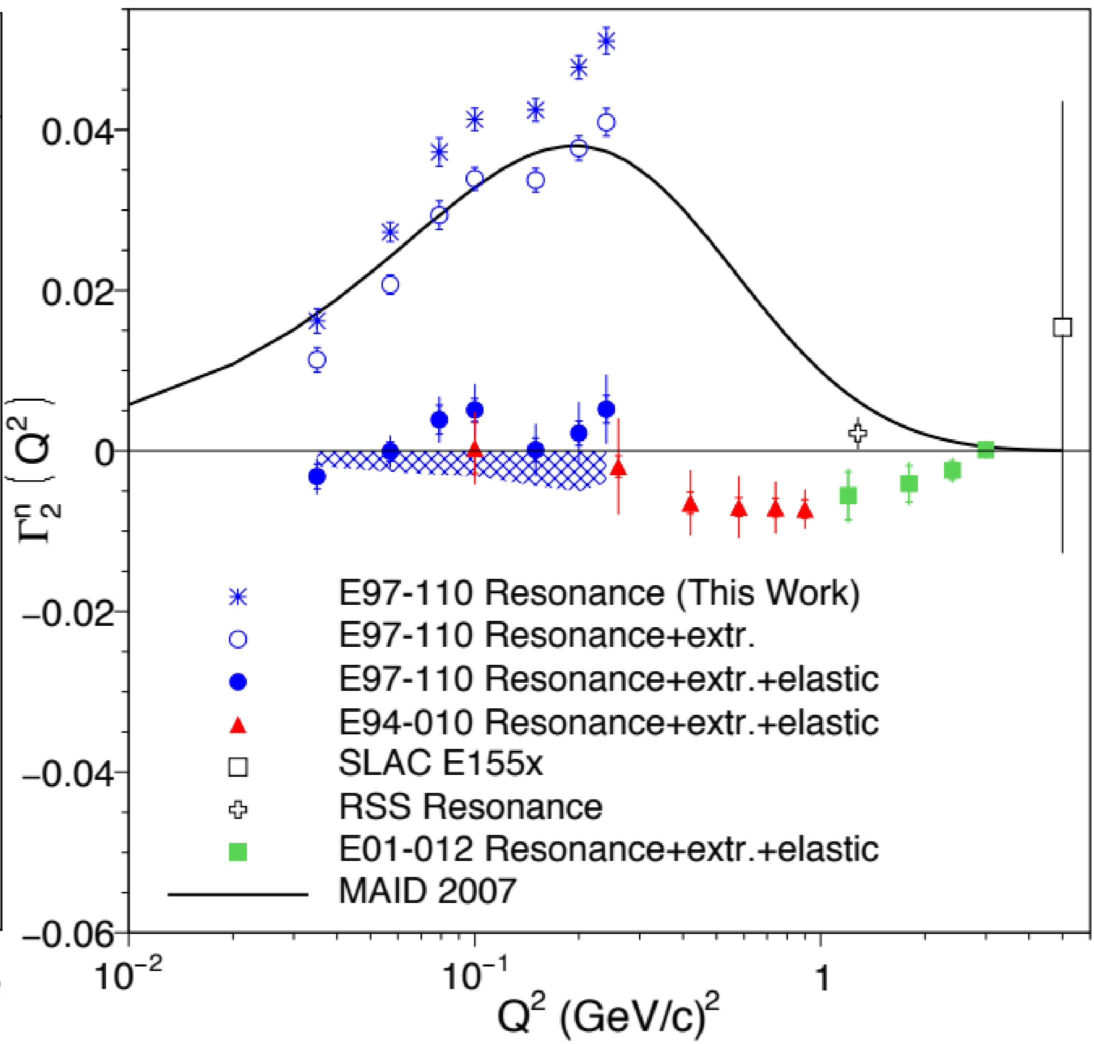


more points to be added here (N. Ton thesis)

V. Sulkosky et al., arXiv 1908.05709 accepted by Phys. Lett. B

New Neutron (3He) Spin Structure Data from E97-110



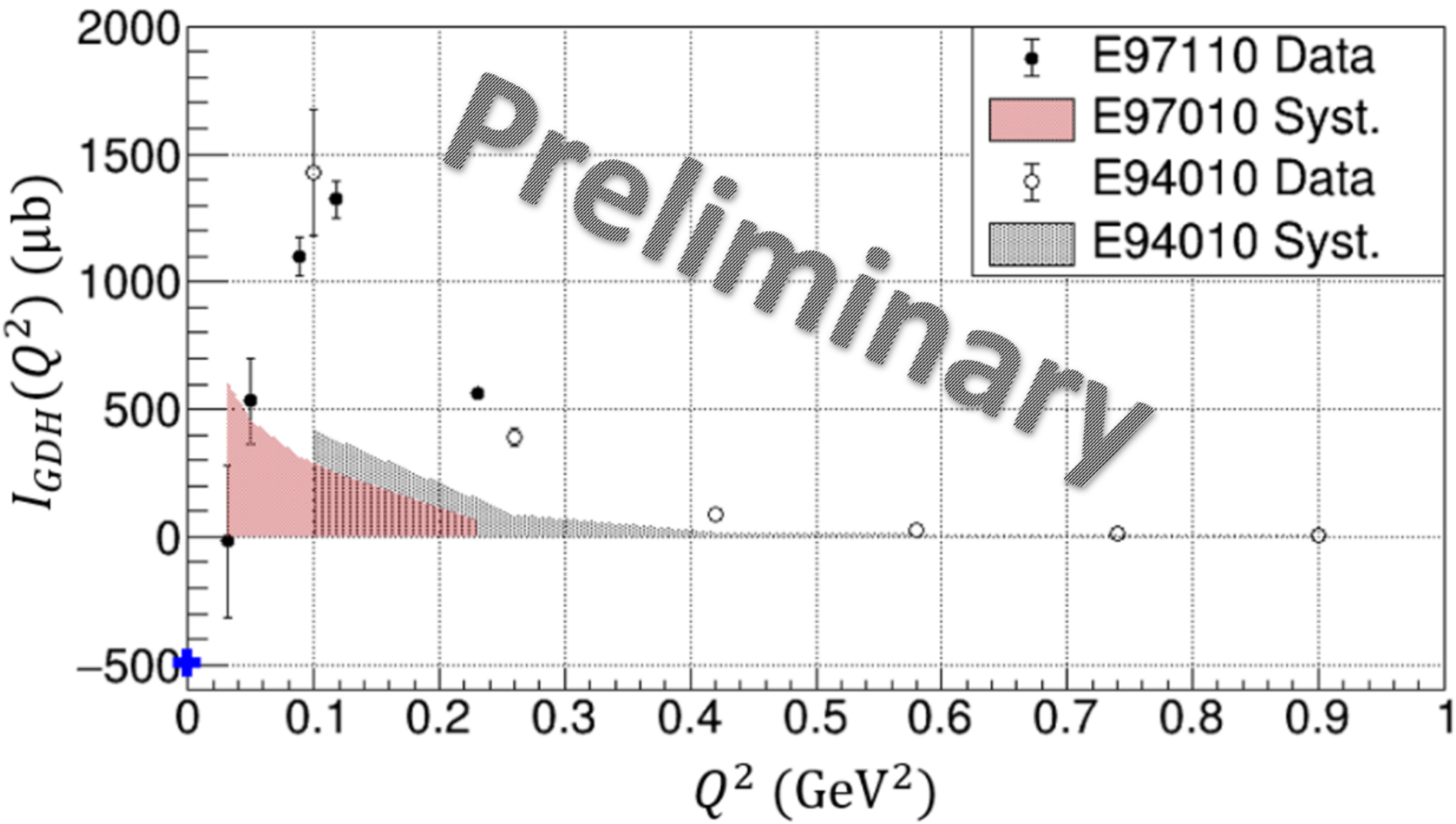


δ_{LT} and γ_0 expected soon

V. Sulkosky et al.,
arXiv 1908.05709
accepted by Phys. Lett. B

New 3He Spin Structure Data from E97-110

Figure credit: C. Peng



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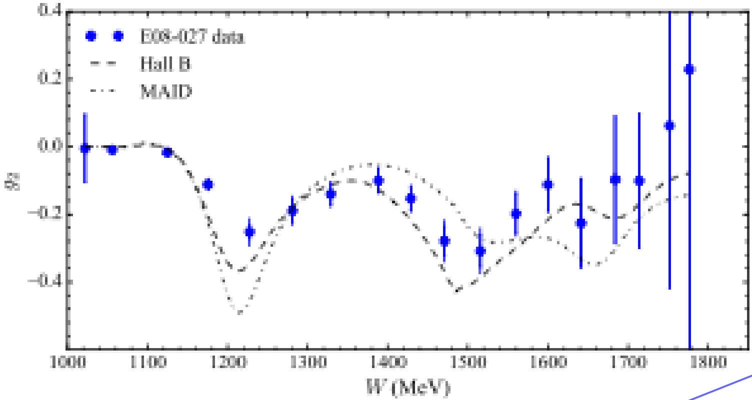
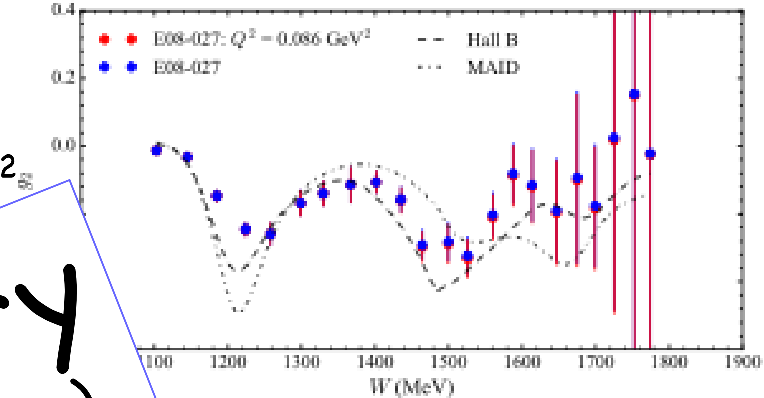
New proton g_2^p results from E08-027

Figure credit: K. Slifer

Q^2= 0.08 GeV^2



(a) E_0 = 2254 MeV 5T Transverse

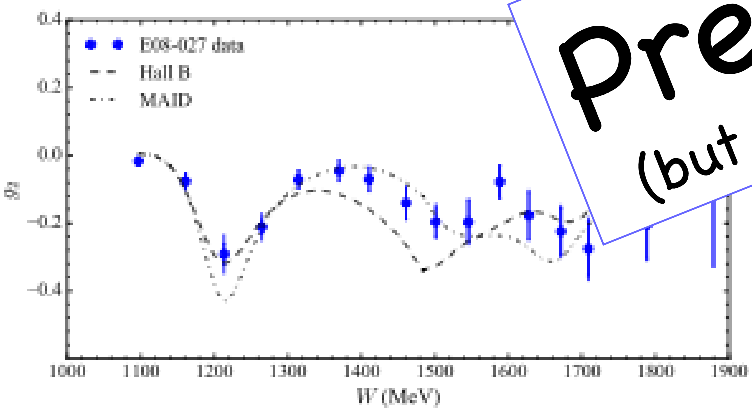


(a) E_0 = 2254 MeV 5T Transverse

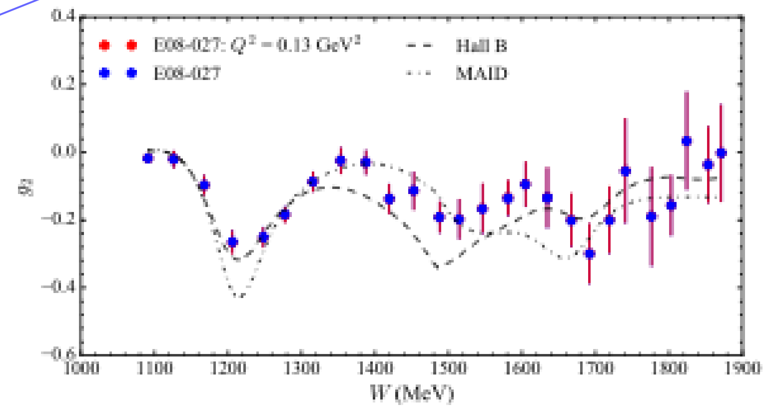
Preliminary

(but analysis complete)

Q^2= 0.13 GeV^2

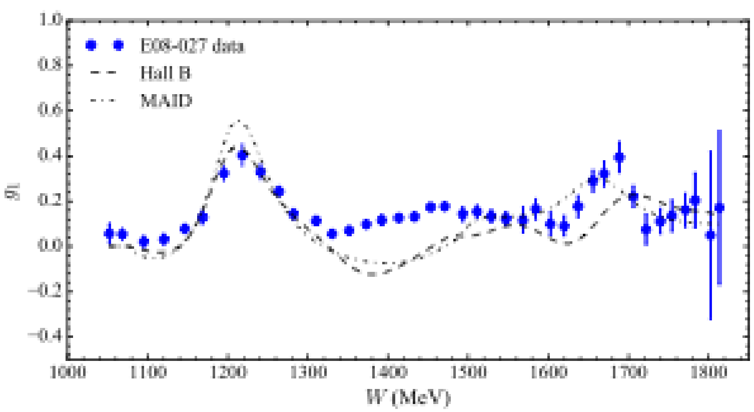


(b) E_0 = 3350 MeV 5T Transverse

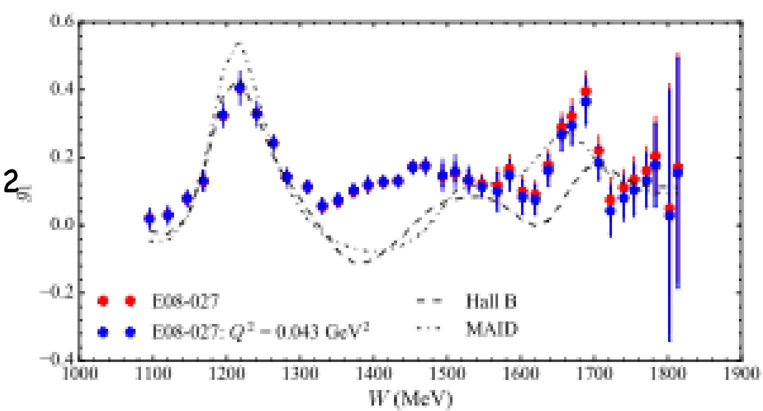


(b) E_0 = 3350 MeV 5T Transverse

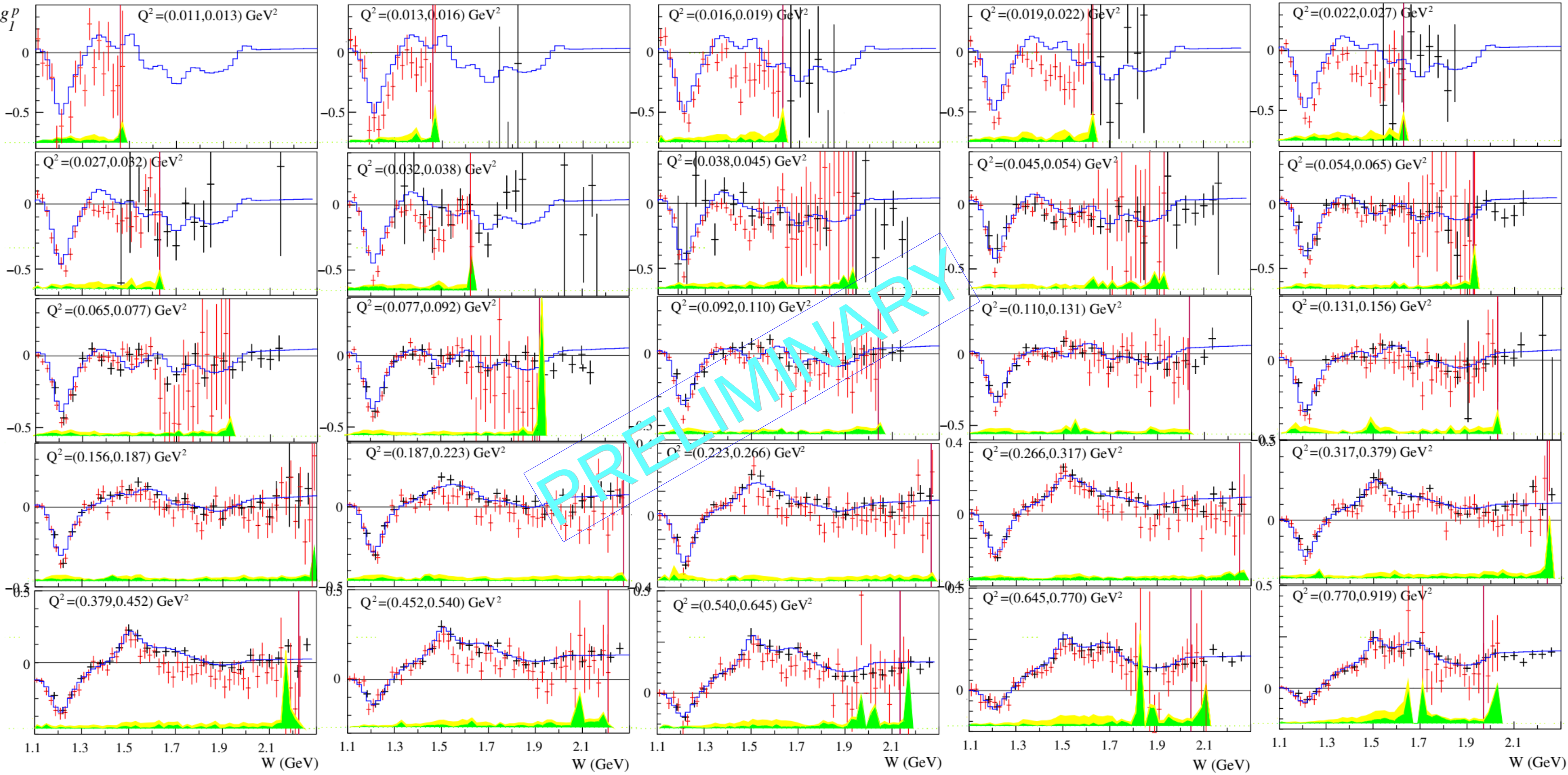
Q^2= 0.04 GeV^2



(c) E_0 = 2254 MeV 5T Longitudinal

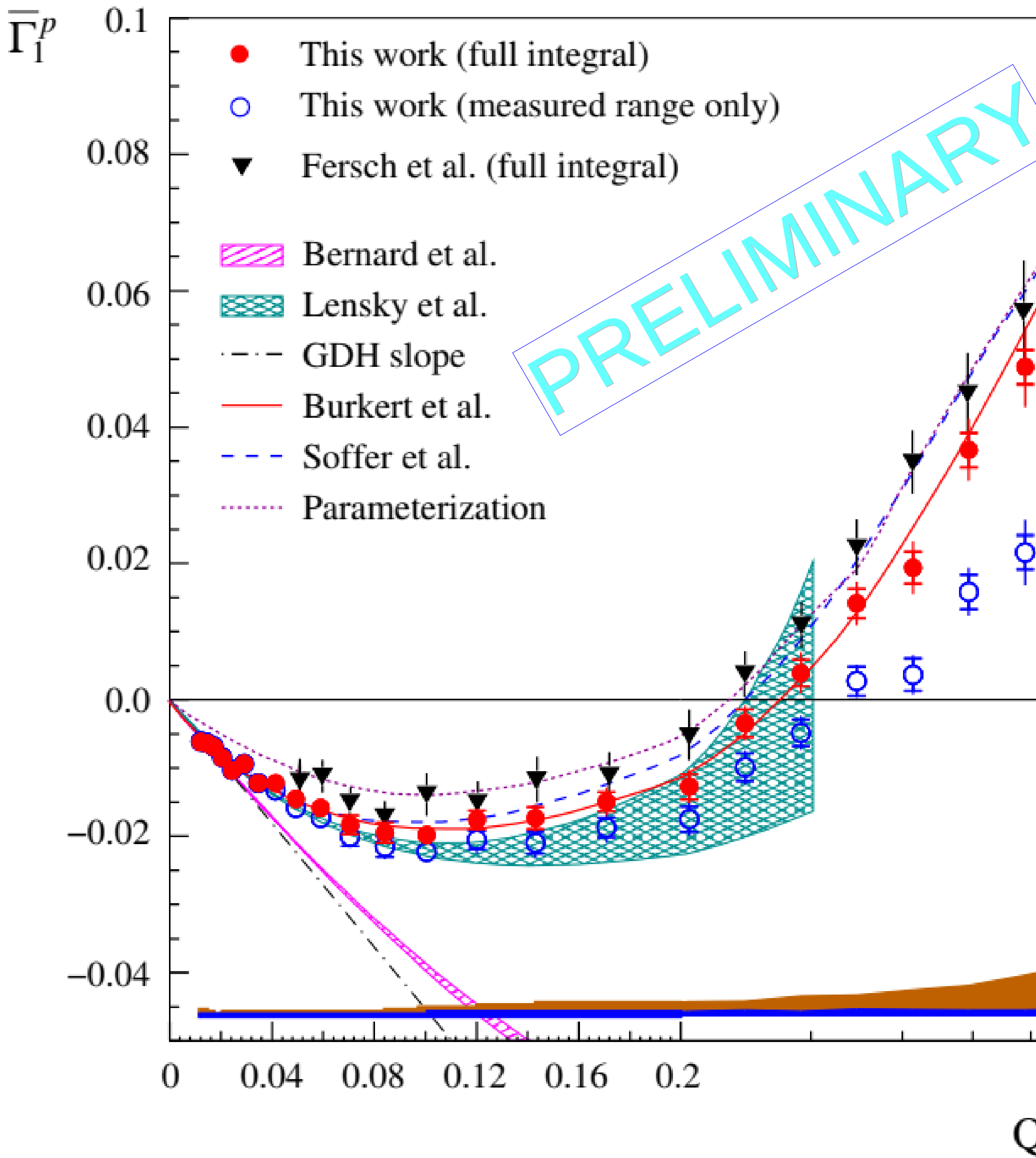


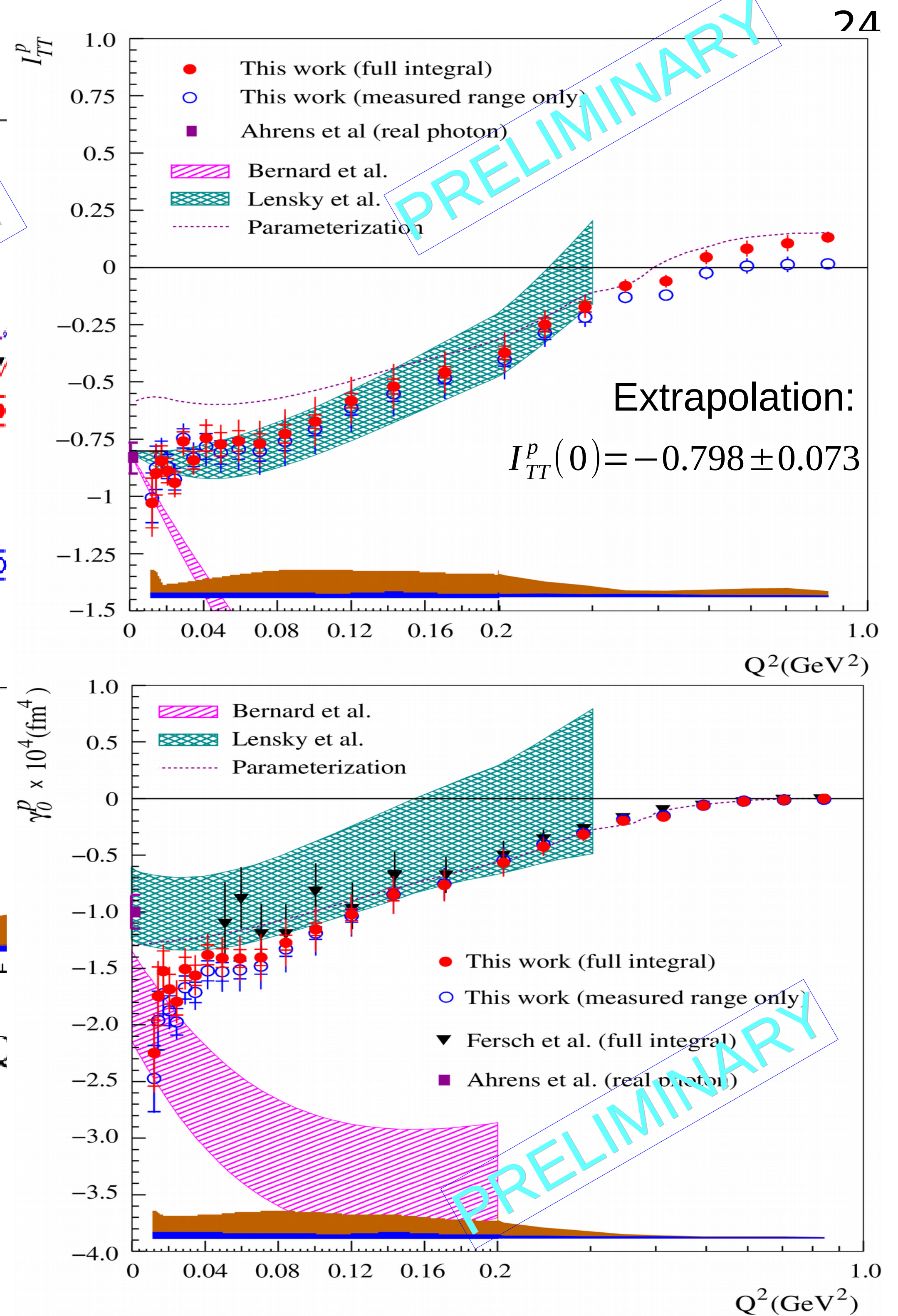
New proton results from EG4



draft paper in progress

New proton results from EG4





draft paper in progress

Data vs. Theory

Data guiding chEFT calculations

Ref.	Γ_1^p	Γ_1^n	$\mathbf{\Gamma_1^{p-n}}$	Γ_1^{p+n}	γ_0^p	γ_0^n	$\boldsymbol{\gamma_0^{p-n}}$	γ_0^{p+n}	$\boldsymbol{\delta_{LT}^n}$	d_2^n
Ji 1999 [194, 196]	X	X	A	X	-	-	-	-	-	-
Bernard 2002 [192, 193]	X	X	A	X	X	A	X	X	X	X
Kao 2002 [197]	-	-	-	-	X	A	X	X	X	X
Bernard 2012 [198]	X	X	A	X	X	A	X	X	X	-
Lensky 2014 [199]	X	A	A	A	A	X	X	X	~ A	A

A = good agreement
X = not that good

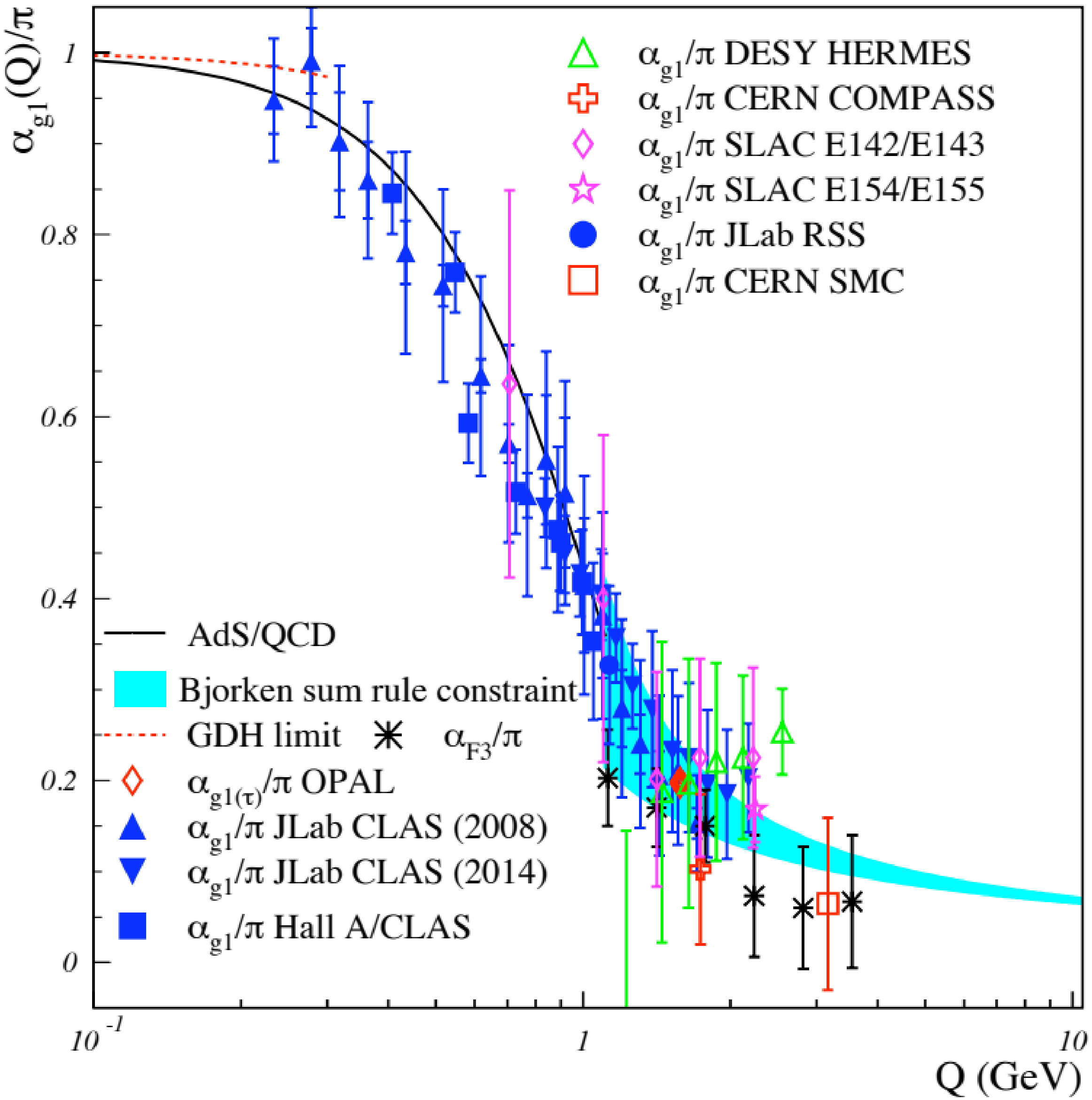
Deur, Brodsky, de Teramond

Rept.Prog.Phys. 82 (2019) 076201

We hope the puzzling discrepancies and new data will motivate Lattice gauge method calculation for spin observables.

Understanding Strong Interaction – effective α_S at all Q^2

$$\int (g_1^p - g_1^n)\, dx = \frac{1}{6} g_A \left(1 + \frac{\alpha_S(Q^2)}{\pi} + \ldots\right) + \text{non-pertubative corrections (higher twist)}$$



at low Q, α_S "flattens" (freezes), indicating QCD becomes conformal → allows new methods to be developed, perhap even help to understand confinement

lower energy values expected by combining new results from EG4(p)+E97110(n)

Deur, Brodsky, de Teramond

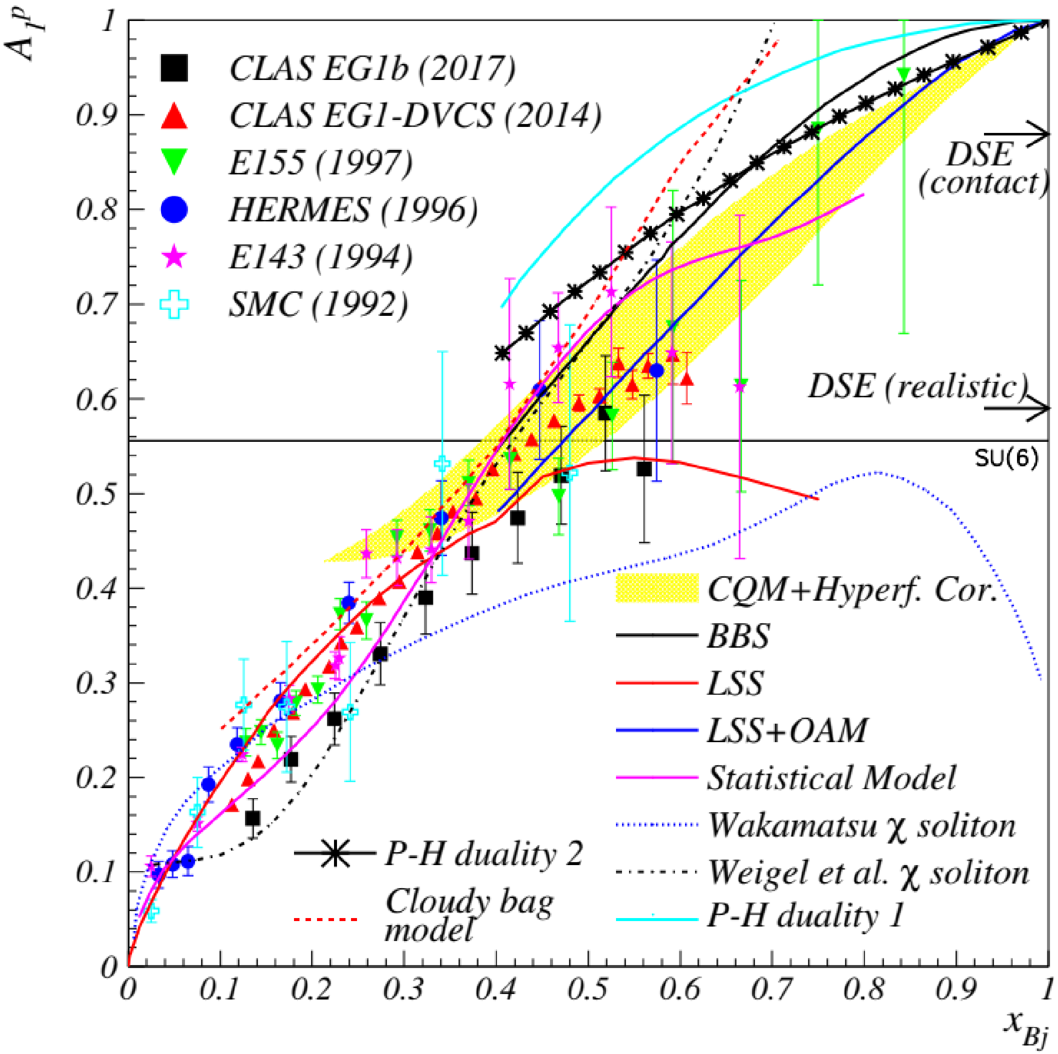
Prog. in Part. and Nucl. Phys. 90 (2016) 1

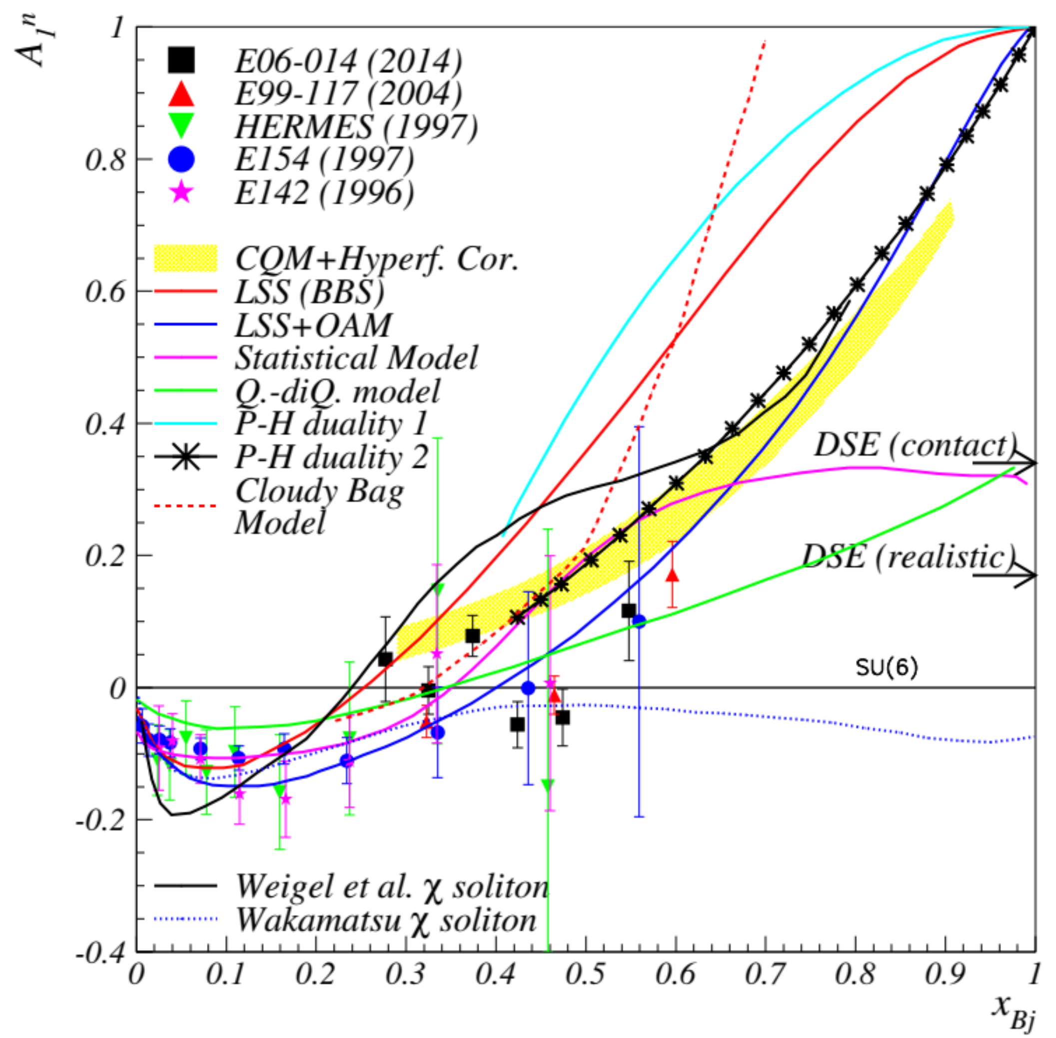
High-x Spin Physics at Jefferson Lab

The A1n and d2n experiments were/are scheduled to run from Nov 2019 to May 2020, aiming for measurement of the neutron spin structure using a polarized 3He target in Hall C.

Similar measurements on polarized protons and deuterons will be carried out in Hall B with CLAS12, using an upgraded NH3/ND3 target. These measurements (Run Group C) will likely run in 2021-2022.

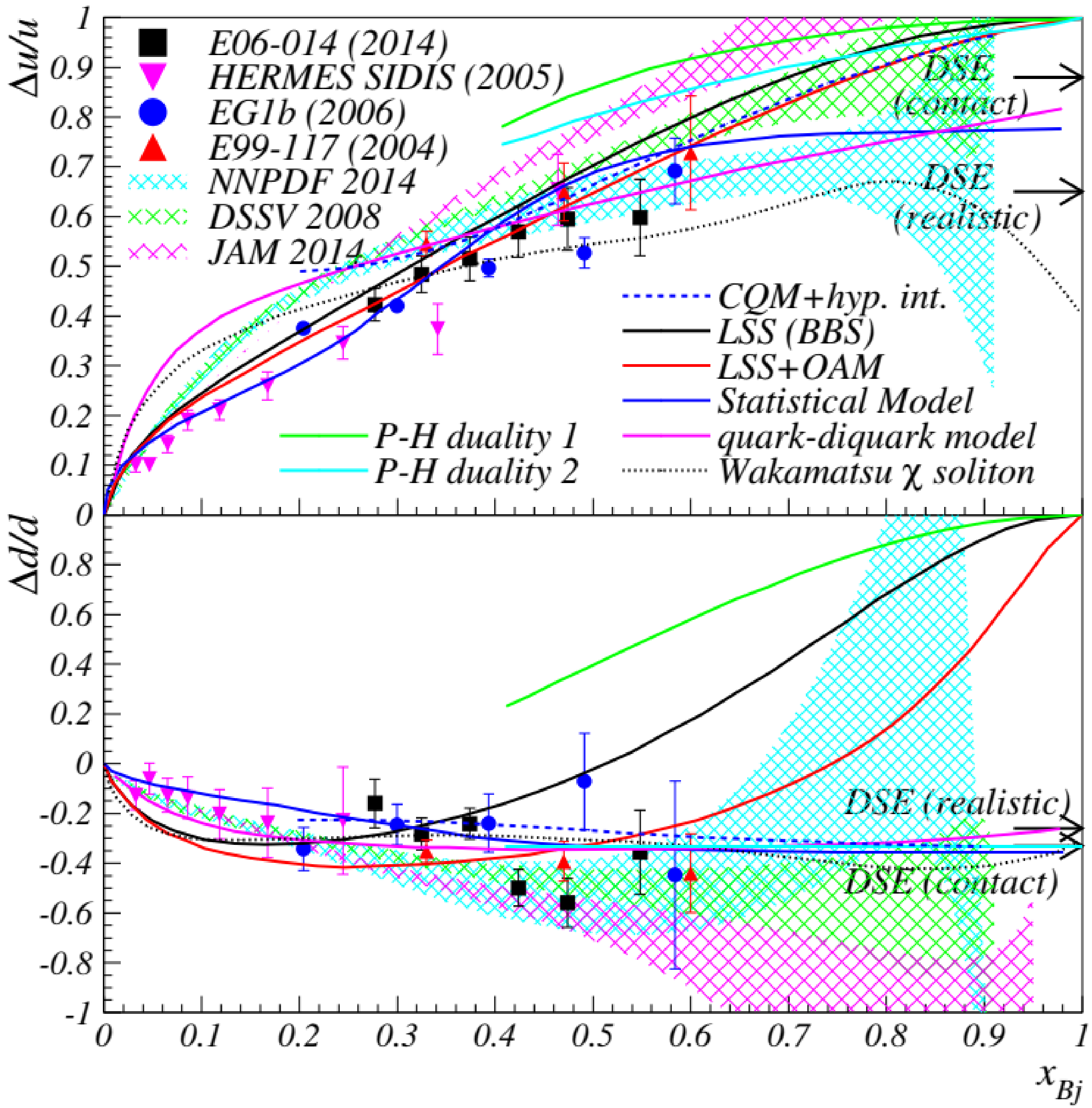
Deep Valence Region allow Testing of Theoretical Predictions





Deep Valence Region allow Testing of Theoretical Predictions

If Δd/d remains negative → may indicate nonperturbative nature (still) dominates high x nucleon structure.

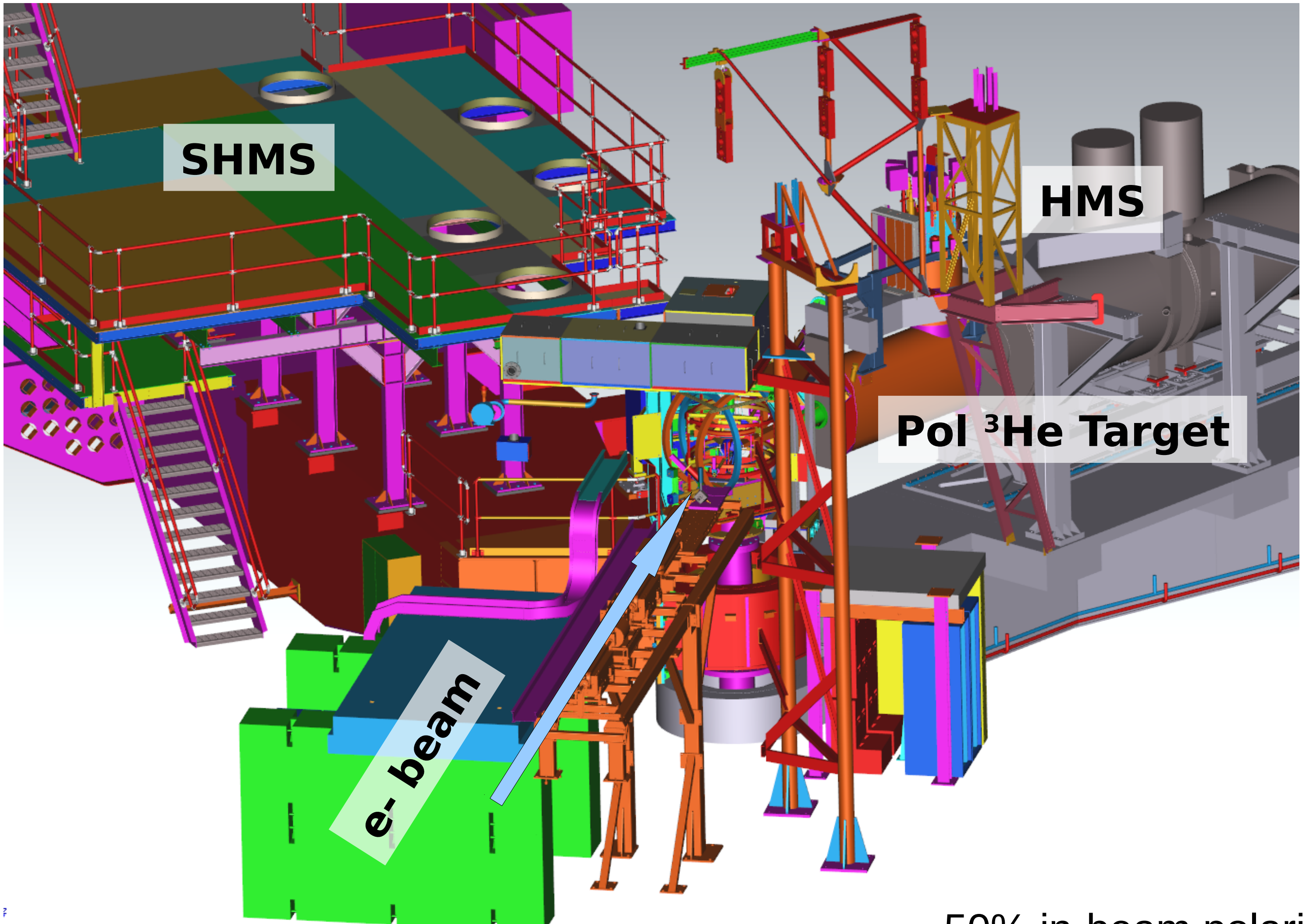


Deur, Brodsky, de Teramond

Rept.Prog.Phys. 82 (2019) 076201

New predictions available, see e.g. Liu et al., PRL 124 (2020) 8, 082003

Major Installation in Hall C (Aug -Dec 2019)

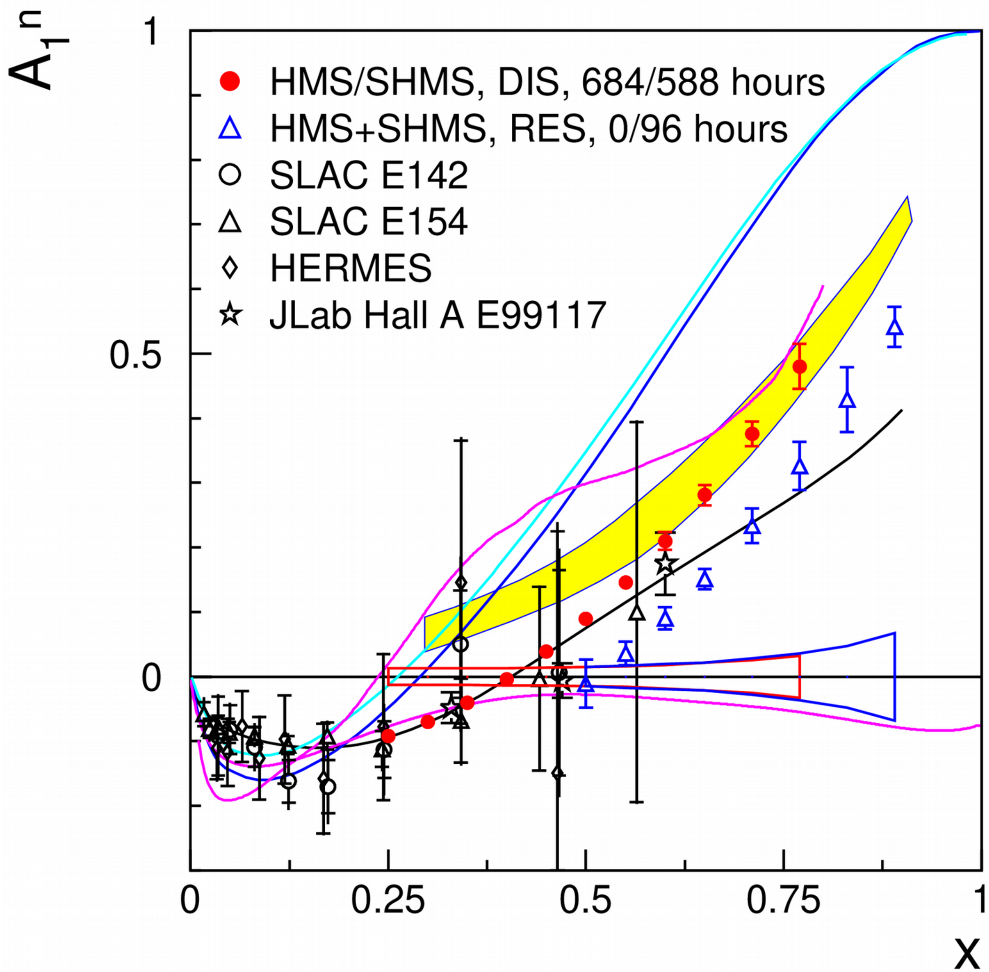


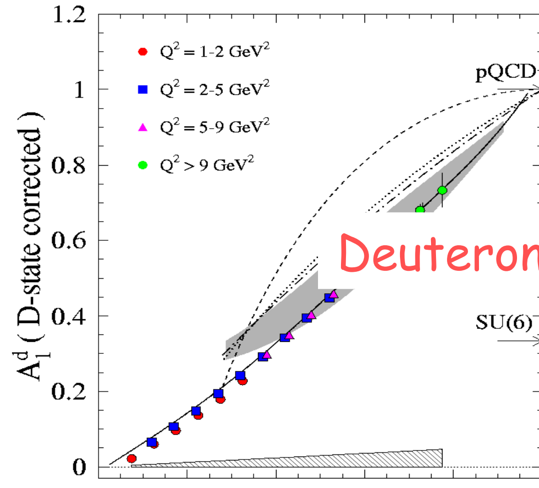
50% in-beam polarization achieved with 30uA current, a near factor 2 improvement over 6 GeV!

Expected Results on Spin Asymmetries:

A1n (3He) Hall C

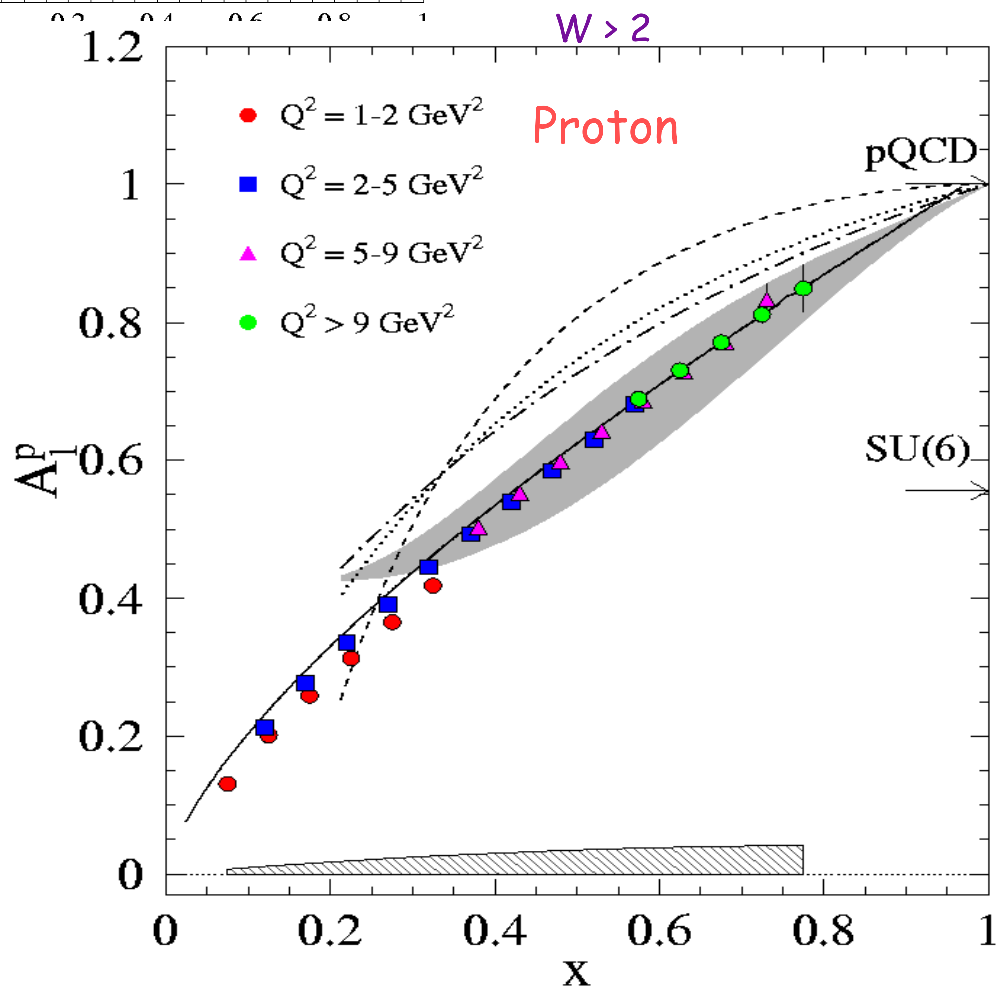
Completed (partially) by March 13th, 2020



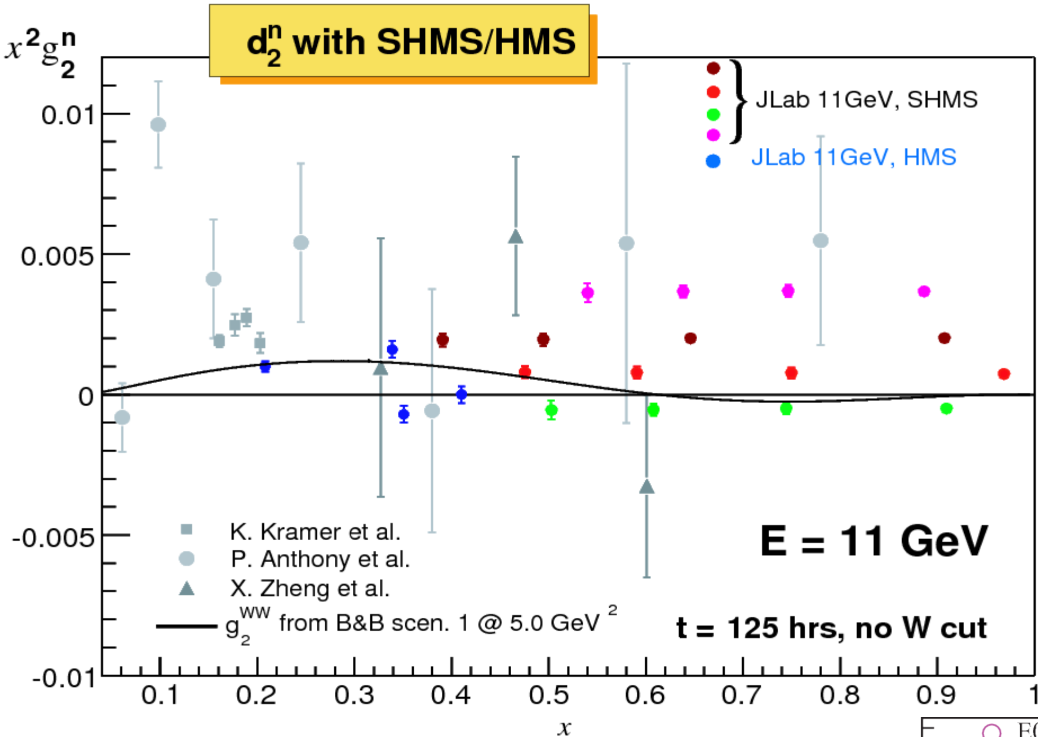


CLAS12 with 80 days (2021/2022?)

CLAS12 figure credit: S. Kuhn



Expected Results on d2n (11 GeV Hall C)

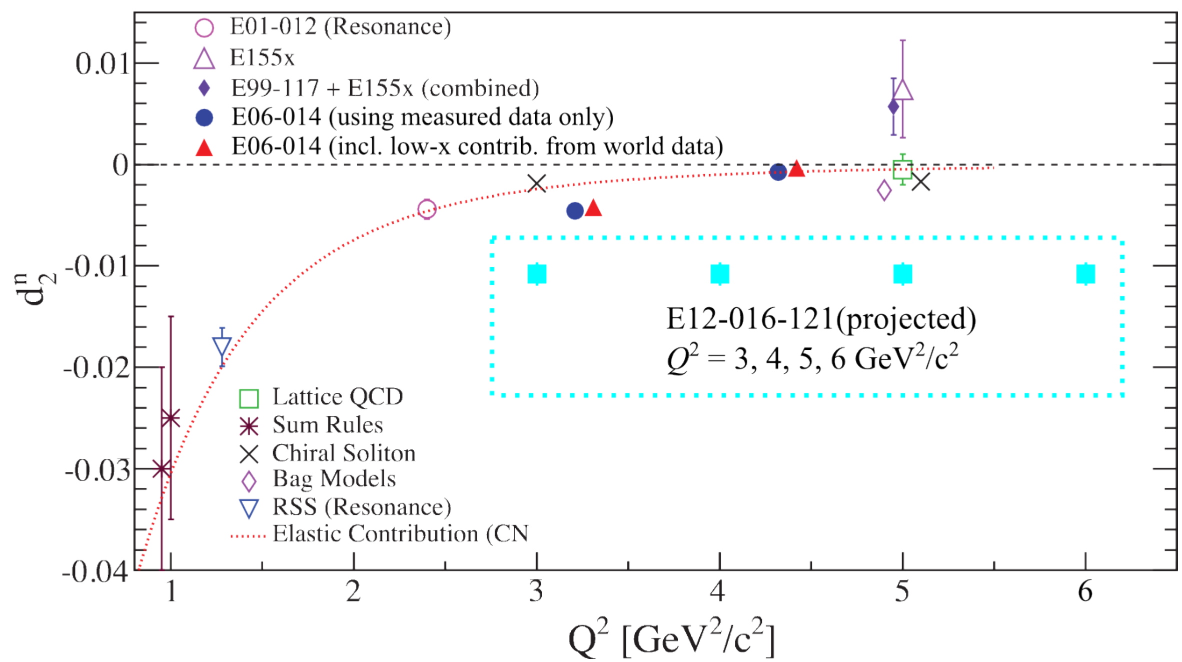


Completed a few days of data in March 2020.

Precision g_2^n data set over broad range of x and Q^2.

d_2 is a clean probe of quark-gluon correlations / higher twist effects

Q^2 evolution of d_2^n in a region where models are thought to be accurate.

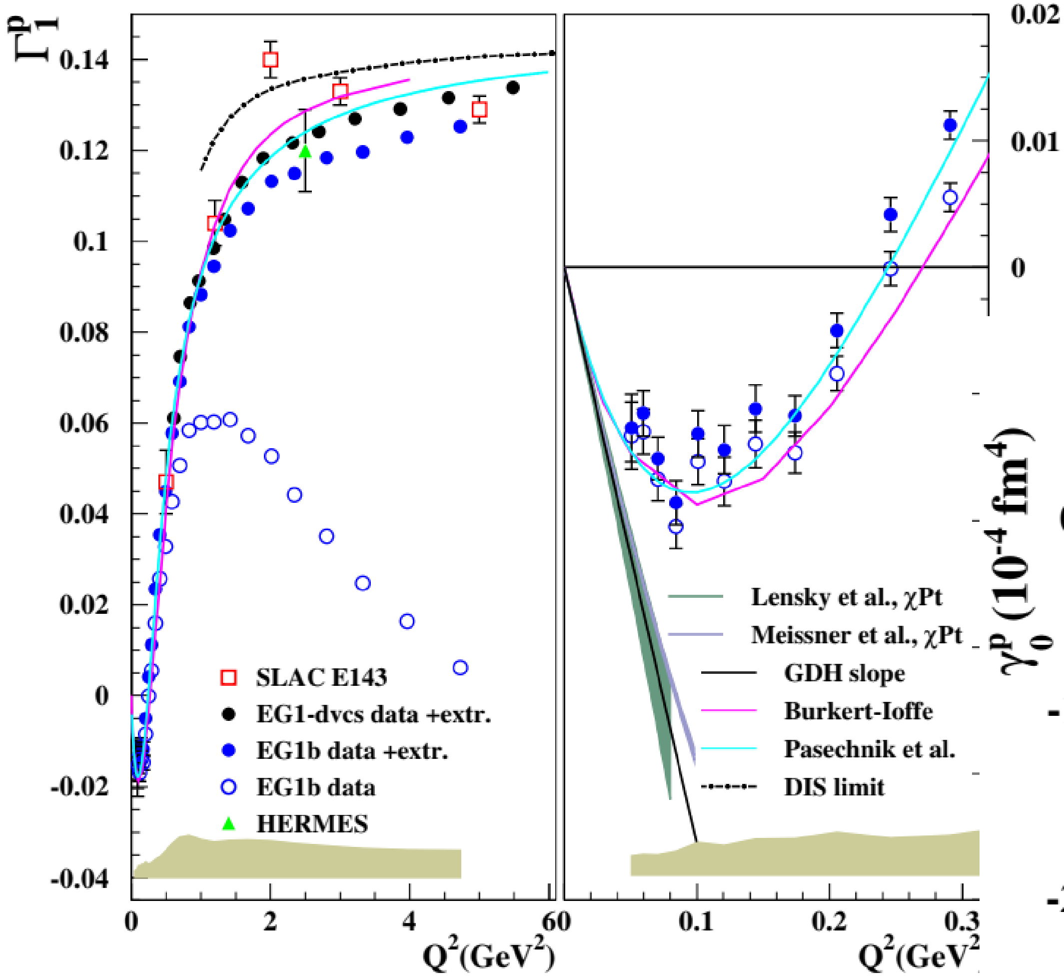


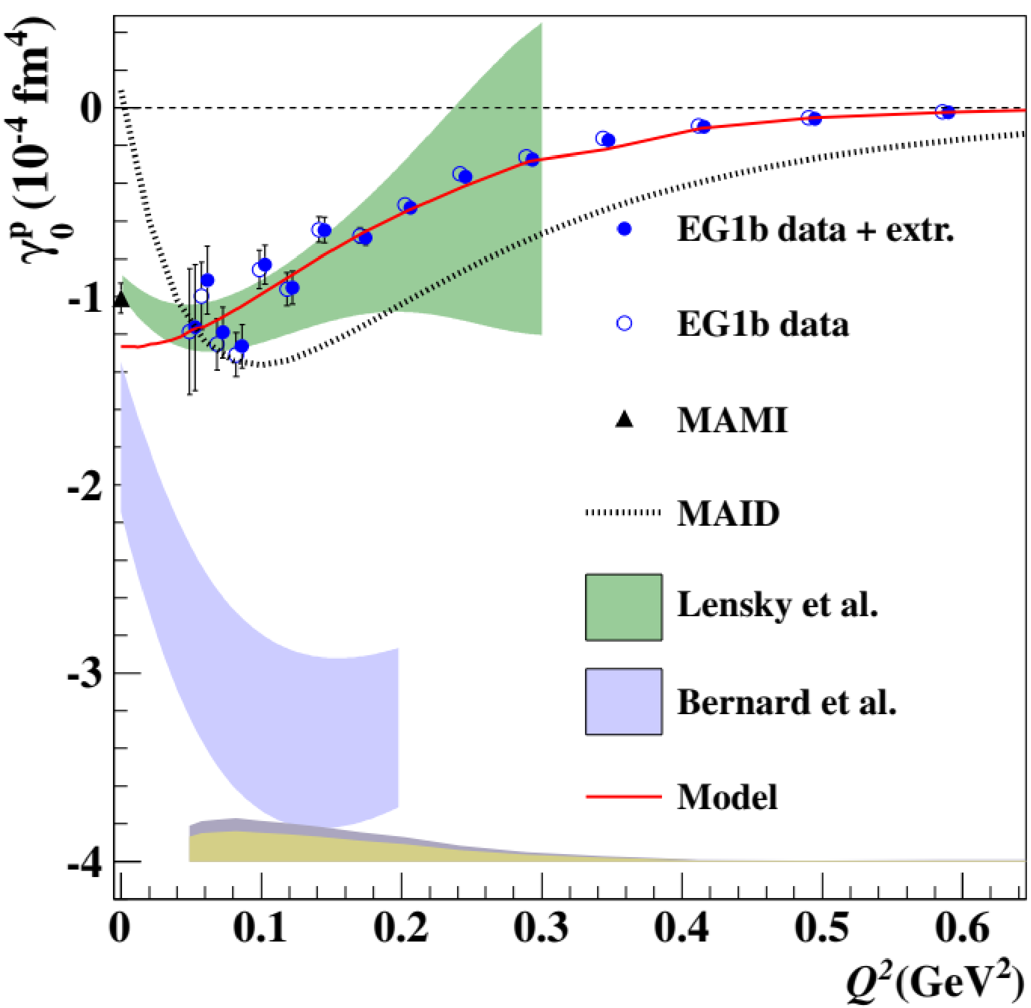
Summary and Outlook

- Understanding confinement and non-perturbative nature of strong interaction is now the most significant unresolved challenge within the Standard Model
- Nucleon spin structure provides crucial information to the study of strong interaction and QCD, from low energy (non-perturbative) to high energy (perturbative) regime, and the transition in between.
- Recent experiments at Jefferson Lab have added wealth of data, in particular the proton and the neutron spin structure functions and their moments at very low Q^2. These provide important check, guidance, and motivation for theory calculations of strong interaction at large distances.
- Spin asymmetries at large x provide a powerful test of models. The polarization of the down quark, $\Delta d/d$, will tell us whether the nucleon's behavior at high x is perturbative in nature. The 12 GeV A_1 experiments in Hall C (neutron) and in Hall B/CLAS12 (proton and deuteron) will venture into a deeper valence quark region. More spin experiments are ongoing and plnned. Stay tuned!

Table 1. Lepton scattering experiments on the nucleon spin structure and their kinematics. The column 'Analysis' indicates wether the analysis was primarily conducted in terms of asymmetries ($A_{1,2}$, or single spin asymmetry) or of cross-sections ($g_{1,2}$), and if transverse data were taken in addition to the longitudinal data.

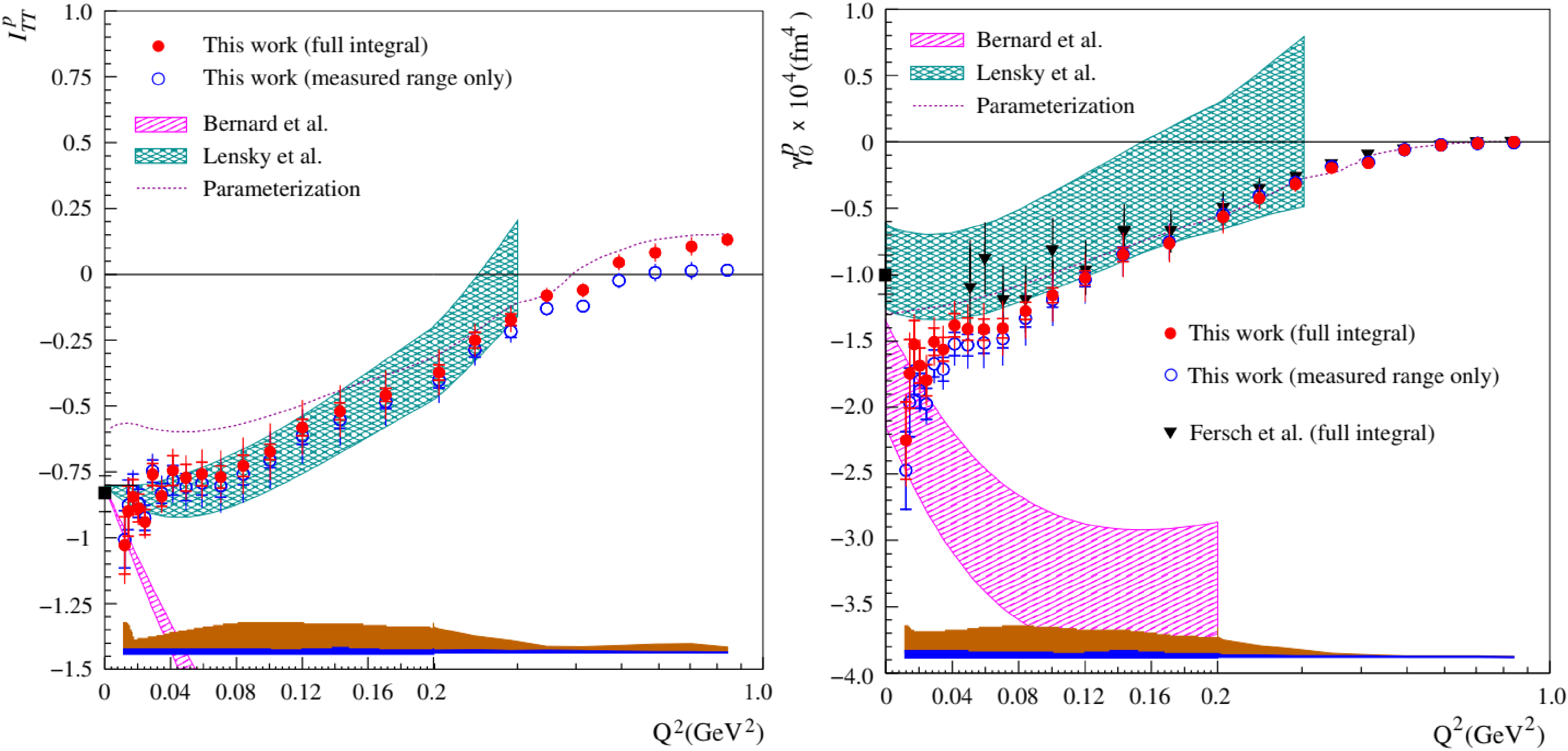
Experiment	Reference	Target	Analysis	W (GeV)	x_{Bj}	Q^2 (GeV^2)
E80 (SLAC)	[112]	p	A_1	2.1–2.6	0.2–0.33	1.4–2.7
E130 (SLAC)	[113]	p	A_1	2.1–4.0	0.1–0.5	1.0–4.1
EMC (CERN)	[114]	p	A_1	5.9–15.2	1.5×10^{-2}–0.47	3.5–29.5
SMC (CERN)	[271]	p, d	A_1	7.7–16.1	10^{-4}–0.482	0.02–57
E142 (SLAC)	[267]	^{3}He	A_1, A_2	2.7–5.5	3.6×10^{-2}–0.47	1.1–5.5
E143 (SLAC)	[268]	p, d	A_1, A_2	1.1–6.4	3.1×10^{-2}–0.75	0.45–9.5
E154 (SLAC)	[256, 269]	^{3}He	A_1, A_2	3.5–8.4	1.7×10^{-2}–0.57	1.2–15.0
E155/E155x (SLAC)	[257, 270]	p, d	A_1, A_2	3.5–9.0	1.5×10^{-2}–0.75	1.2–34.7
HERMES (DESY)	[273, 274]	p, ^{3}He	A_1	2.1–6.2	2.1×10^{-2}–0.85	0.8–20
E94010 (JLab)	[275]	^{3}He	g_1, g_2	1.0–2.4	1.9×10^{-2}–1.0	0.019–1.2
EG1a (JLab)	[276]	p, d	A_1	1.0–2.1	5.9×10^{-2}–1.0	0.15–1.8
RSS (JLab)	[277, 278]	p, d	A_1, A_2	1.0–1.9	0.3–1.0	0.8–1.4
COMPASS (CERN) DIS	[272]	p, d	A_1	7.0–15.5	4.6×10^{-3}–0.6	1.1–62.1
COMPASS (CERN) low-Q^2	[325]	p, d	A_1	5.2–19.1	4×10^{-5}–4×10^{-2}	0.001–1.
EG1b (JLab)	[279–282]	p, d	A_1	1.0–3.1	2.5×10^{-2}–1.0	0.05–4.2
E99-117 (JLab)	[283]	^{3}He	A_1, A_2	2.0–2.5	0.33–0.60	2.7–4.8
E97-103 (JLab)	[284]	^{3}He	g_1, g_2	2.0–2.5	0.16–0.20	0.57–1.34
E01-012 (JLab)	[285, 286]	^{3}He	g_1, g_2	1.0–1.8	0.33–1.0	1.2–3.3
E97-110 (JLab)	[287]	^{3}He	g_1, g_2	1.0–2.6	2.8×10^{-3}–1.0	0.006–0.3
EG4 (JLab)	[243]	p, n	g_1	1.0–2.4	7.0×10^{-3}–1.0	0.003–0.84
SANE (JLab)	[289]	p	A_1, A_2	1.4–2.8	0.3–0.85	2.5–6.5
EG1dvcs (JLab)	[288]	p	A_1	1.0–3.1	6.9×10^{-2}–0.63	0.61–5.8
E06-014 (JLab)	[290, 291]	^{3}He	g_1, g_2	1.0–2.9	0.25–1.0	1.9–6.9
E06-010/011 (JLab)	[296]	^{3}He	single spin asy.	2.4–2.9	0.16–0.35	1.4–2.7
E07-013 (JLab)	[297]	^{3}He	single spin asy.	1.7–2.9	0.16–0.65	1.1–4.0
E08-027 (JLab)	[326]	p	g_1, g_2	1.–2.1	3.0×10^{-3}–1.0	0.02–0.4





Fersch et al. PRC 96 065208 (2017)

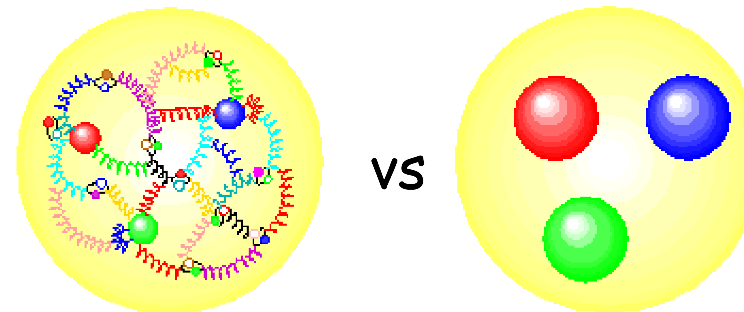
New proton results from EG4



draft paper in progress

Nucleon (spin) Structure at High x_{Bj}

- We need structure function measurements for which QCD can make absolute predictions!

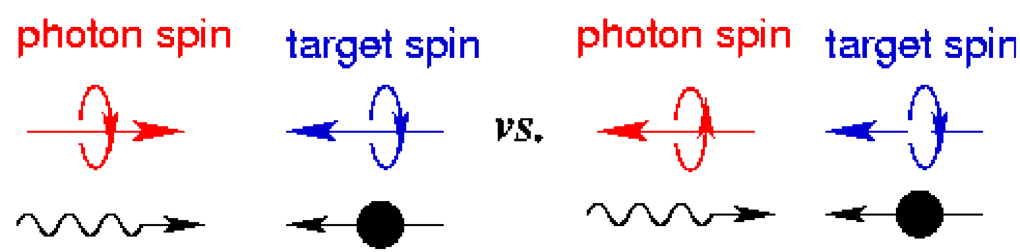


The far valence domain (x>0.5)

- involve only valence quarks
- is the only domain where QCD (and many other models) can make absolute predictions for (the ratio of) structure functions
- "the ratio of structure functions at x→ 1 provide unambiguous, scale invariant, non-perturbative features of QCD"

☆ F_2^p/F_2^n and d/u

☆ A_1^p, A_1^n , or $\Delta u/u$ and $\Delta d/d$

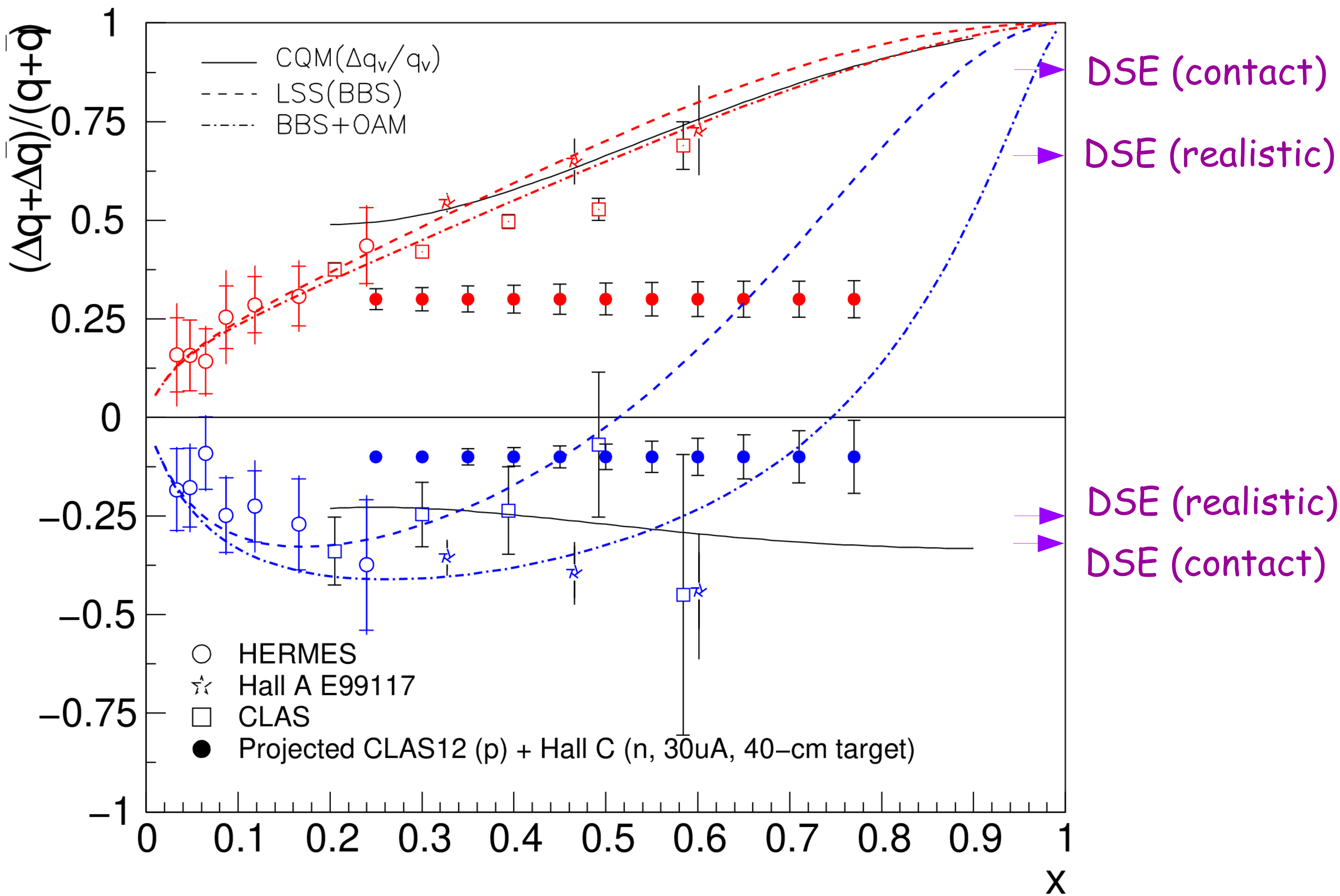


$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

$$A_1 = \frac{g_1 - \gamma^2 g_2}{F_1} \approx \frac{g_1}{F_1}$$ at large Q^2

$$\gamma^2 = \frac{Q^2}{\nu^2} = \frac{4M^2x^2}{Q^2}$$

Extracting Δq/q from both proton and neutron (^{3}He) data



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