Overview of Spin Physics Program at JLab

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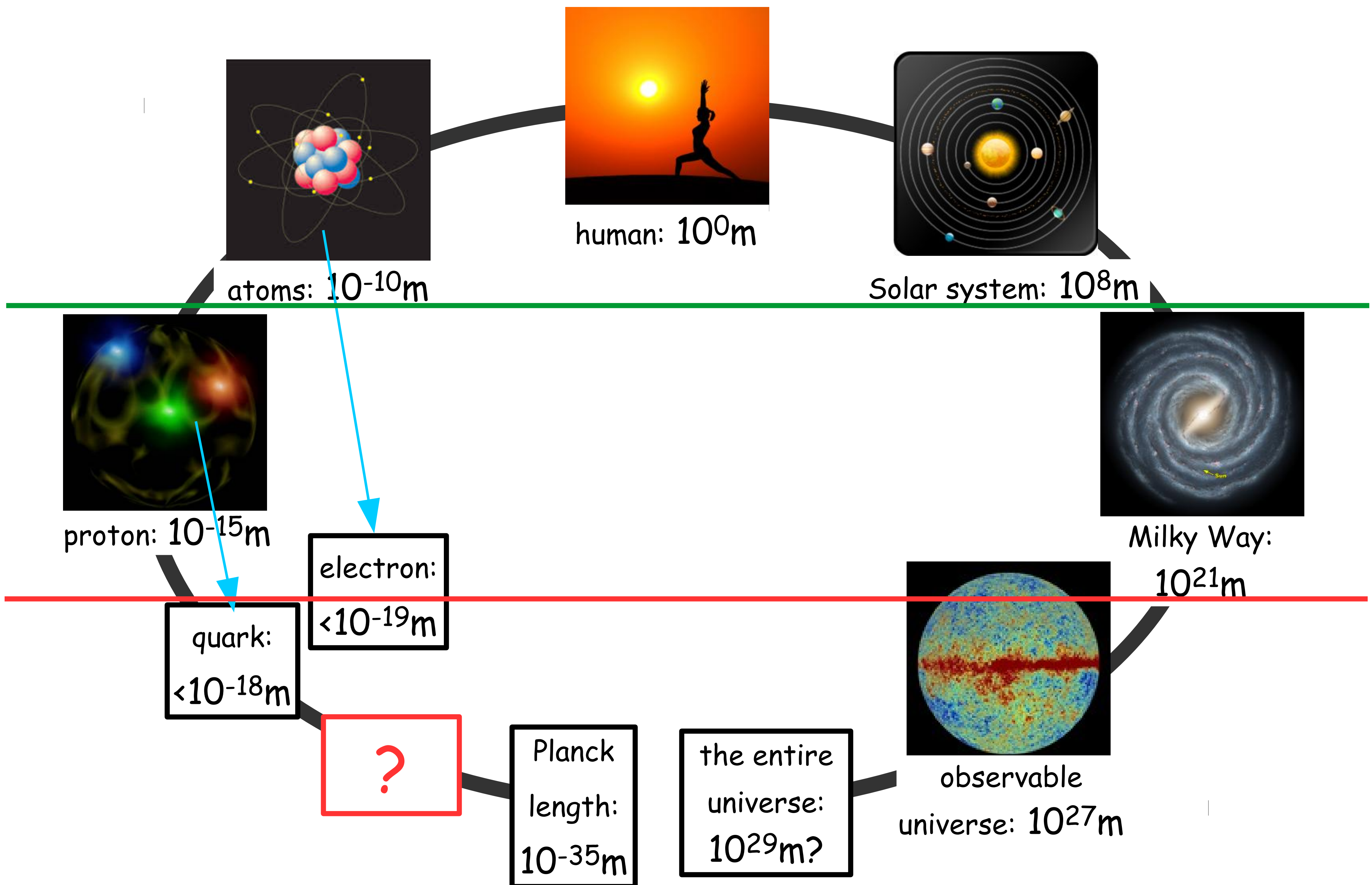
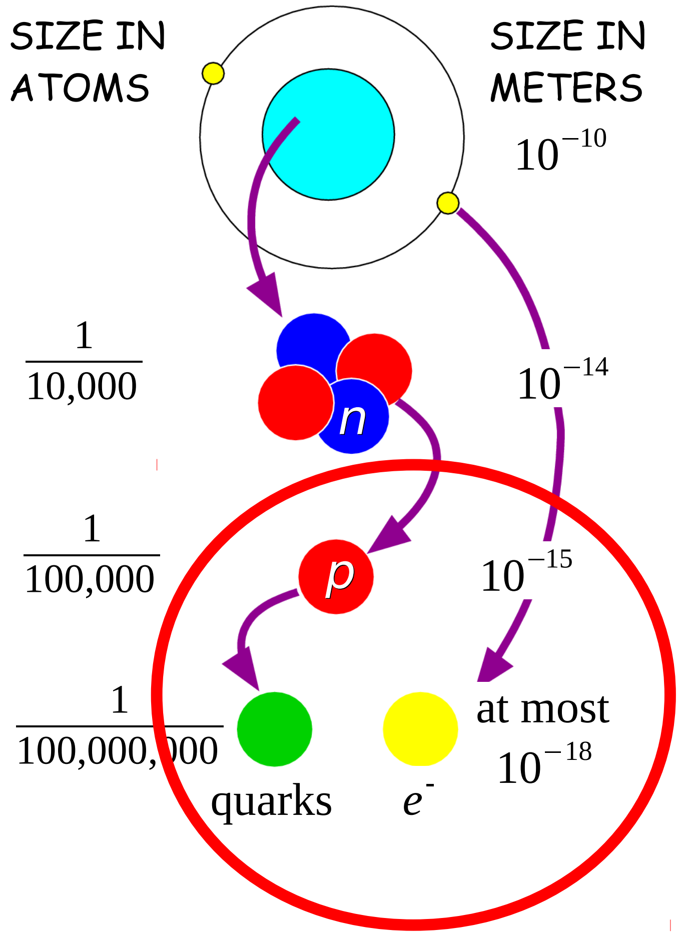
- The Standard Model of subatomic physics
- How does nucleon spin study fit in
- Inclusive spin physics program at JLab
  - low Q^2 spin physics and results from the past year
  - high x spin physics and upcoming experiments
- Summary and outlook

The Beauty of Physics – From Leptons and Quarks to the Cosmos



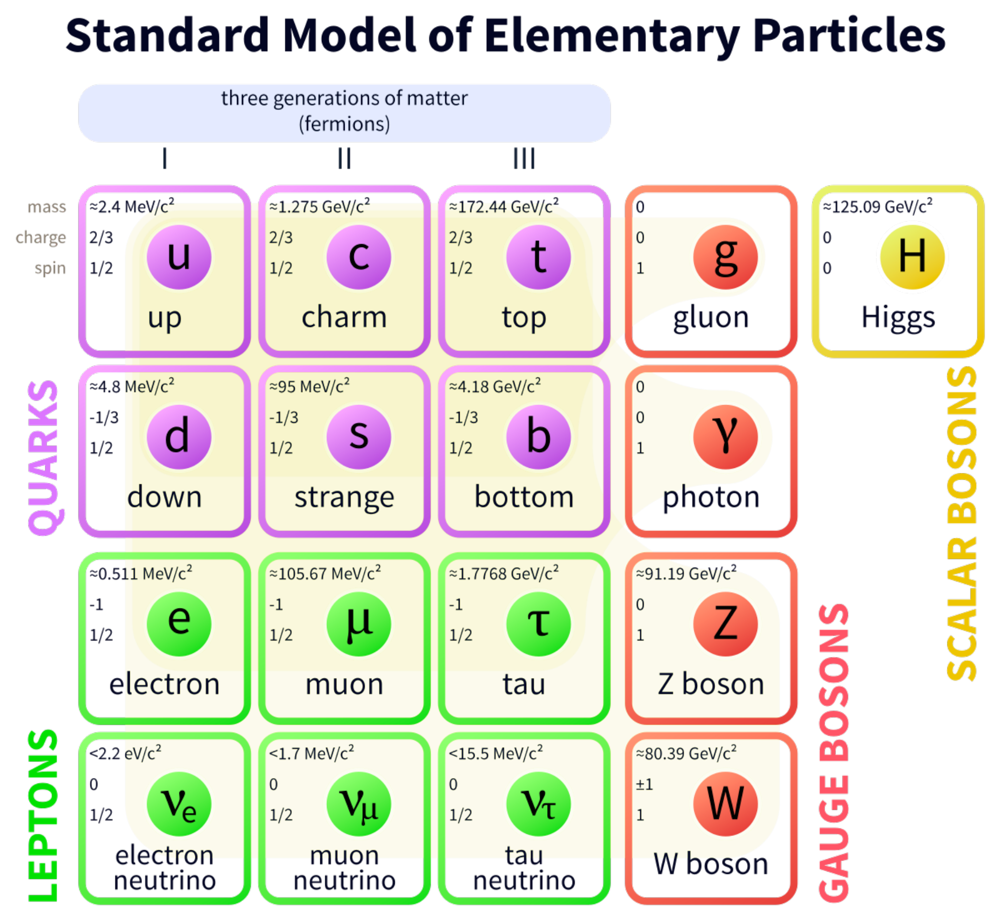
The Standard Model



(1) the elementary fermions - quarks and leptons

(2) the symmetries + gauge invariance → interactions

(3) the origin of masses



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

Within the Standard Model, or Beyond the Standard Model?

The Standard Model is "an effective theory at the electroweak scale"

Many subatomic physicists are now focusing on searching for new physics beyond the Standard Model – new particles, new symmetries, new interactions, new structures, high precision measurement of all couplings and other parameters...

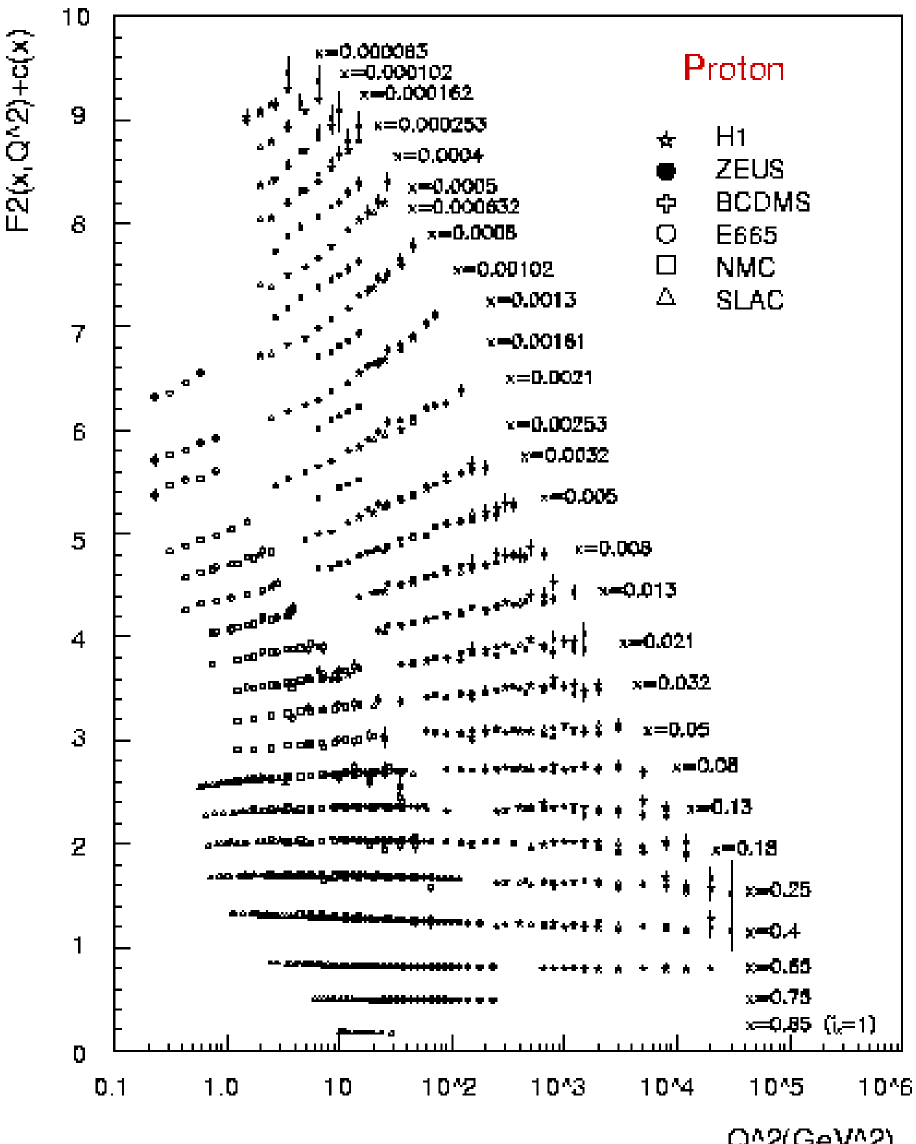
Or, within the Standard Model:

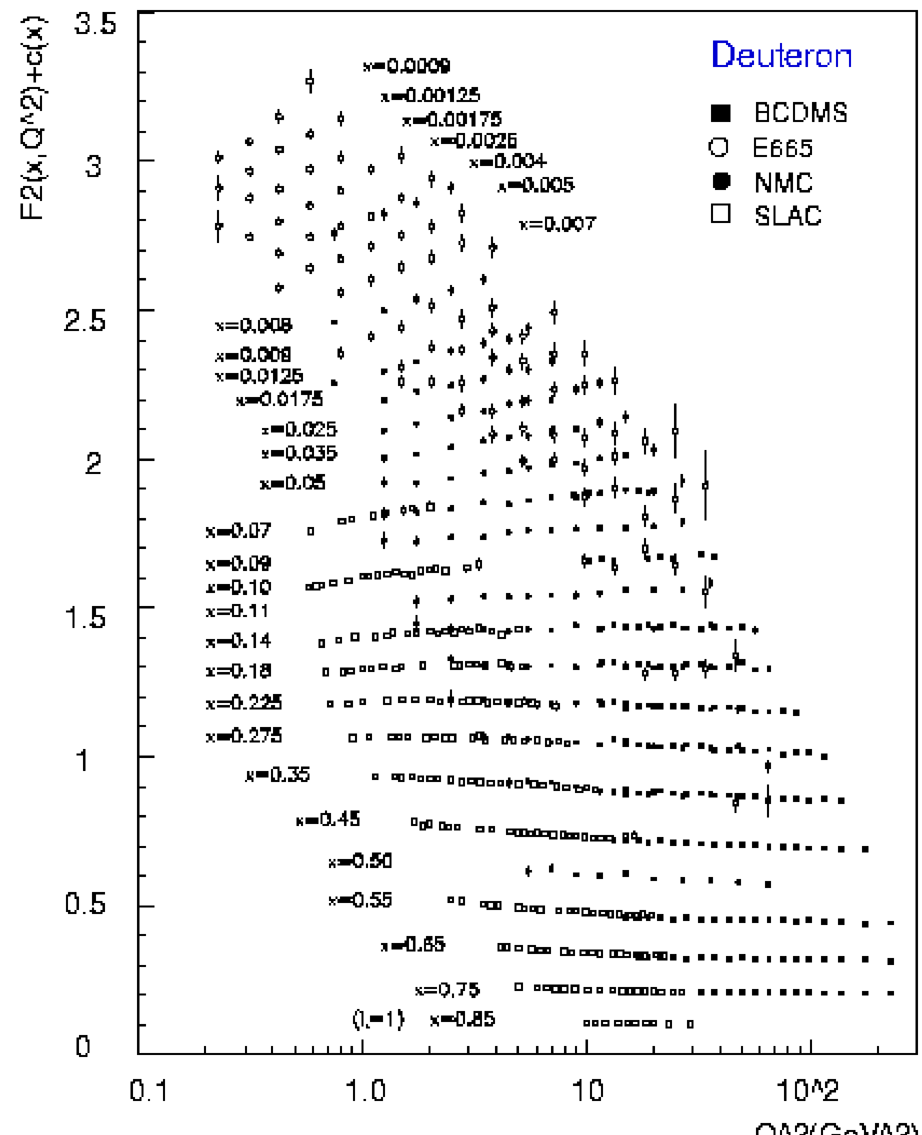
- QED: tested to 9 orders of magnitude
- Electroweak unification has been tested rigorously and so far data do not indicate any new physics
- Strong interaction: asymptotic freedom vs. confinement

Success of QCD – but only in the perturbative regime

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

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





Success and Challenges – Hadronic Structure Study and QCD

- DIS established the existence of quarks
- QCD can successfully explain asymptotic freedom, and perturbative calculations explain well the Q^2-evolution of structure functions
- But we do not know or understand:
  - how confinement arises from QCD Lagrangian, quantitatively – this is a serious problem, are quarks even real?
  - the mechanism of chiral symmetry breaking
  - the nature of the QCD vacuum and to explain it theoretically (the strong CP problem?)
  - how to calculate/predict the value of form factors or structure functions

Within the Standard Model, or Beyond the Standard Model?

The Standard Model is "an effective theory at the electroweak scale"

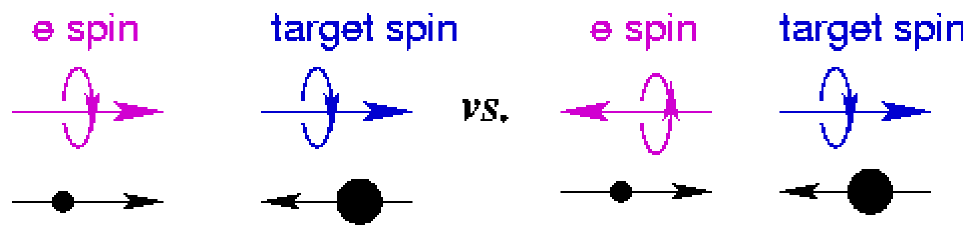
Many subatomic physicists are now focusing on searching for new physics beyond the Standard Model – new particles, new symmetries, new interactions, new structures, high precision measurement of all masses (neutrinos) and couplings...

But is the Standard Model that successful yet?

- QED has been tested to 9 orders of magnitude
- Electroweak unification has been tested rigorously and so far data do not indicate any new physics
- Strong interaction: asymptotic freedom vs. confinement
- We do not yet know how to explain nonperturbative phenomena → We should boldly claim that we are still missing 1/6 of the Standard Model!

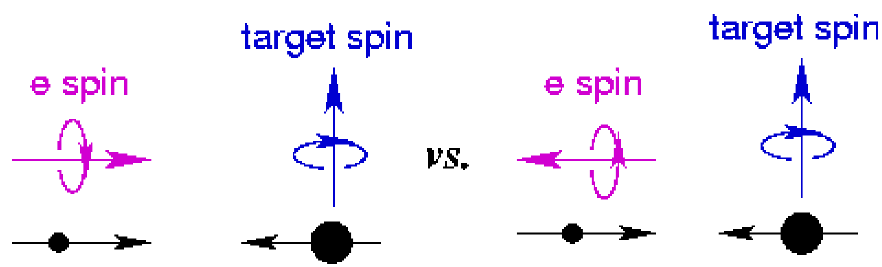
Nucleon Spin Structure from Polarized Inclusive DIS

- Scattering cross section is spin-dependent
- Longitudinal



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

- Transverse



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

- in QPM and the infinite momentum frame:

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

How does Nucleon Spin Physics Contribute to QCD/Strong Interaction Study? – Theoretical Aspect

- To understand the compositeness – how do partons form the nucleon spin? – the proton spin crisis/puzzle
- perturbative/high-energy/short-distance regime: to verify perturbative QCD calculations
- non-perturbative/low-energy/long-distance regime: to test effective field theories that use the hadronic degrees of freedom
- to provide predictions for structure functions
- how hadrons arise from quark and gluon degrees of freedom? – lattice QCD

How does Nucleon Spin Physics Contribute to QCD/Strong Interaction Study? – Observables

- To understand the compositeness – how do partons form the nucleon spin? – moments (of polarized structure functions)
- perturbative/high-energy/short-distance regime: to verify perturbative QCD calculations – Q^2 evolution of g1, etc
- non-perturbative/low-energy/long-distance regime: to test effective field theories that use the hadronic degrees of freedom – moments at very low Q^2/long distances
- to provide predictions for structure functions – structure function ratios at large x
- how hadrons arise from quark and gluon degrees of freedom? – Q^2 dependence of moments

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  - structure function ratios at large x
- how hadrons arise from quark and gluon degrees of freedom?
  - Q^2 dependence of moments

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)

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

axial charge

- GDH Sum Rule (real photon):

anomalous magnetic moment

(unitarity)

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

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

$$\frac{16\alpha\pi^2}{Q^2} \int_0^1 g_1\, dx = 2\alpha\pi^2 S_1 \xrightarrow[Q^2 \to 0]{} -\frac{2\alpha\pi^2\kappa^2}{M^2}$$

low-to-intermediate Q²: chiral PT, OPE

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:

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

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

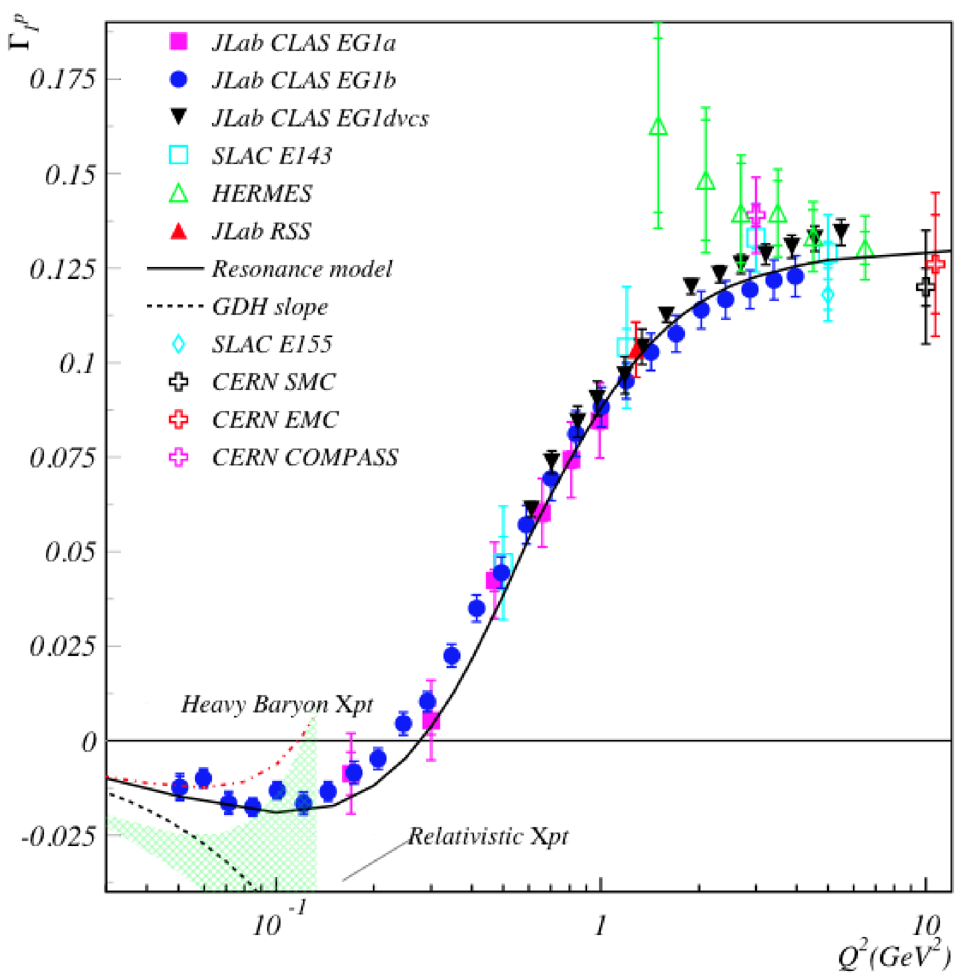
Lepton scattering spin structure experiments (mostly inclusive):

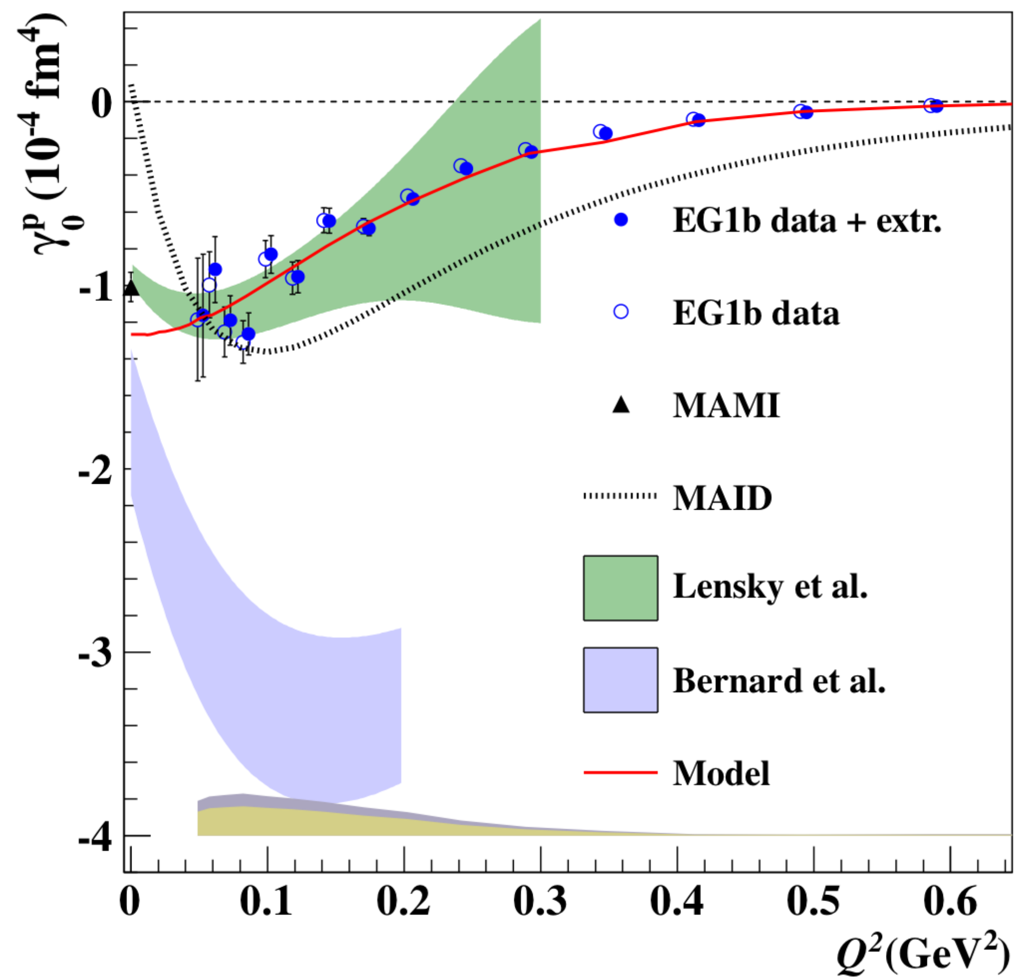
Experiment	Ref.	Target	Analysis	W (GeV)	x_{Bj}	Q^2 (GeV^2)
E80 (SLAC)	[101]	p	A_1	2.1 to 2.6	0.2 to 0.33	1.4 to 2.7
E130 (SLAC)	[102]	p	A_1	2.1 to 4.0	0.1 to 0.5	1.0 to 4.1
EMC (CERN)	[103]	p	A_1	5.9 to 15.2	1.5×10^{-2} to 0.47	3.5 to 29.5
SMC (CERN)	[250]	p, d	A_1	7.7 to 16.1	10^{-4} to 0.482	0.02 to 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

JLab's focus is high precision and low to intermediate Q^2 values

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

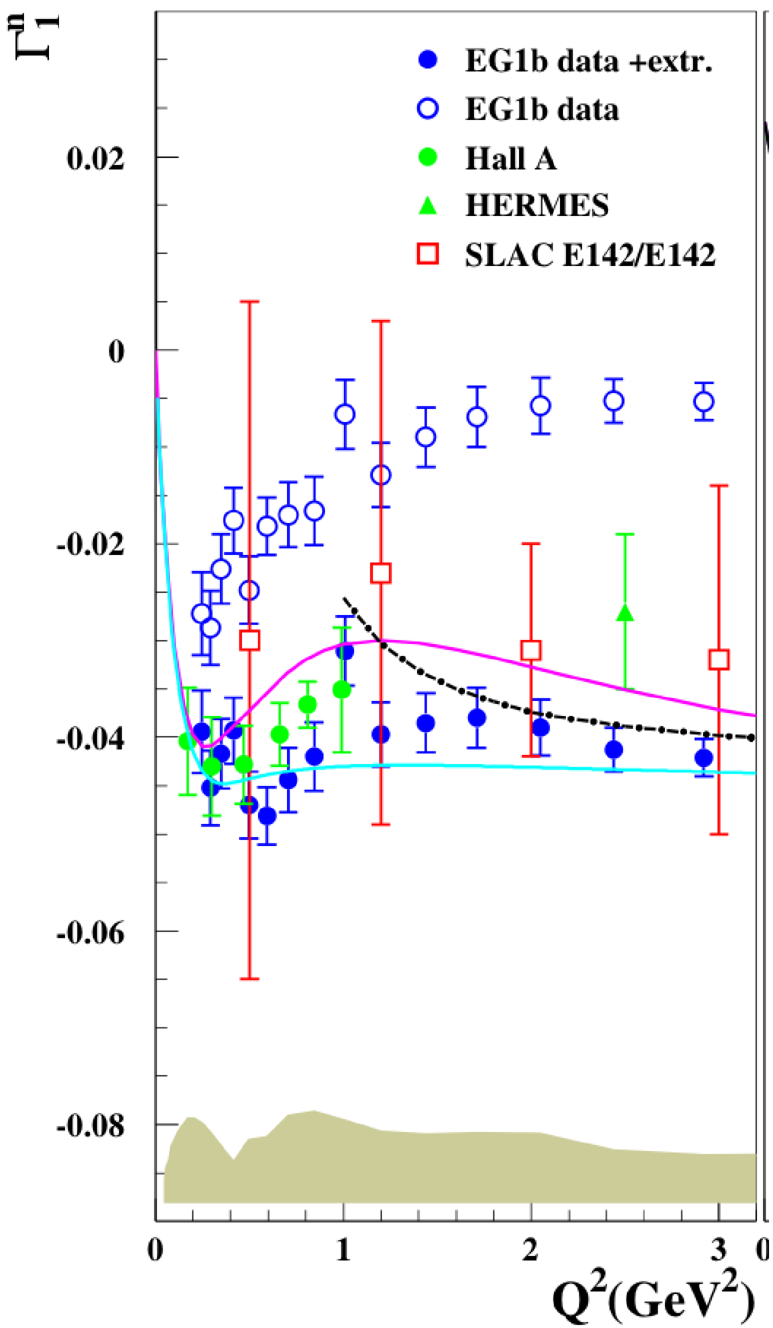
Existing data (proton) – up to 2017

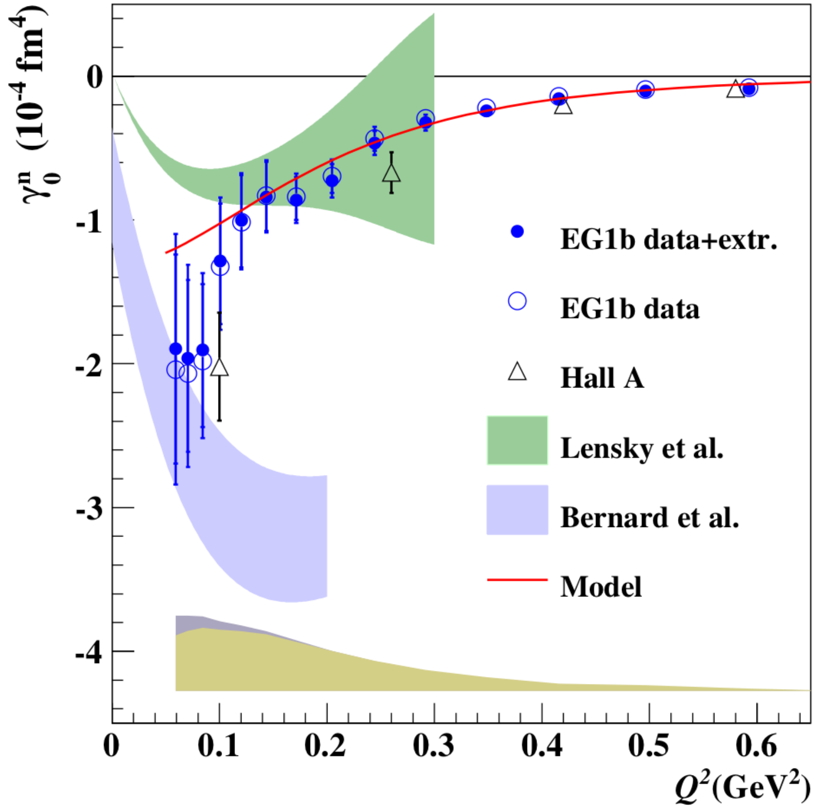


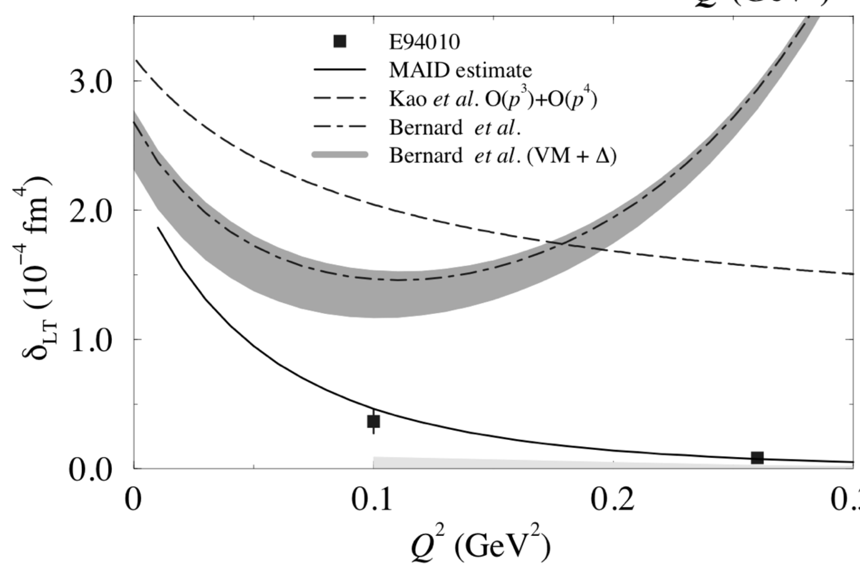


Recently published
Fersch et al. PRC 96 065208 (2017)

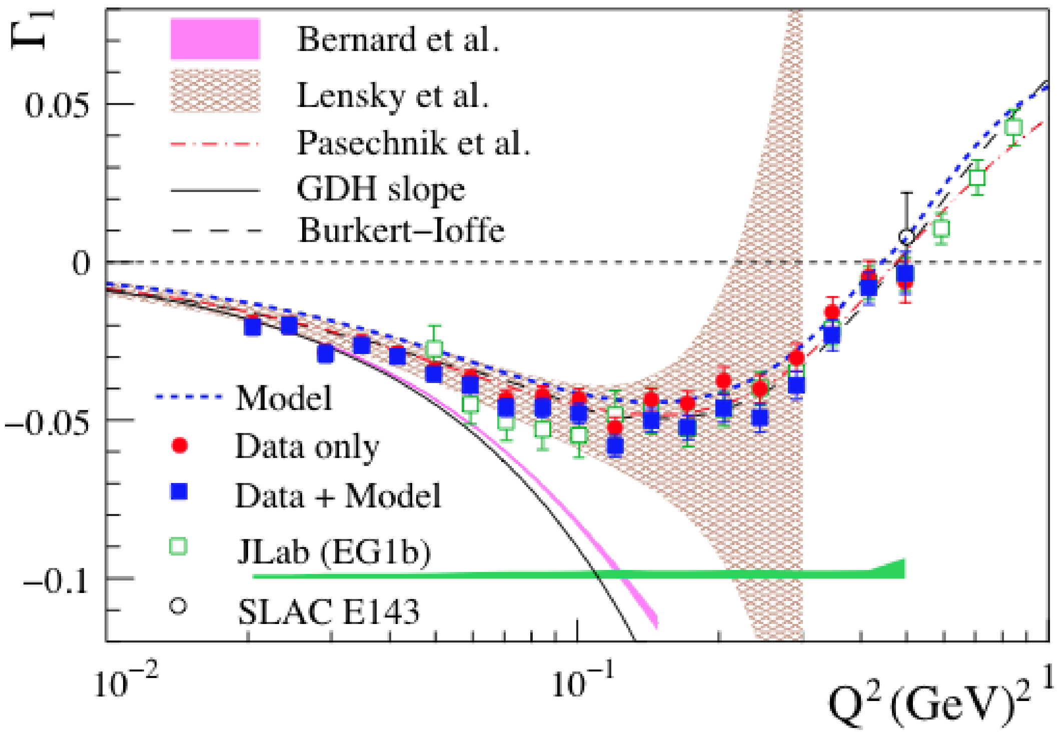
Existing data (neutron) – up to 2017

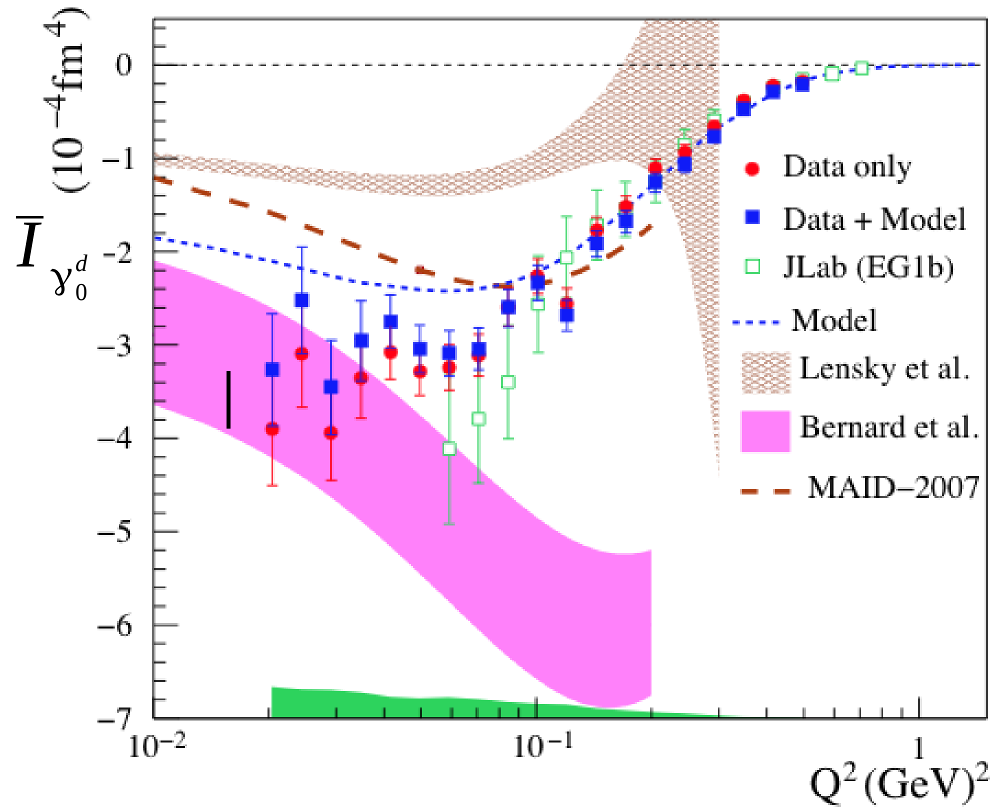






New deuteron results from EG4 (Hall B)





Just Published.

Adhikari et al. PRL 120, 062501 (2018)

E97-110 preliminary neutron(^{3}He) results on $\int g_1\,dx$

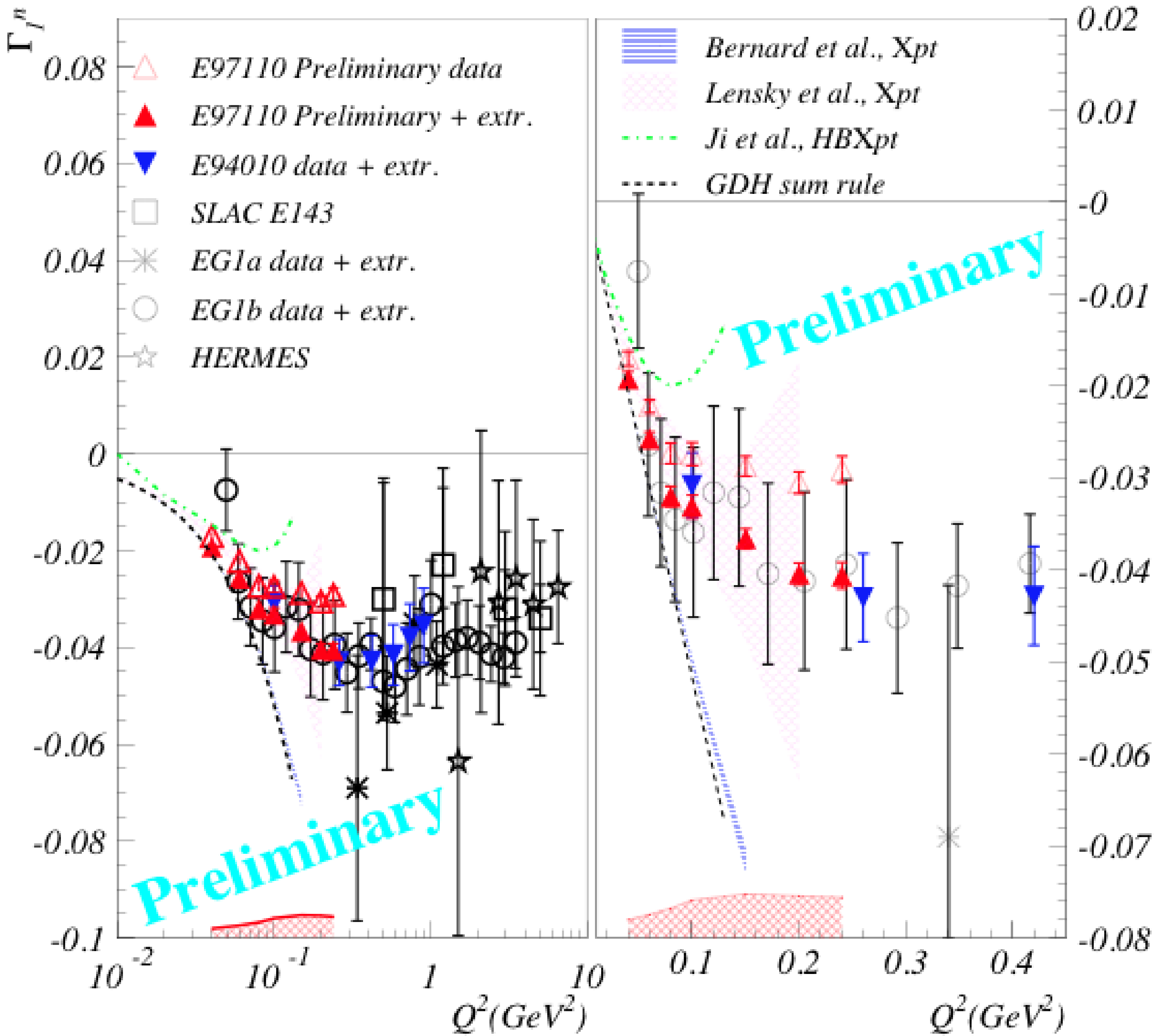
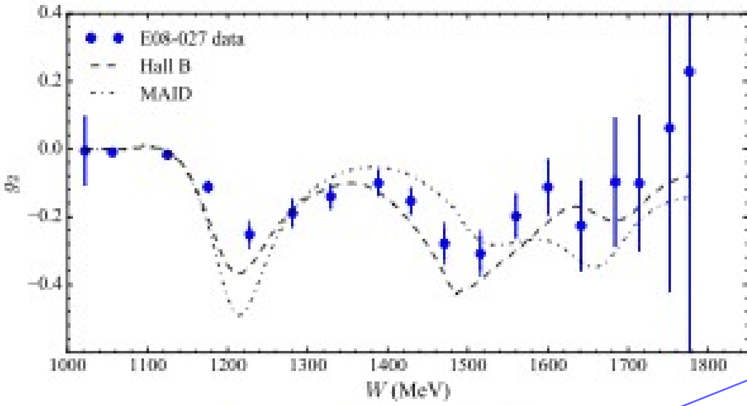


Figure credit:
V. Sulkosky

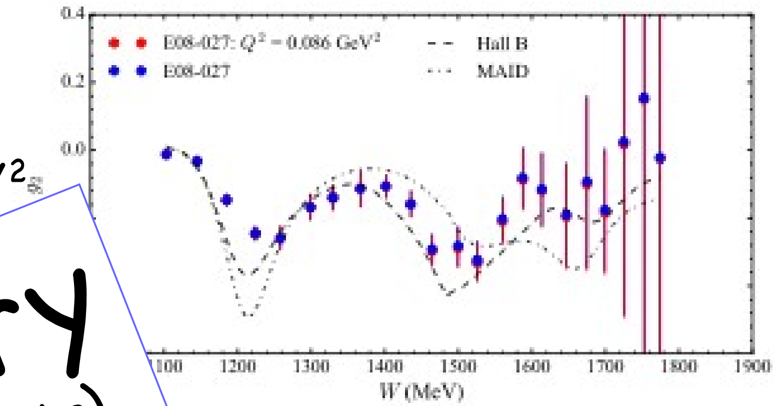
draft paper in prep

New proton results from Hall A – g_2^p at low Q^2

Figure credit: K. Slifer



(a) E_0 = 2254 MeV 5T Transverse

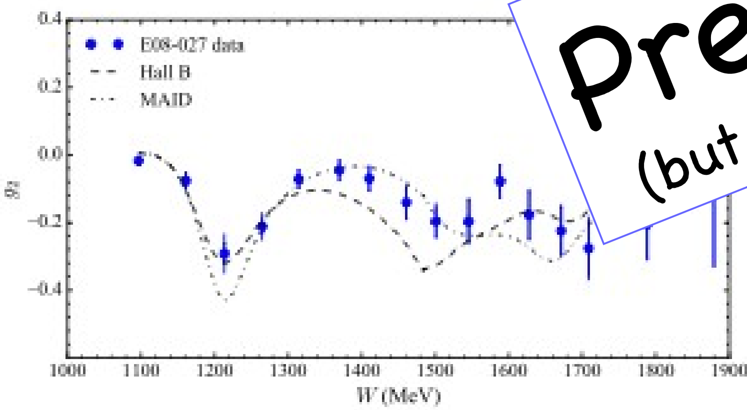


(a) E_0 = 2254 MeV 5T Transverse

Q^2= 0.08 GeV^2

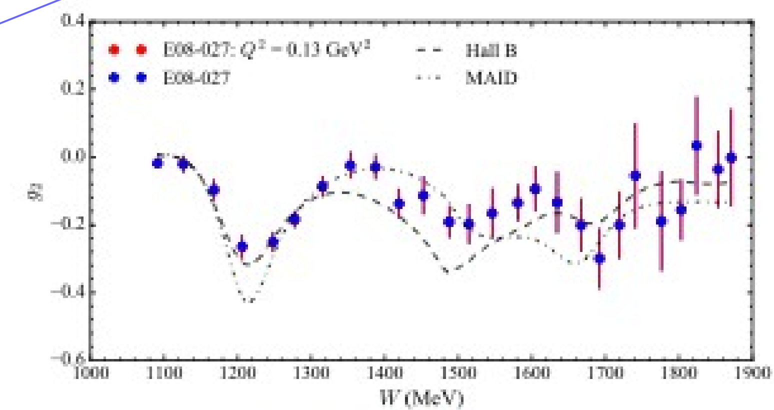
Preliminary

(but analysis complete)



(b) E_0 = 3350 MeV 5T Transverse

Q^2= 0.13 GeV^2



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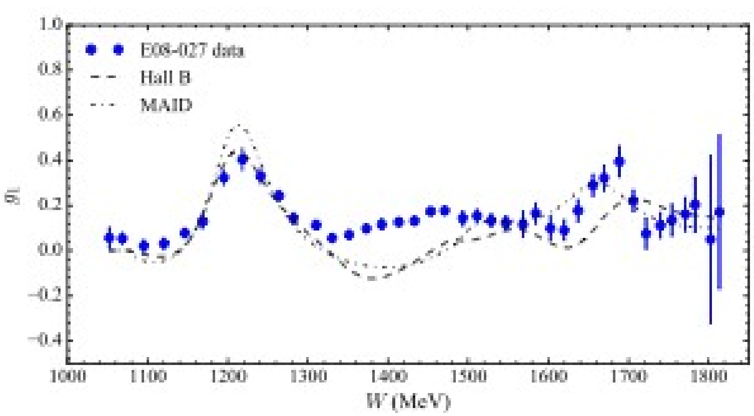
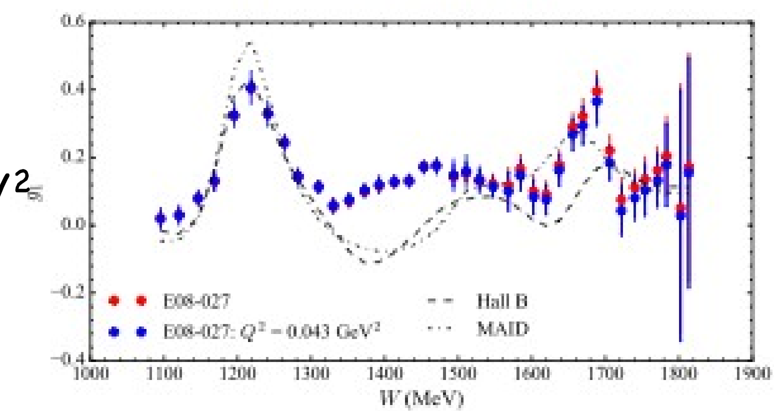


(c) E_0 = 2254 MeV 5T Longitudinal

Q^2= 0.04 GeV^2



New proton (preliminary) results from EG4

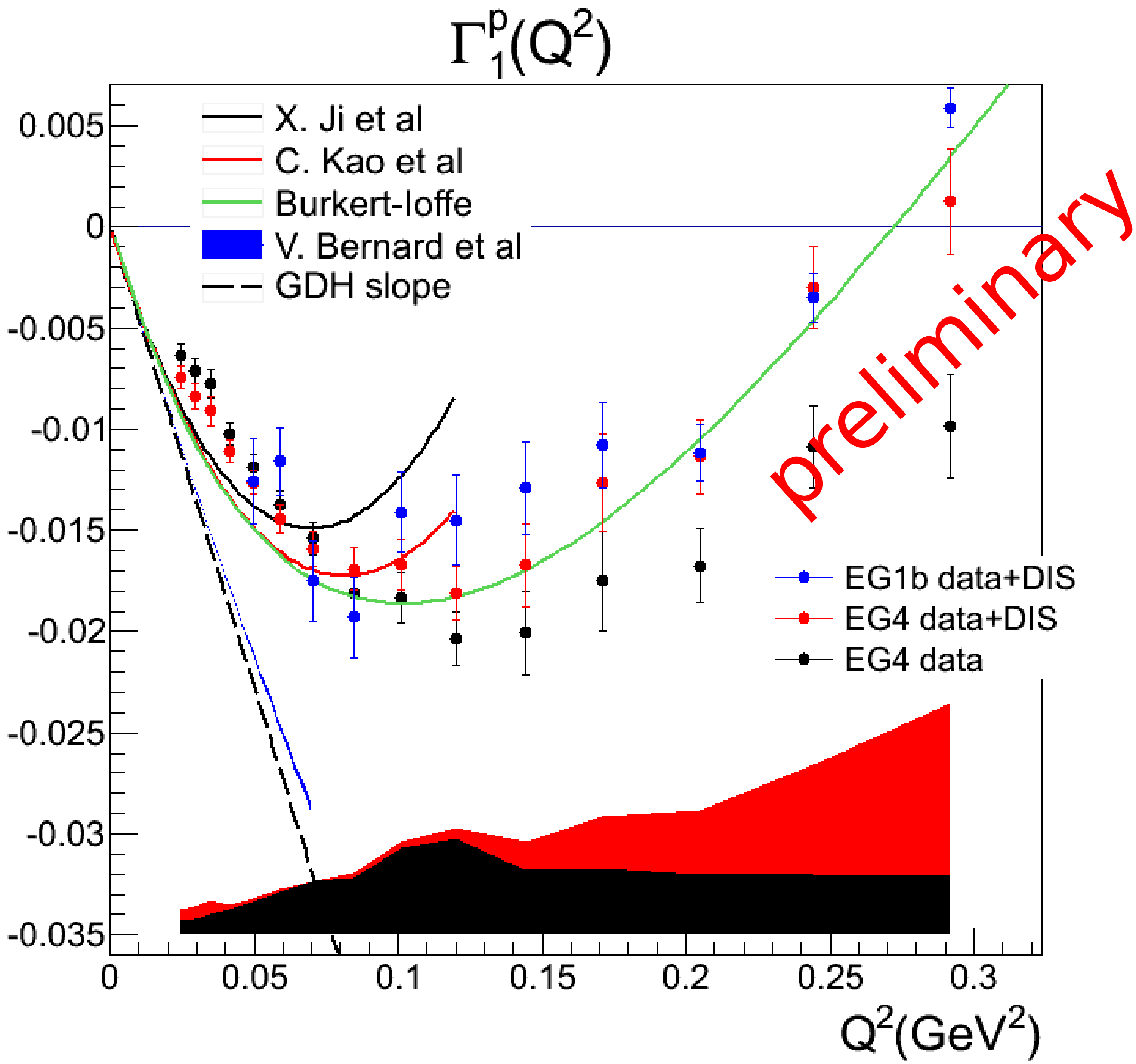
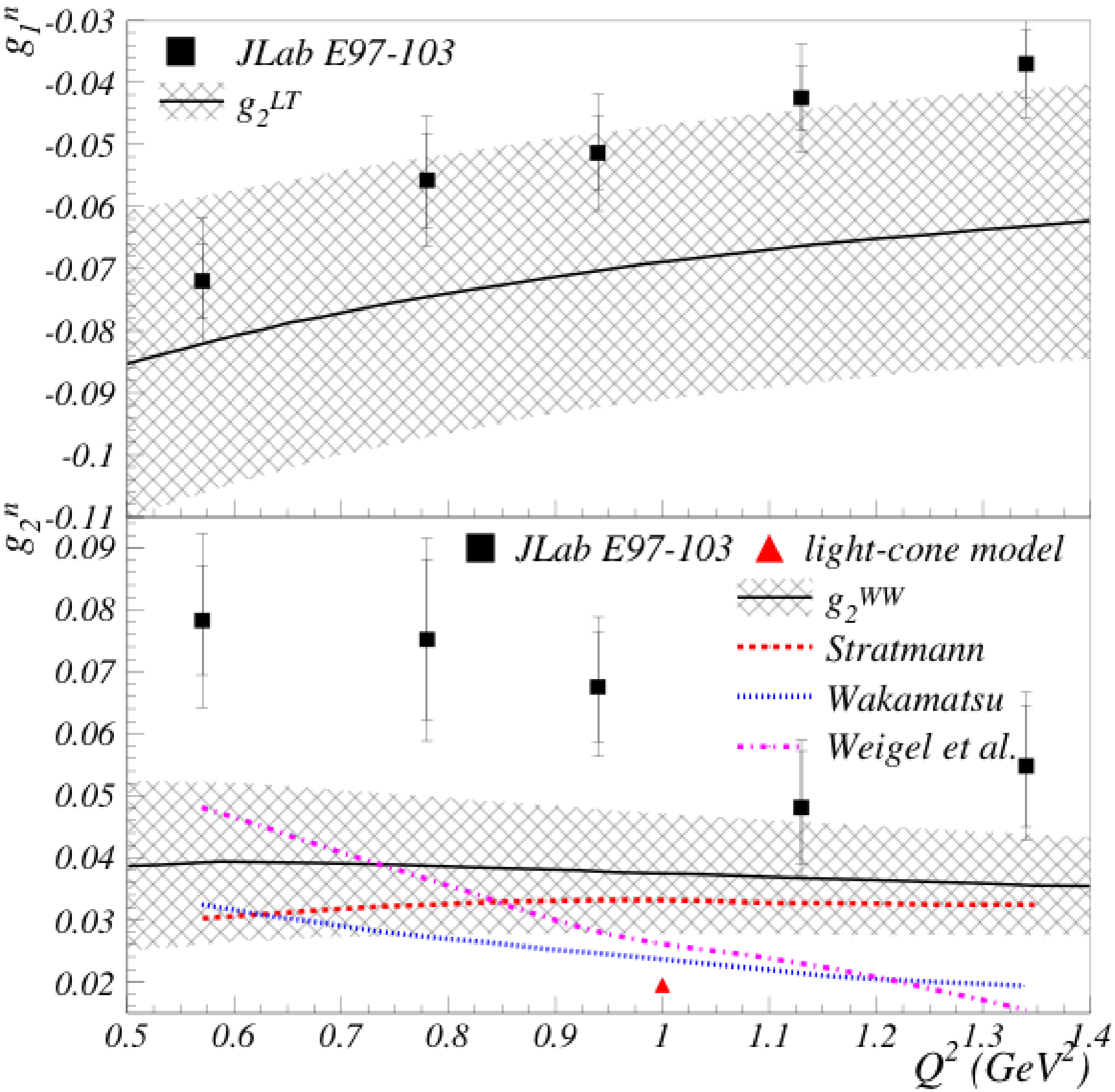


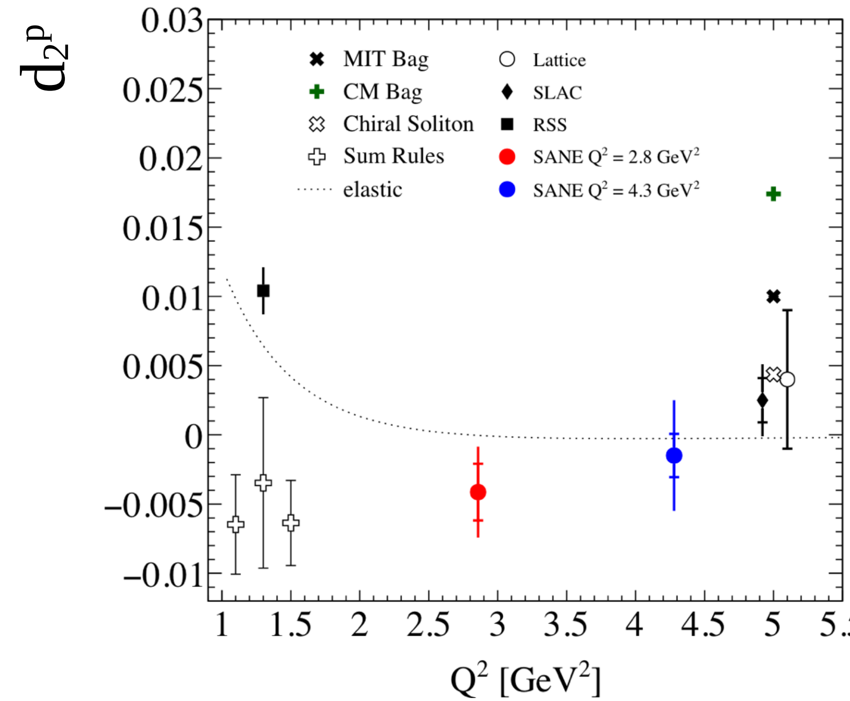
Figure credit:
H. Kang

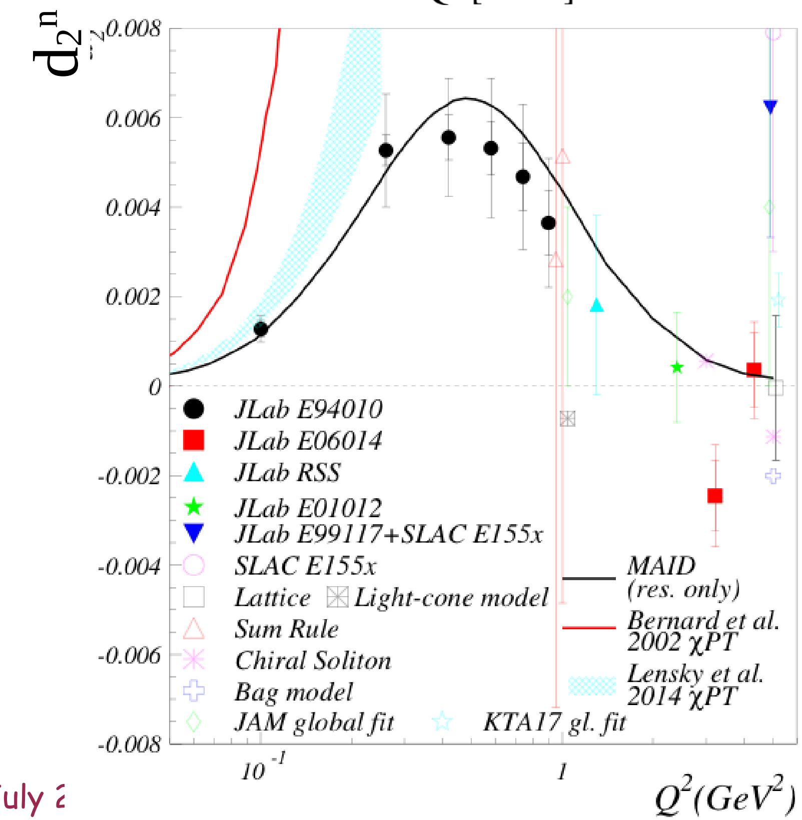
Higher Twist Study

Dedicated HT measurements:
Hall A E97-103, E01012, E06014, Hall C SANE

SANE results on arXiv:1805:08835







Test of Chiral Perturbation Theory

Ref.	Γ_1^p	Γ_1^n	$\boldsymbol{\Gamma_1^{p-n}}$	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 between chPT prediction and data
X = not that well

(Data guiding chPT calculations)

Table credit: A. Deur, S.J. Brodsky, G.F. de Teramond, review article in progress

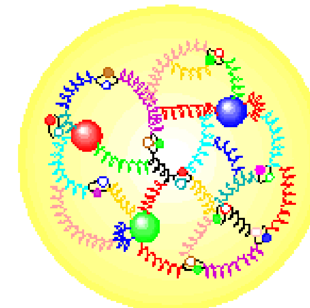
Upcoming Experiments

The A1n and d2n experiments are scheduled to run in Fall 2019, using the polarized 3He target in Hall C.

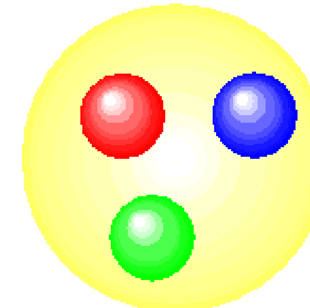
Similar proton measurements will be carried out in Hall B (CLAS12), using an upgraded NH3/ND3 target. It will likely run in or after 2020.

Nucleon (spin) Structure at High x_{Bj}

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



vs

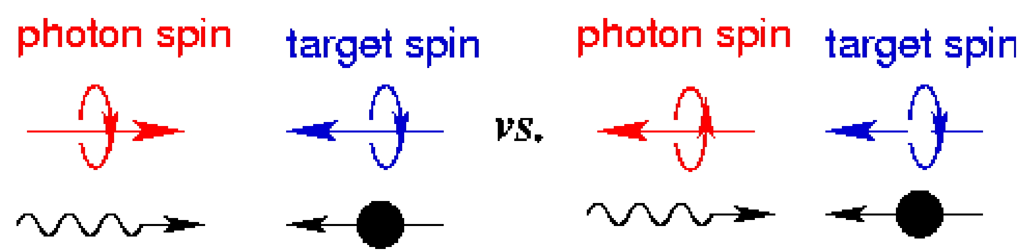


The far valence domain (x>0.5)

- 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

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

Predictions for A_1 and $\Delta q/q$ at large x

$$\left|p^{\uparrow}\right\rangle = \frac{1}{\sqrt{2}}\left|u^{\uparrow}(ud)_{00}\right\rangle + \frac{1}{\sqrt{18}}\left|u^{\uparrow}(ud)_{10}\right\rangle - \frac{1}{3}\left|u^{\downarrow}(ud)_{11}\right\rangle$$

$$-\frac{1}{3}\left|d^{\uparrow}(uu)_{10}\right\rangle - \frac{\sqrt{2}}{3}\left|d^{\downarrow}(uu)_{11}\right\rangle$$

Model	F_2^n/F_2^p	d/u	Δ u/u	Δ d/d	A_1^n	A_1^p
SU(6) = SU3 flavor + SU2 spin	2/3	1/2	2/3	-1/3	0	5/9
Valence Quark + Hyperfine	1/4	0	1	-1/3	1	1
pQCD + HHC	3/7	1/5	1	1	1	1
DSE-1 (realistic)	0.49	0.28	0.65	-0.26	0.17	0.59
DSE-2 (contact)	0.41	0.18	0.88	-0.33	0.34	0.88

- The only place where models and/or QCD can make absolute predictions for structure functions.

Predictions for A_1 and $\Delta q/q$ at large x

$$|p^{\uparrow}\rangle = \frac{1}{\sqrt{2}}|u^{\uparrow}(ud)_{00}\rangle + \frac{1}{\sqrt{18}}|u^{\uparrow}(ud)$$

$$-\frac{1}{3}|d^{\uparrow}(uu)_{10}\rangle - \frac{\sqrt{2}}{3}|d^{\downarrow}($$

hyperfine interaction: the two quarks in the spectator di-quark prefer to form a S=0 to a S=1 state.
– based on nucleon-Delta mass plitting, etc.
– but the breaking of SU(6) may not be that big.

Model	F_2^n/F_2^p	d/u	Δ u/u	Δ d/d	A_1^n	A_1^p
SU(6) = SU3 flavor + SU2 spin	2/3	1/2	2/3	-1/3	0	5/9
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Predictions for A_1 and $\Delta q/q$ at large x

$$|p^{\uparrow}\rangle = \frac{1}{\sqrt{2}}|u^{\uparrow}(ud)_{00}\rangle + \frac{1}{\sqrt{18}}|u^{\uparrow}(ud)_{10}\rangle - \frac{1}{3}$$

$$-\frac{1}{3}|d^{\uparrow}(uu)_{10}\rangle - \frac{\sqrt{2}}{3}|d^{\downarrow}(uu)_{11}\rangle$$

pQCD: the struck quark is free + constraint on the gluon exchange within the diquark → the struck quark must carry nucleon's helicity at x→1

Model	F_2^n/F_2^p	d/u	Δ u/u	Δ d/d	A_1^n	A_1^p
SU(6) = SU3 flavor + SU2 spin	2/3	1/2	2/3	-1/3	0	5/9
Valence Quark + Hyperfine	1/4	0	1	-1/3	1	1
pQCD + HHC	3/7	1/5	1	1	1	1
DSE-1 (realistic)	0.49	0.28	0.65	-0.26	0.17	0.59
DSE-2 (contact)	0.41	0.18	0.88	-0.33	0.34	0.88

- The only place where models and/or QCD can make absolute predictions for structure functions.

Predictions for A_1 and $\Delta q/q$ at

A non-perturbative, (low-energy) effective theory. Non-pointlike diquark correlations as a result of dynamical chiral symmetry breaking. Predictions used diquark probabilities extracted from nucleon elastic form factors

$$\left|p^{\uparrow}\right\rangle = \frac{1}{\sqrt{2}}\left|u^{\uparrow}(ud)_{00}\right\rangle + \frac{1}{\sqrt{18}}\left|u^{\uparrow}(ud)_{10}\right\rangle - \frac{1}{3}$$

$$-\frac{1}{3}\left|d^{\uparrow}(uu)_{10}\right\rangle - \frac{\sqrt{2}}{3}\left|d^{\downarrow}(uu)_{11}\right\rangle$$

Model	F_2^n/F_2^p	d/u	Δ u/u	Δ d/d	A_1^n	A_1^p
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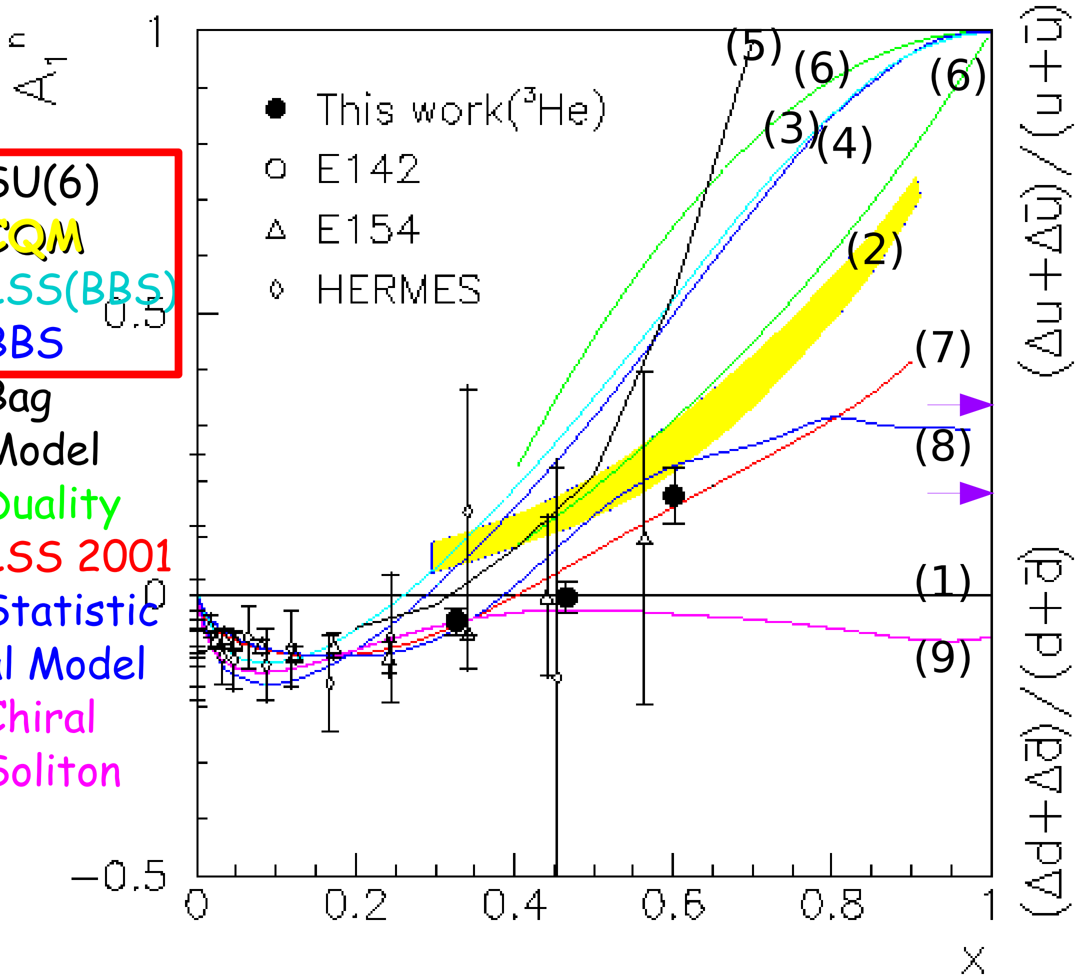
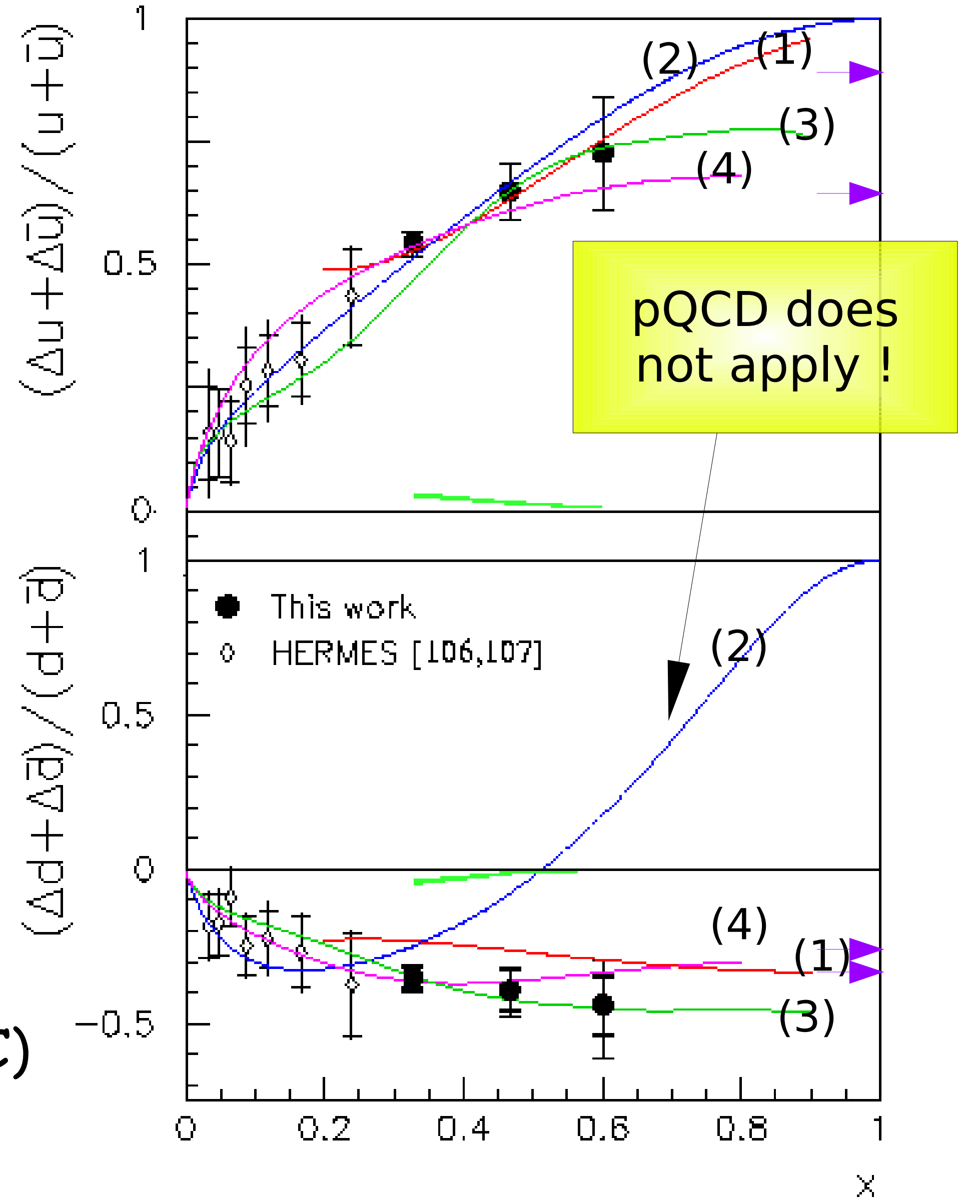
The 6 GeV Hall A Measurement (21 PAC days, 2001)

(1) SU(6)
(2) CQM
(3) LSS(BBS)
(4) BBS
(5) Bag Model
(6) Duality
(7) LSS 2001
(8) Statistical Model
(9) Chiral Soliton

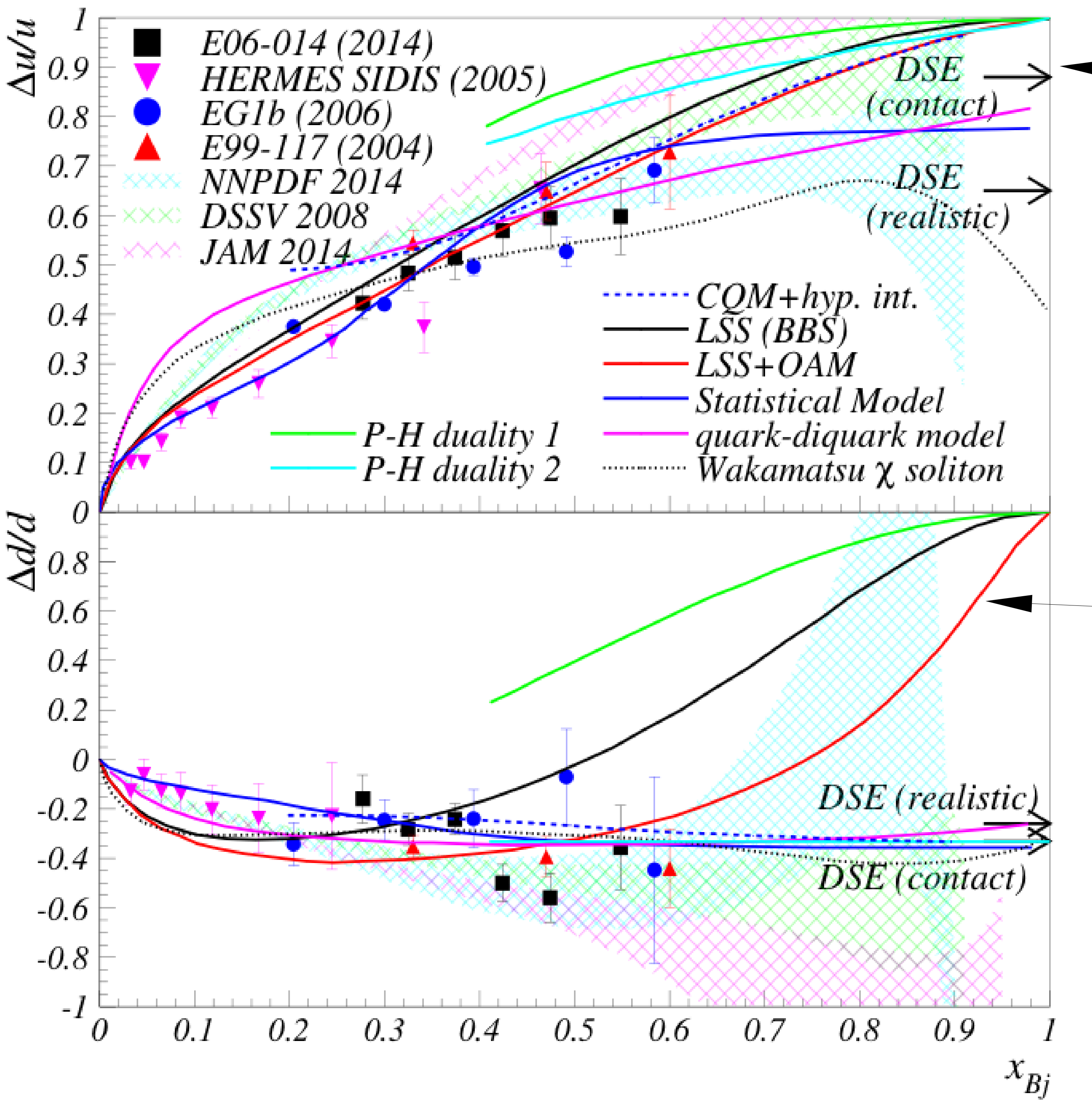




(Deutron data not shown: E143, E155, SMC)

X. Zheng *et al.*, Phys. Rev. Lett. 92, 012004 (2004); Phys. Rev. C 70, 065207 (2004)

(1)CQM (2)LSS(BBS):pQCD+HHC
(3)Statistical Model (4)LSS 2001



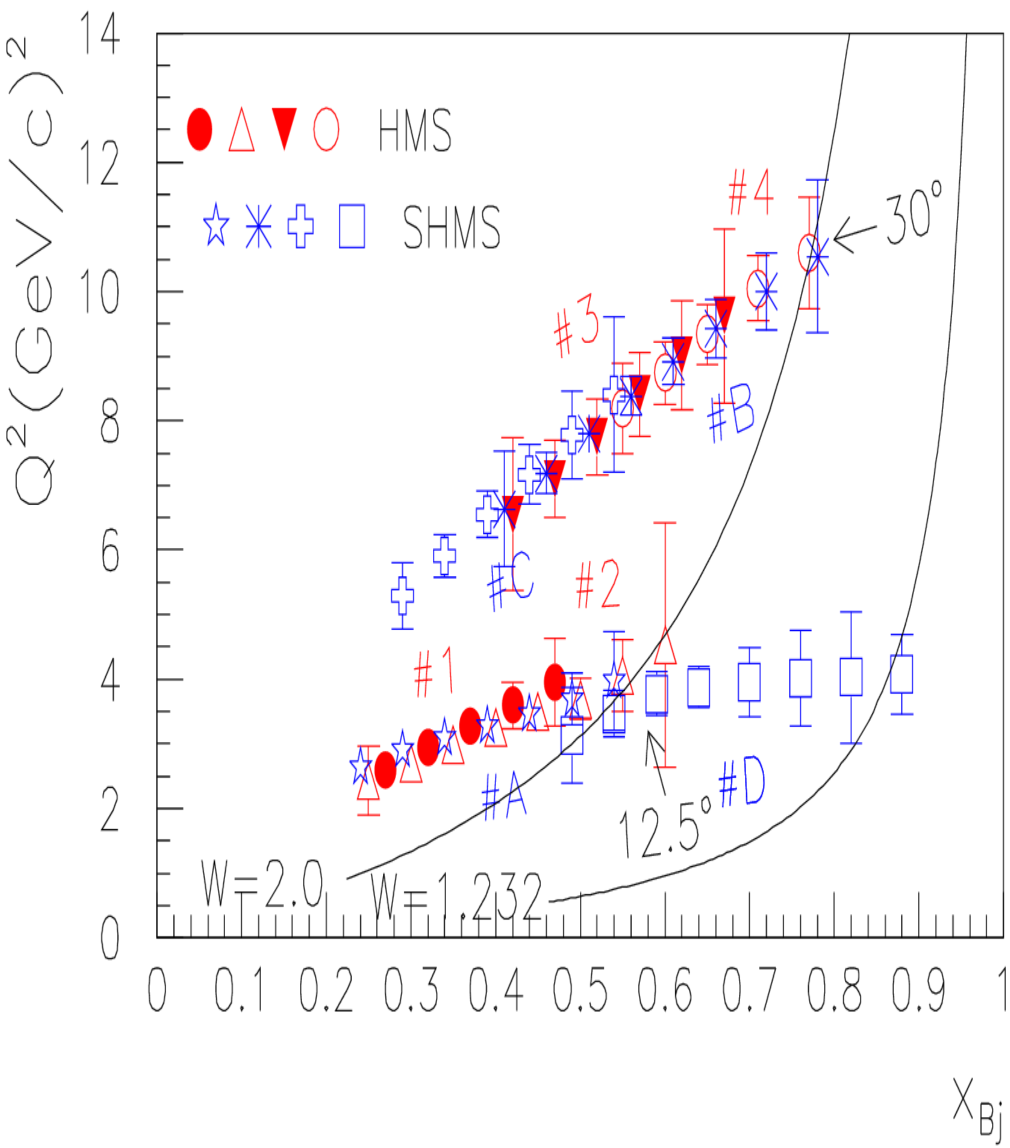
A non-perturbative, (low-energy) effective theory. Non-pointlike diquark correlations as a result of dynamical chiral symmetry breaking. Predictions used diquark probabilities extracted from nucleon elastic form factors

pQCD: the struck quark is free + constraint on the gluon exchange within the diquark → the struck quark must carry nucleon's helicity at x→1

now added quark OAM, but Δd/d still must be 1 at x=1

Reaching Deeper Valence Quarks Region with 12 GeV

A_1^n Kinematics



CLAS12 Kinematics

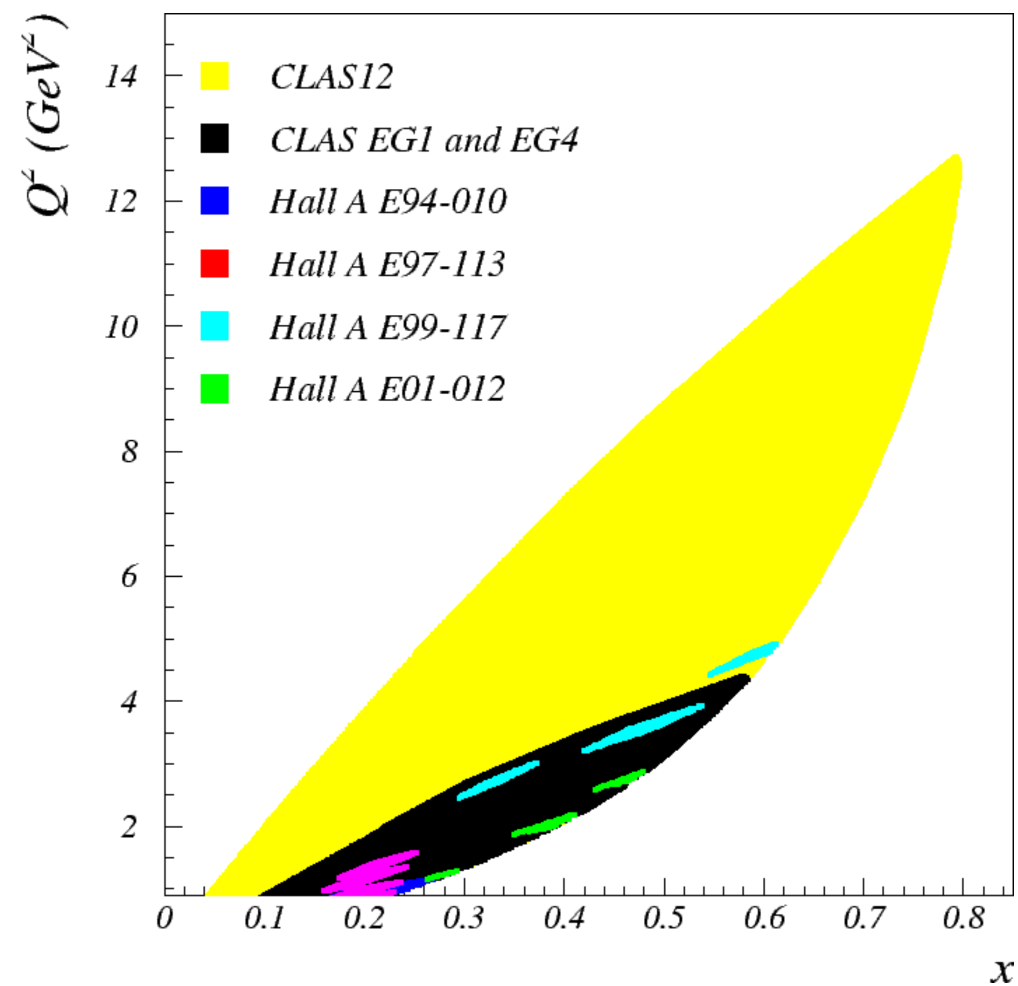
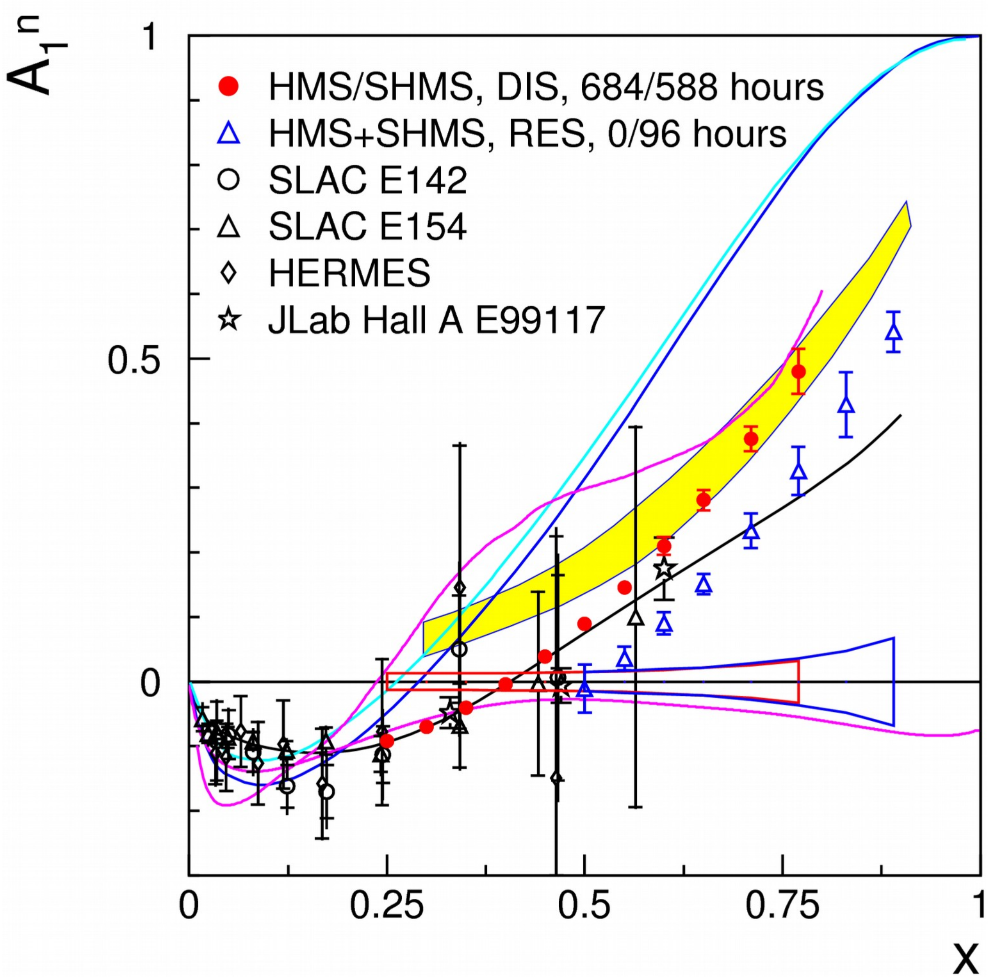


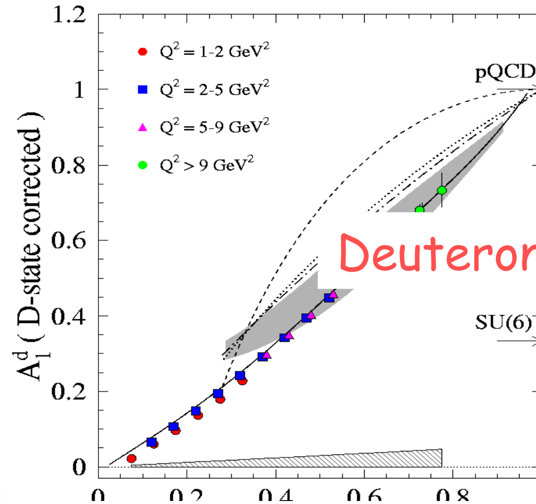
Figure credit:
S. Kuhn

Expected Results on Spin Asymmetries:

Hall C with 36 days

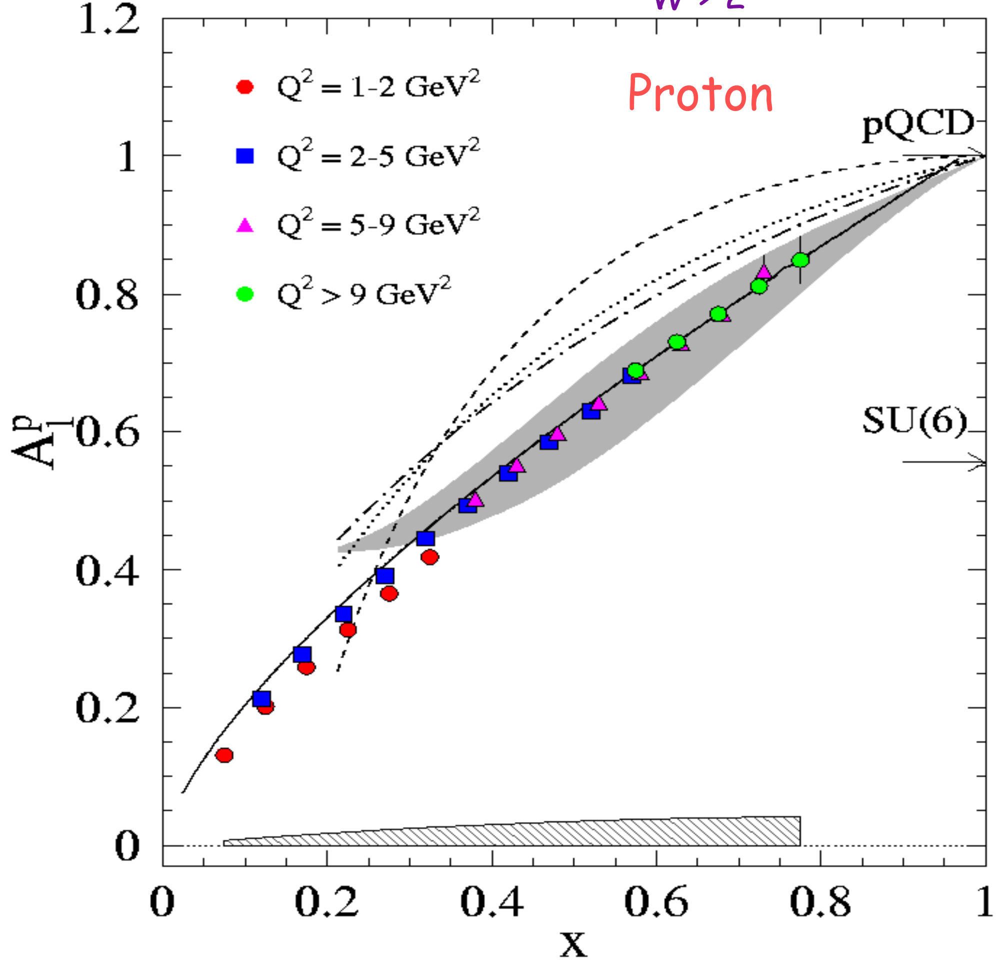


CLAS12 with 80 days

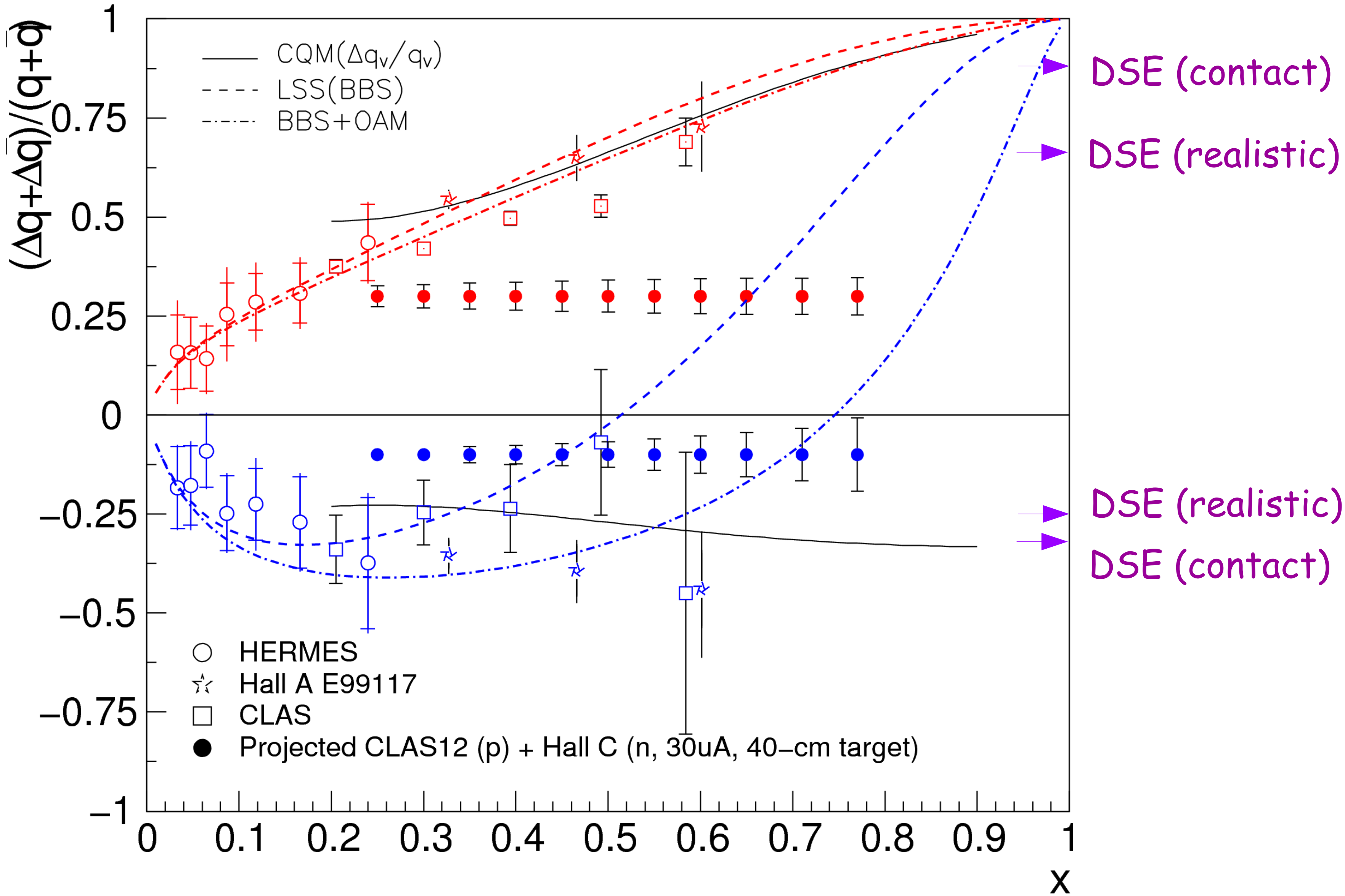


CLAS12 figure credit: S. Kuhn

W > 2



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



Summary and Outlook

- Understanding confinement and non-perturbative nature of strong interaction is the most significant unresolved challenge within the Standard Model
- Nucleon spin structure study provide 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 a plethora of data, in particular the proton and the neutron spin structure functions and their moments at very low Q^2 values. These provide important check (and guidance) for chiral perturbation theory calculations.
- 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 upcoming (2019-2020) A_1 experiments in Hall C (neutron) and in Hall B/CLAS12 (proton and deuteron) will venture into a deeper valence quark region. Stay tuned!