Nucleon Spin Structure at JLab

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MENU 2010, Williamsburg, 31st May

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Fairfield UNIVERSITY

Jefferson Laboratory

CEBAF is a superconductive electron accelerator

- → **continuous beam**
- → **high longitudinal polarization**
- → **energy range → 0.75 –5.9 GeV**
- → **current range → 0.1 nA –200µA**
- → **Beam polarization 80-90%**

Jefferson Lab experiments

Hall A

- E94-010 – Neutron extended GDH
- E97-103 – g2n
- E97-110 – GDH sum rule, spin structure ^3He
- E99-117 – High precision A_1^n at large x
- E01-012 – Spin duality

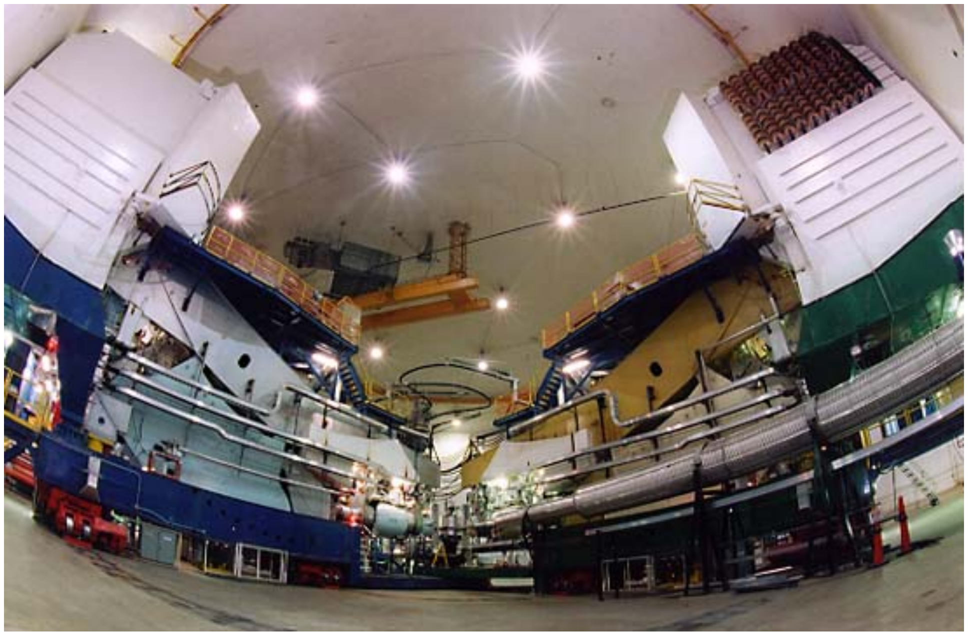
Hall B

- eg1 – p and D spin structure and moments,duality
- eg4 – low Q2 GDH
- eg1dvcs – semiinclusive and GPD

Hall C

- RSS – Resonance Spin Structure
- SANE – Spin Asymmetries on the Nucleon

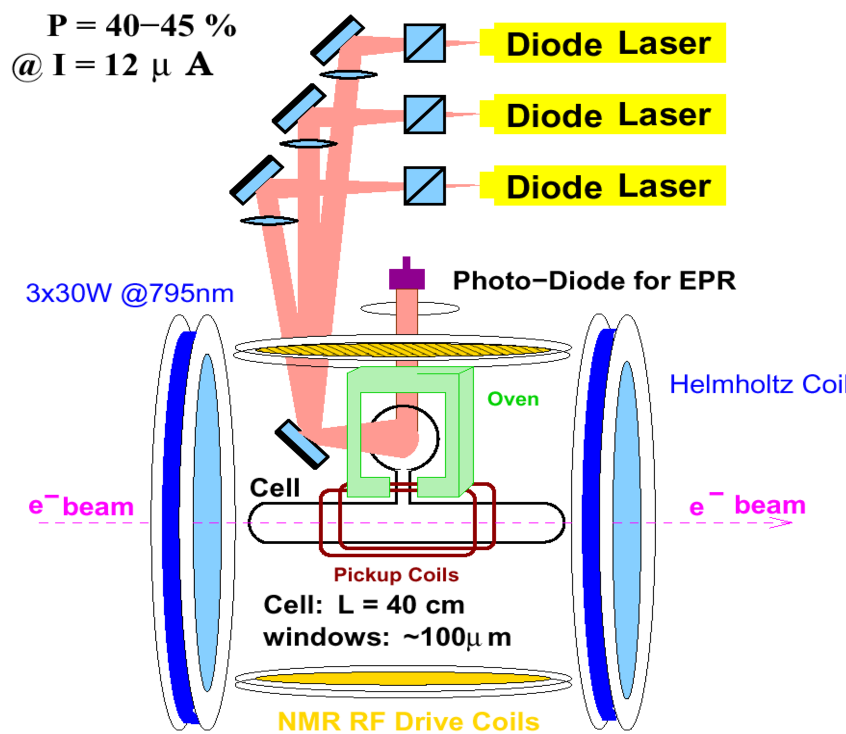
Hall A



High Resolution Spectrometers (HRS)

- Angular acceptance 6 msr
- Resolution 1x10^{-4} FWHM
- Large momentum range (0.3-4.3 GeV, 0.3-3.3 GeV)
- Proton Polarimeter

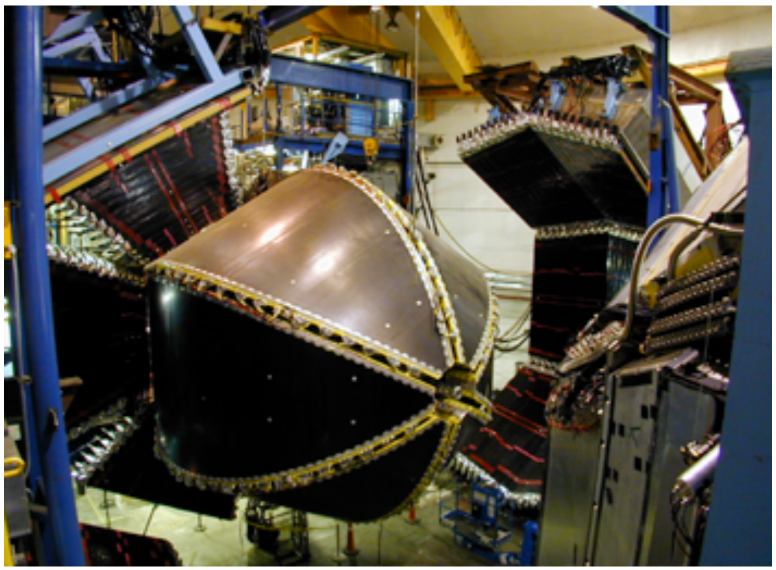
- Longitudinal, transverse and vertical
- Luminosity=10^{36} (1/s) (highest in the world)
- Effective polarized neutron target
- P=40% with 12μA beam



Hall B: EG1 and EG4 with CLAS

CEBAF
Large
Acceptance
Spectrometer

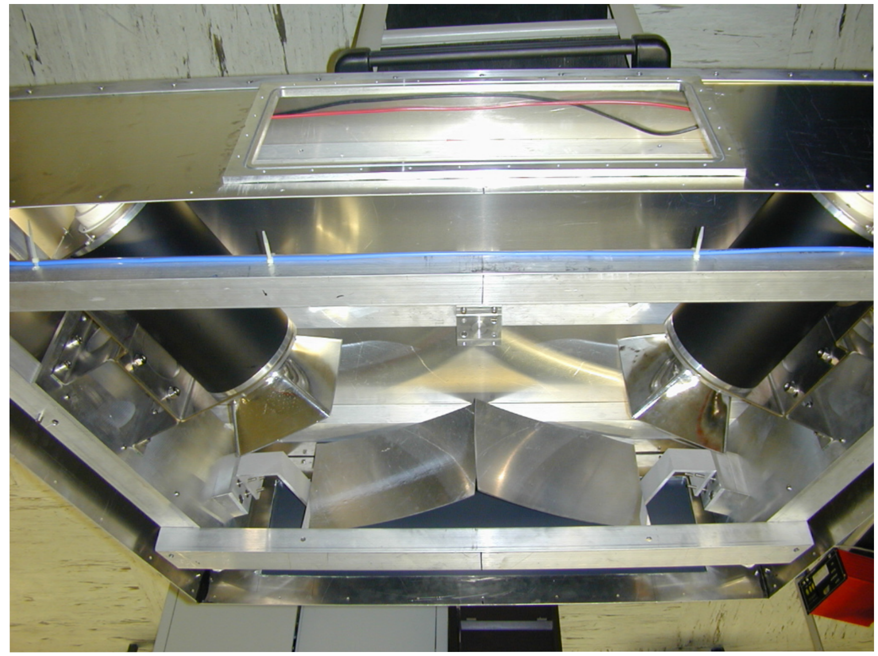
- Six individually instrumented sectors
- Toroidal magnetic field
- Multi-particle final state
- Large acceptance



1998 - 2001 **EG1**: $Q^2 = 0.05\ldots5$ GeV^2

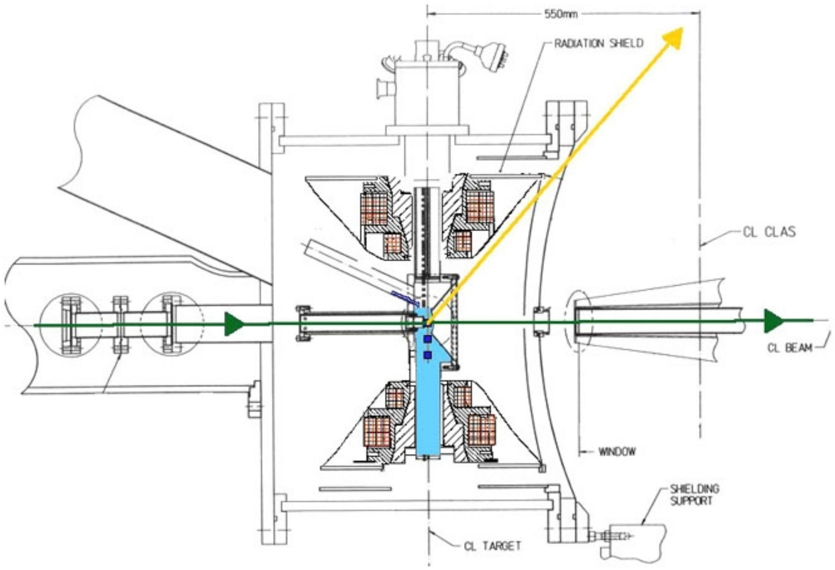
Largest possible kinematic coverage
→ inbending and outbending configuration, E = 1.6…5.8 GeV

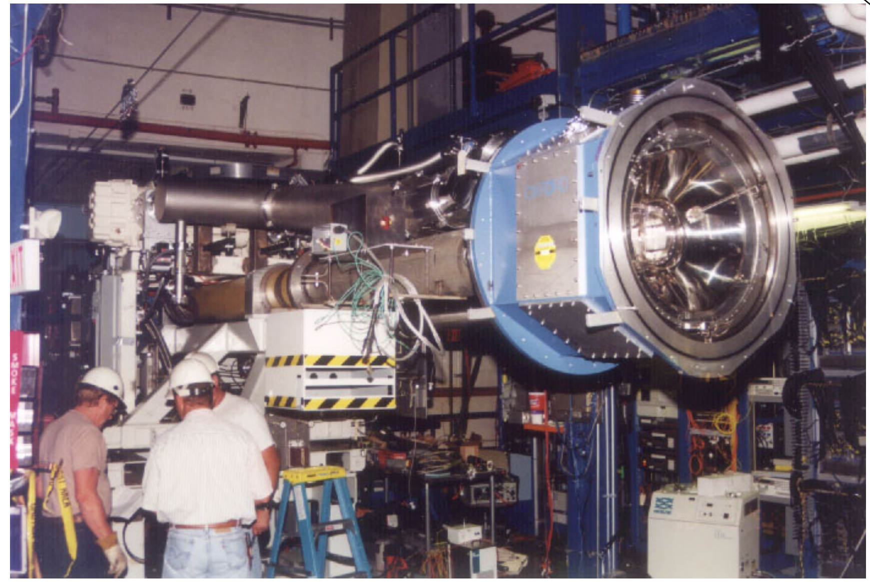
2006 EG4: Q^2_{min}=0.015 GeV^2



Focus on low Q^2 (GDH, χPT) => lower beam energies (up to 3 GeV), new Cherenkov for optimal acceptance in outbending configuration, θ_e as small as 6 degrees

The polarized target

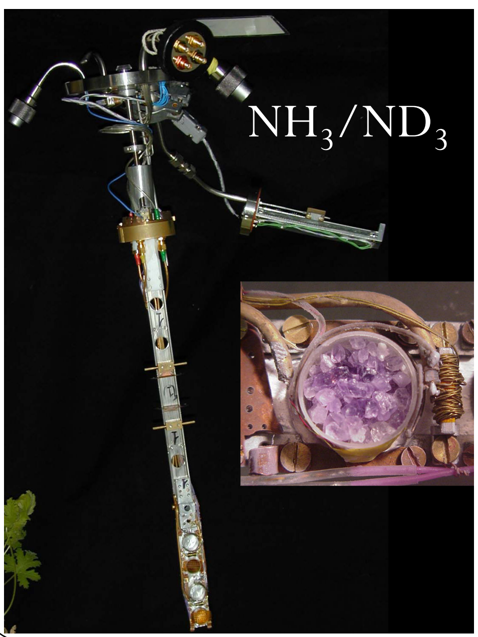


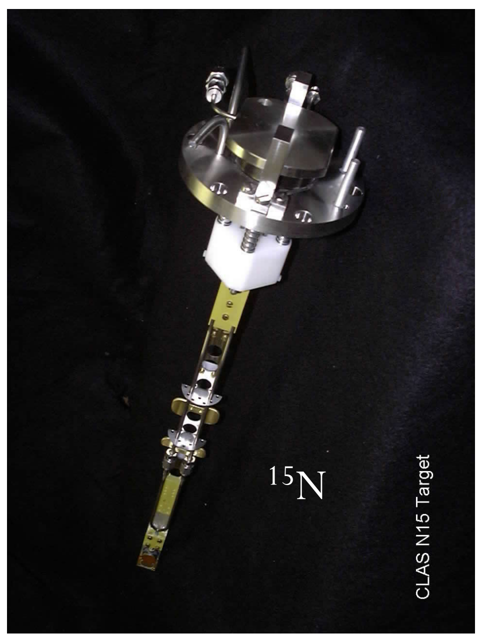


EG1/EG4 target (CLAS):

Polarization up to 0.9 (p) or 0.4 (d)

Luminosity up to ~ 10^{34}



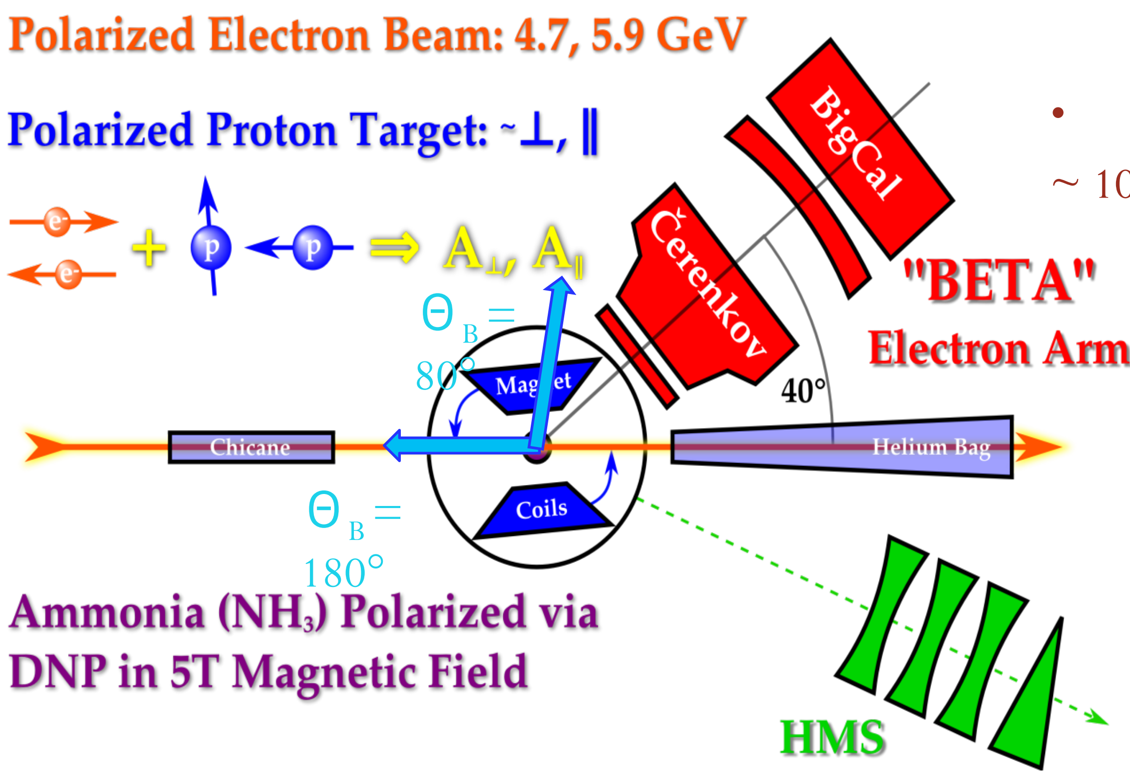


Hall C: RSS and SANE

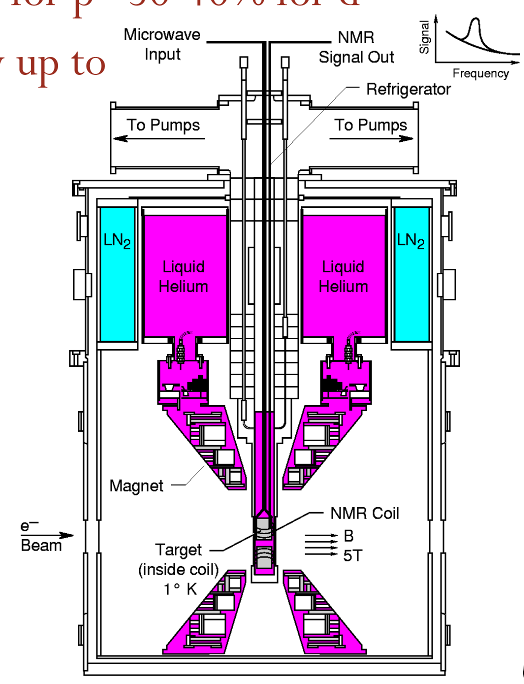
SANE setup

Electron Arm:
- Tracker
- Cerenkov
- Lucite
- BigCal

HMS: High Momentum Spectrometer
- Hall-C Spectrometer
- Packing Fractions



Target
- Polarized NH_3/ND_3 targets
- Dynamical Nuclear Polarization
- Same as Hall B, but it can be rotated
  - Transverse polarization!
- In-beam average polarization
  70-90% for p 30-40% for d
- Luminosity up to ~ 10^{35} (Hall C)



JLab experiments

"Everything"

Sum Rules at low Q^2

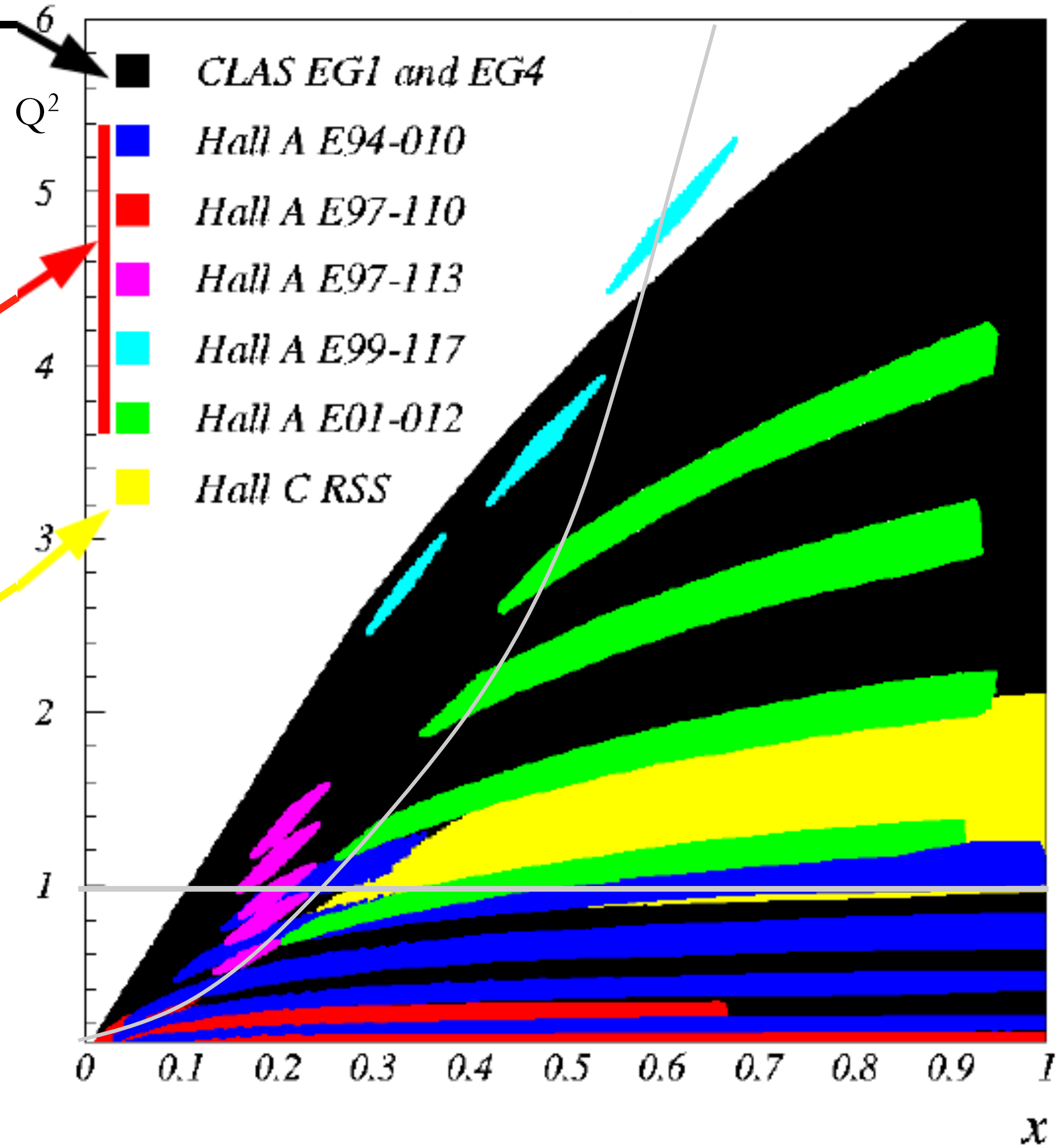
very low Q^2 - χPT

Q^2-dep. of g_2

A_{1n} at high x

Duality

Res. Region, Duality

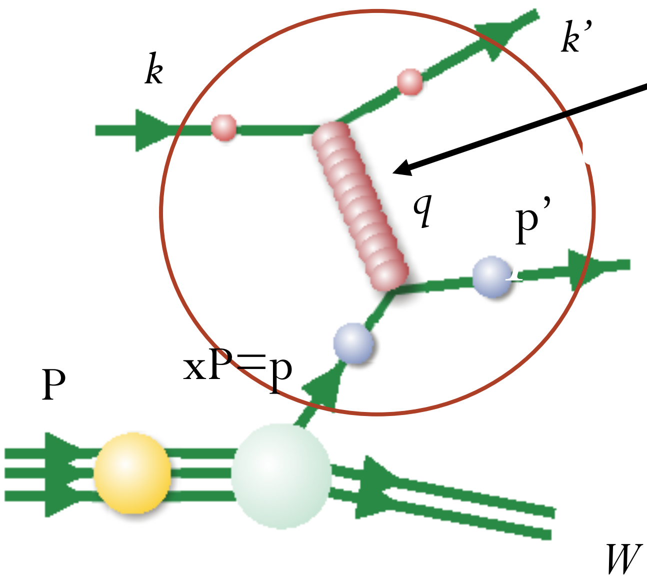


✓8 completed experiments

3 (+3) approved with 6 GeV JLab

3 (+1) approved with 12 GeV (A/B/C)

DIS of lepton off nucleon



Virtual photon probes the structure

Important variables:

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

$$W^2 = M^2 + 2M\nu - Q^2$$

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

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\tfrac{\theta}{2}\right]$$

$$\frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2E'}{\nu EQ^2}\left[(E + E'\cos\theta)g_1(x,Q^2) - 2Mxg_2(x,Q^2)\right]$$

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

Virtual photon asymmetries

Experimentally: $$A_{\parallel} = \frac{d\sigma^{\uparrow\Uparrow} - d\sigma^{\downarrow\Uparrow}}{2d\sigma_{unpol}} = D\left(A_1 + \eta A_2\right)$$

D, η, d, ζ are functions of Q^2, E', E, $R=\sigma_L/\sigma_T$....

$$A_{\perp} = \frac{d\sigma^{\uparrow\Rightarrow} - d\sigma^{\downarrow\Leftarrow}}{2d\sigma_{unpol}} = d\left(A_1 + \zeta A_2\right)$$

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

$$A_1 = \frac{g_1 - \gamma^2 g_2}{F_1}$$

$$A_2 = \gamma^2 \frac{g_1 + g_2}{F_1}$$

The virtual photon asymmetries **A_1** and **A_2** can be extracted by varying the *direction of the nucleon polarization*

or by varying the *beam energy* at fixed Q^2, ν

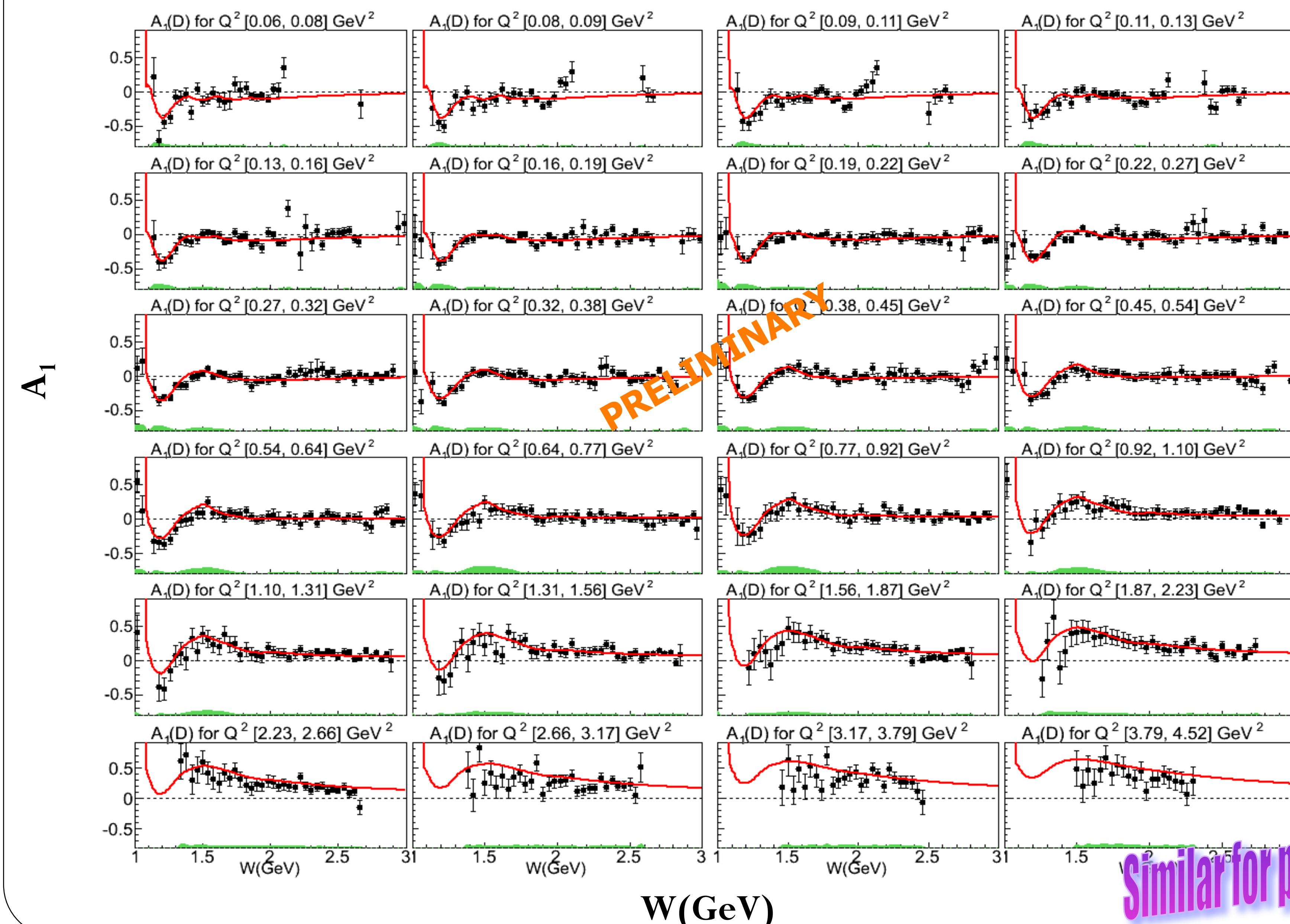
Large-x behavior of the A_1 asymmetry

- SU(6) ➔ $A_1^p = \frac{5}{9}, \; A_1^n = 0$
- Hyperfine perturbed QM
  - ✓ makes S=1 pairs more energetic than S=0 pairs ➔ $A_1 \to 1$
- In DIS, and in pQCD
  - ✓ Minimal gluon exchanges
  - ✓ Spectator pair: quarks have opposite helicities
  - ✓ At large x struck quark carries the helicity of the nucleon
  - ✓ $A_1 \to 1$

Isgur, PRD 59, 034013 (1999)

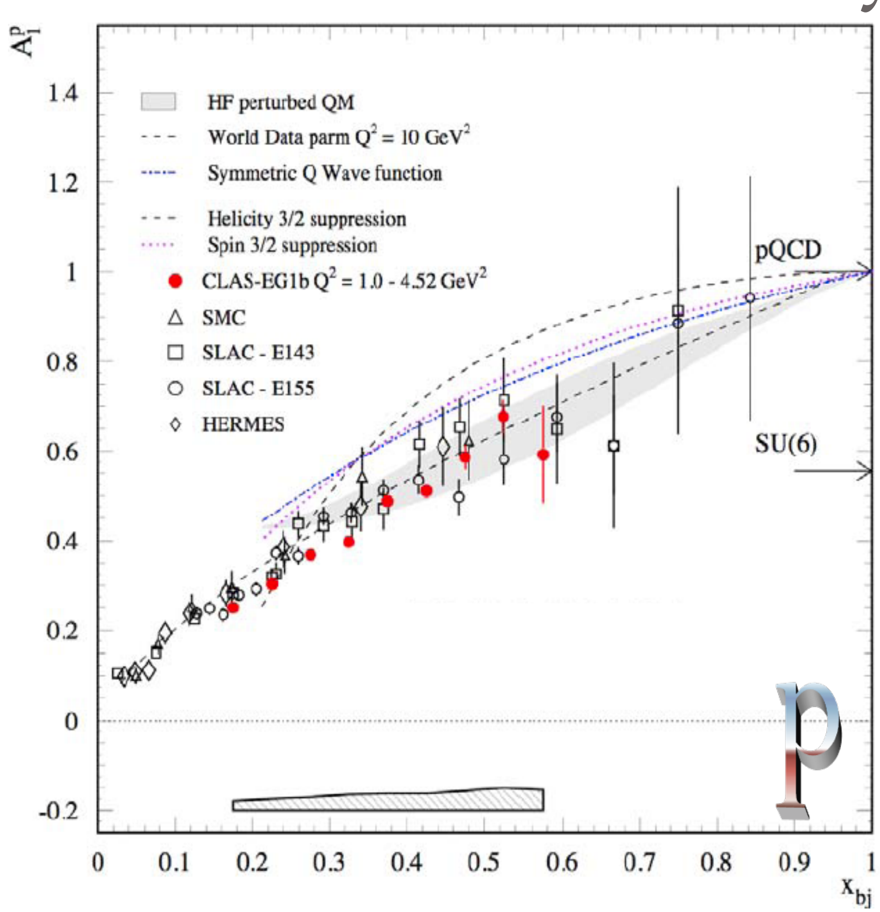
Farrar and Jackson, PRL 35, 1416 (1975)

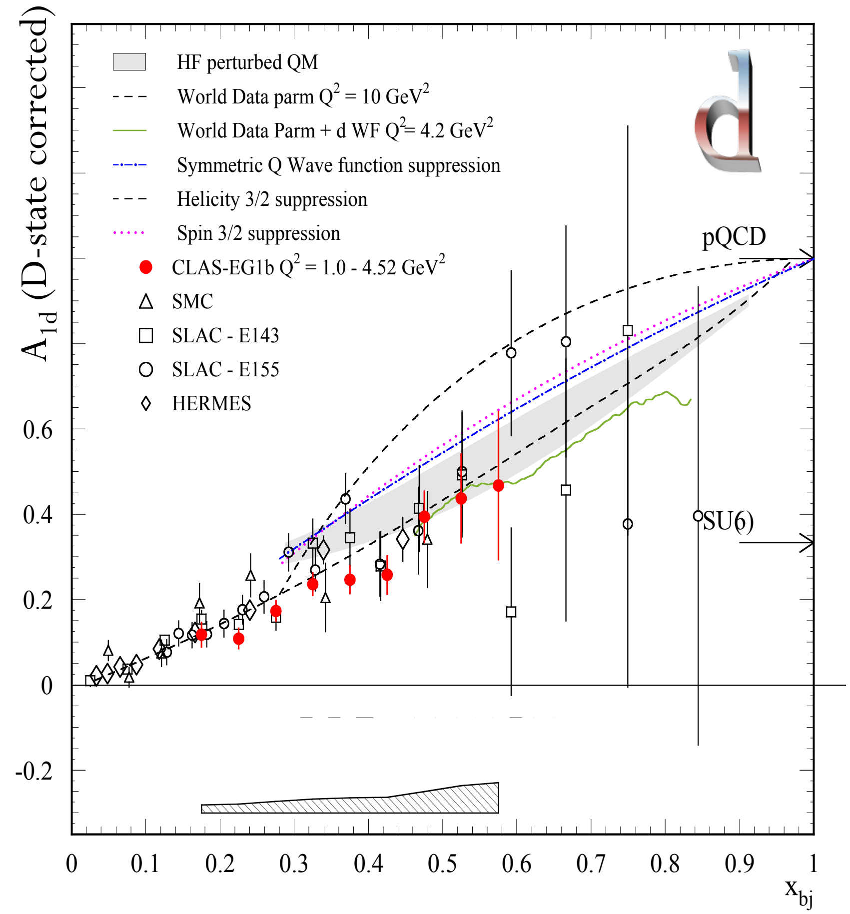
A_1 deuteron for different Q^2 bins



Similar for proton...

Virtual Photon Asymmetry A_1





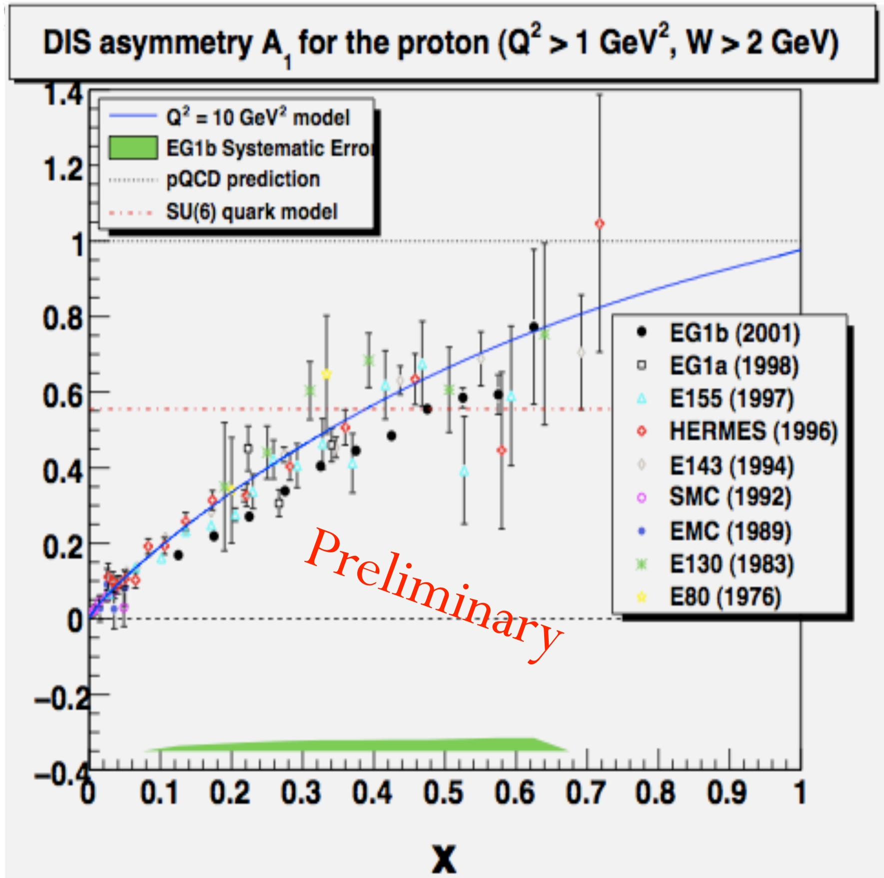
- P and d results fall below parameterization of world data at 10 GeV^2 → include in DGLAP fits
- To be used to extract $\Delta q/q$ in this momentum transfer region
- p and d results are in better agreement with the HFP quark model

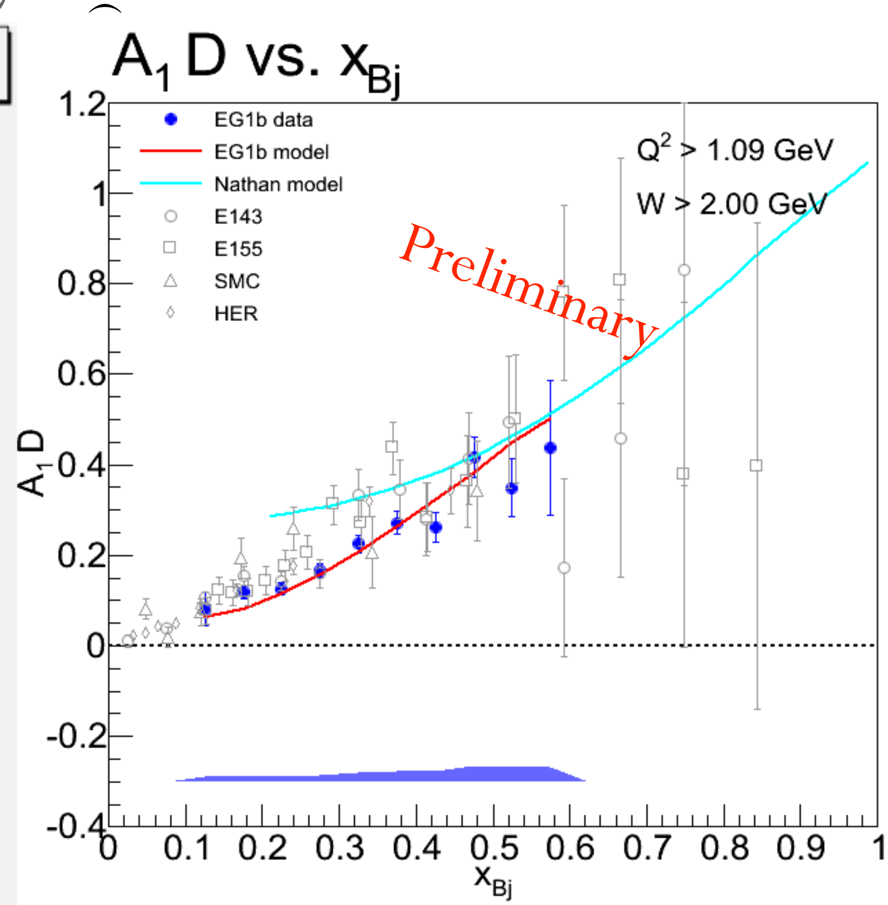
Hall B CLAS, Phys.Lett. B641 (2006) 11

HP perturbed QM N. Isgur, Phys. Rev. D 59, 34013

F. Close and W. Melnitchouk, Phys. Rev. C 68, 035210

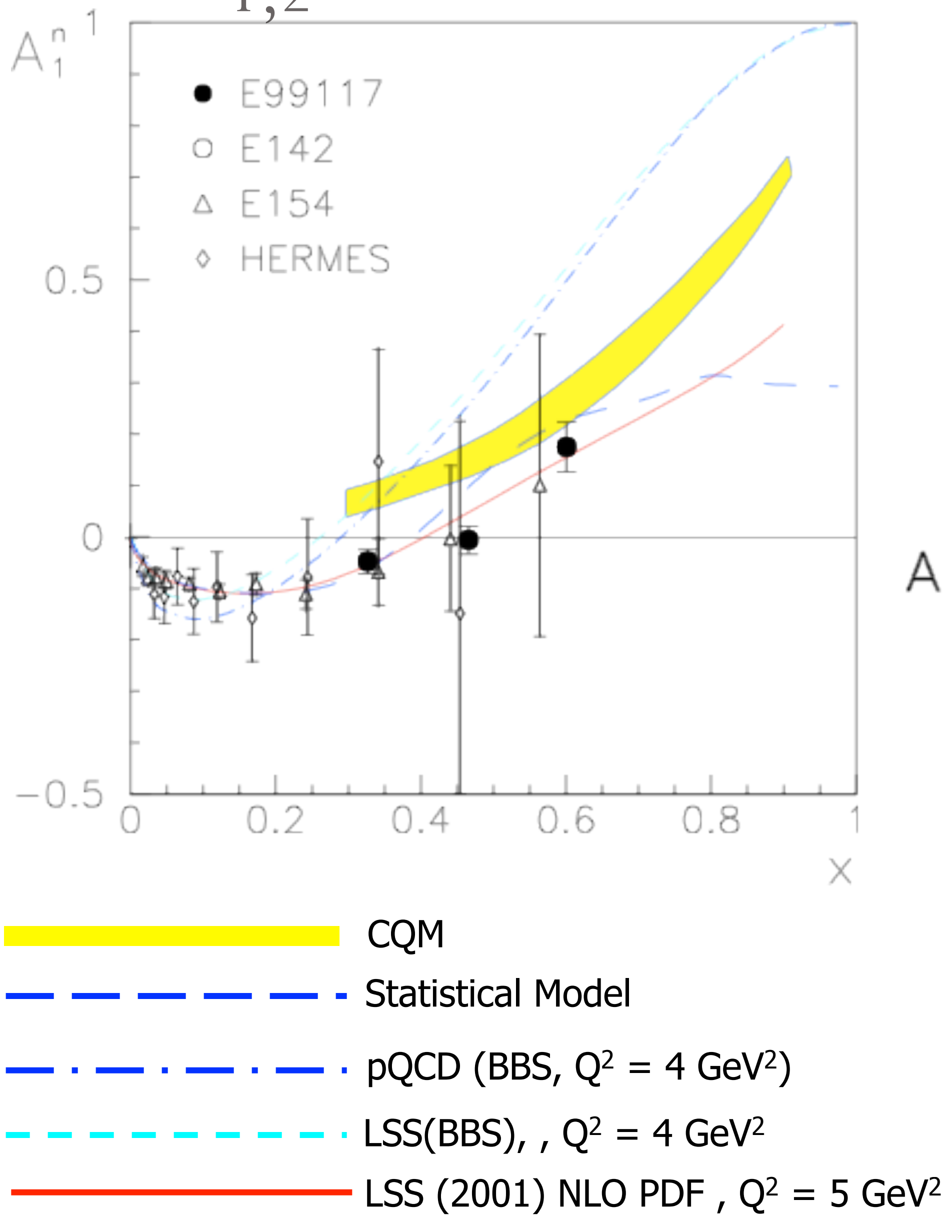
Virtual Photon Asymmetry A_1





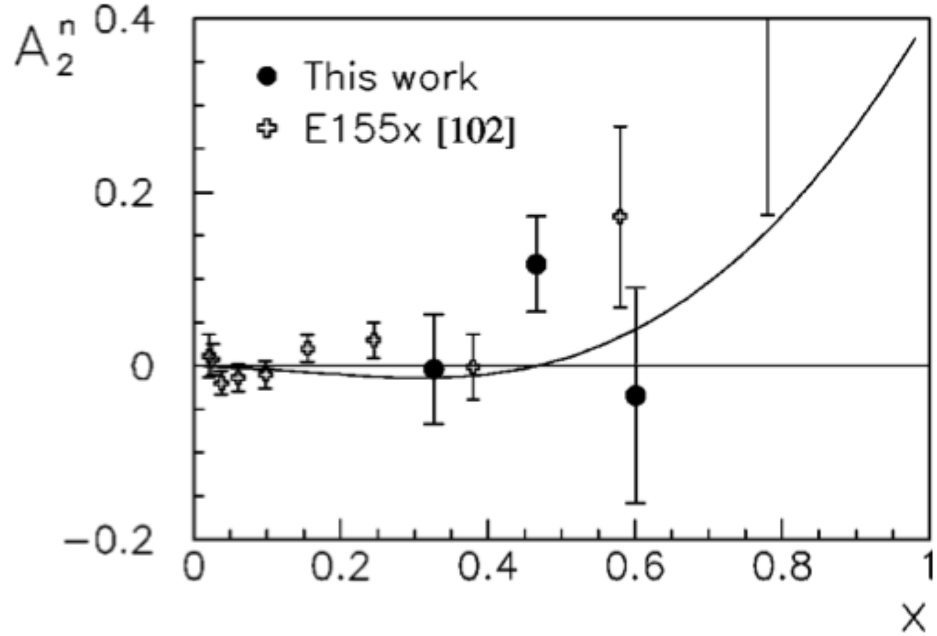
- New results from CLAS eg1b
- Better statistical precision
- Better systematic errors

$A_{1,2}^n$ – Hall A



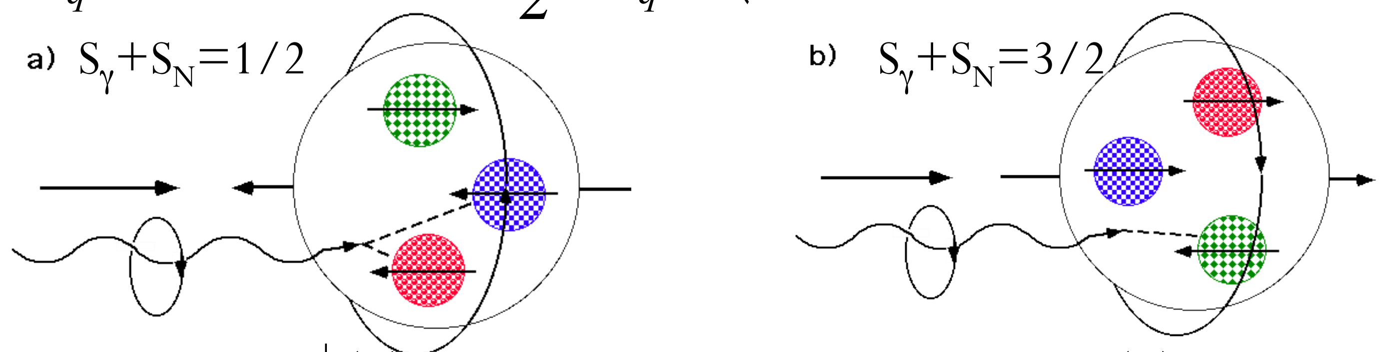
- $Q^2 = 2.7 – 4.8$ GeV^2
- Large x
- A_1^n crosses zero and becomes positive ->SU(6) breaking

Hall A E99-117, PRL 92, 012004 (2004)
PRC 70, 065207 (2004)



Spin Structure Function g_1 and g_2

$$g_1(x) = \frac{1}{2}\sum_q e_q^2\left(\Delta q + \Delta\bar{q}\right) = \frac{1}{2}\sum_q e_q^2\left(q^+(x) - q^-(x) \ + \bar{q}^+(x) - \bar{q}^-(x)\right)$$



$\sigma_{1/2} \approx q^+(x)$ $\sigma_{3/2} \approx q^-(x)$

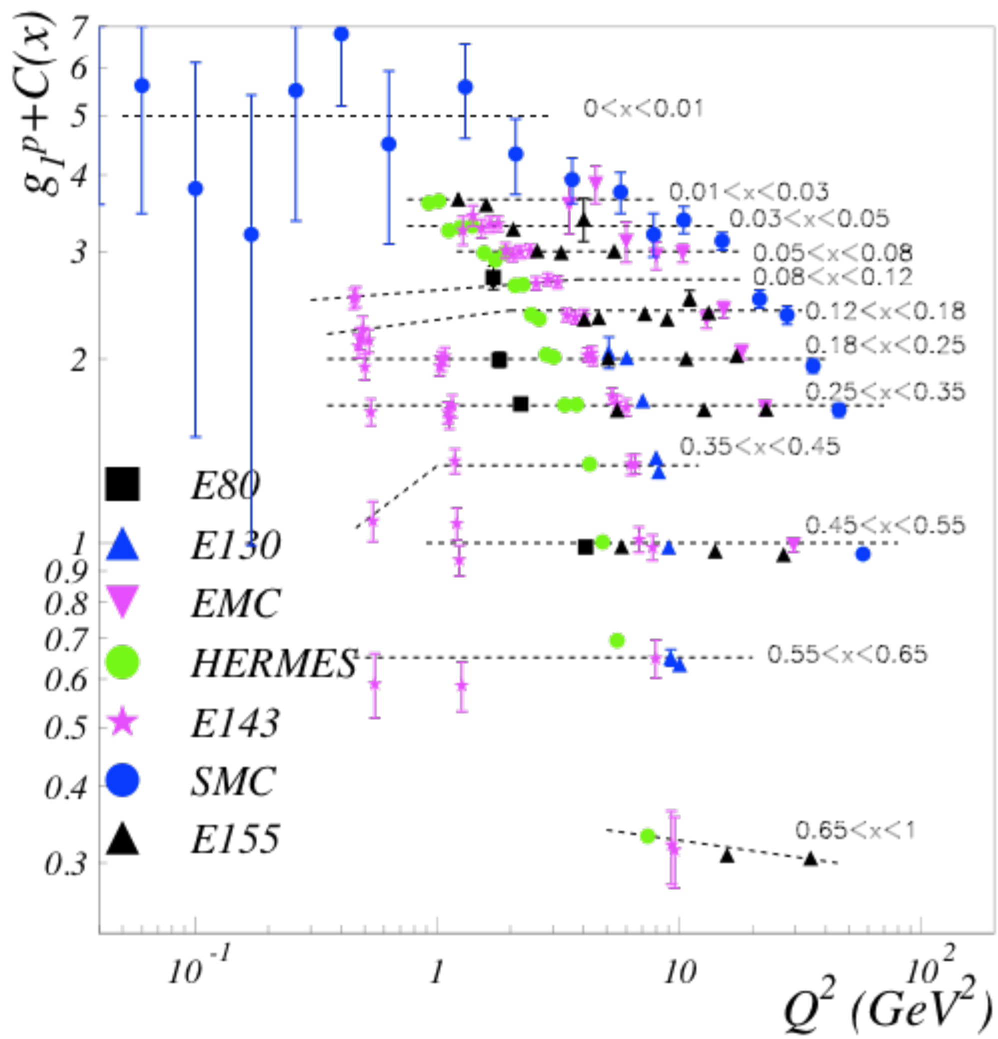
- Virtual photon couples to quarks of opposite helicity
- $q^+(x)$ or $q^-(x)$ are chosen by changing the configuration of the incident lepton and target nucleon spin
- $g_1(x) \sim \sigma_{1/2} - \sigma_{3/2}$

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \overline{g_2}(x,Q^2)$$

- Not a simple interpretation
- g_2^{WW} leading twist (twist 2)
- g_2^{WW} related to g_1 by the Wandzura-Wilczek relation $g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2)\frac{dy}{y}$
- $\overline{g_2}$ higher twist – quark-gluon, quark-quark correlations

$g_1{}^p$ @ Jefferson Lab

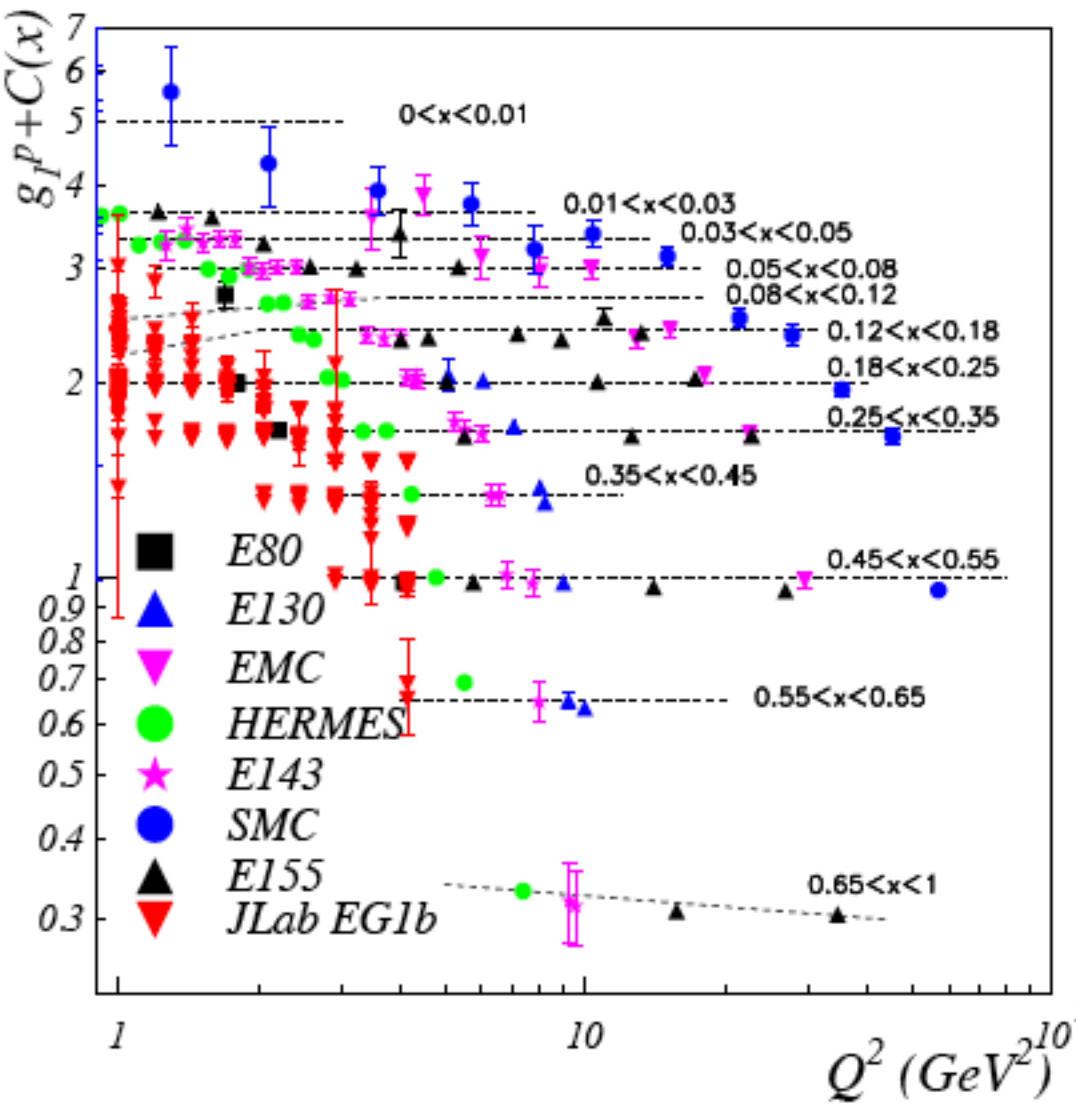
World data on the proton before JLab (without COMPASS)



g_1^p @ Jefferson Lab

World data on the proton before JLab (without COMPASS)

World data on the proton including EG1

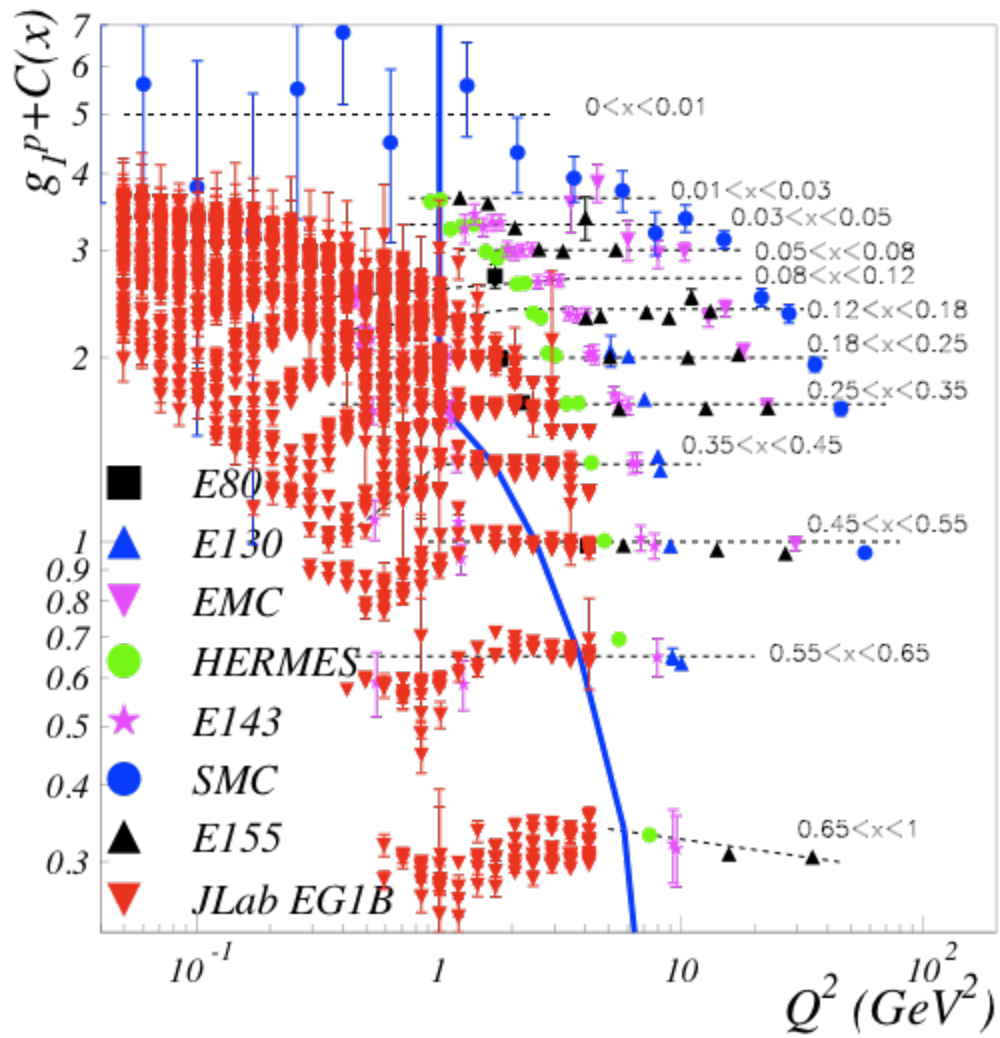


$g_1{}^p$ @ Jefferson Lab

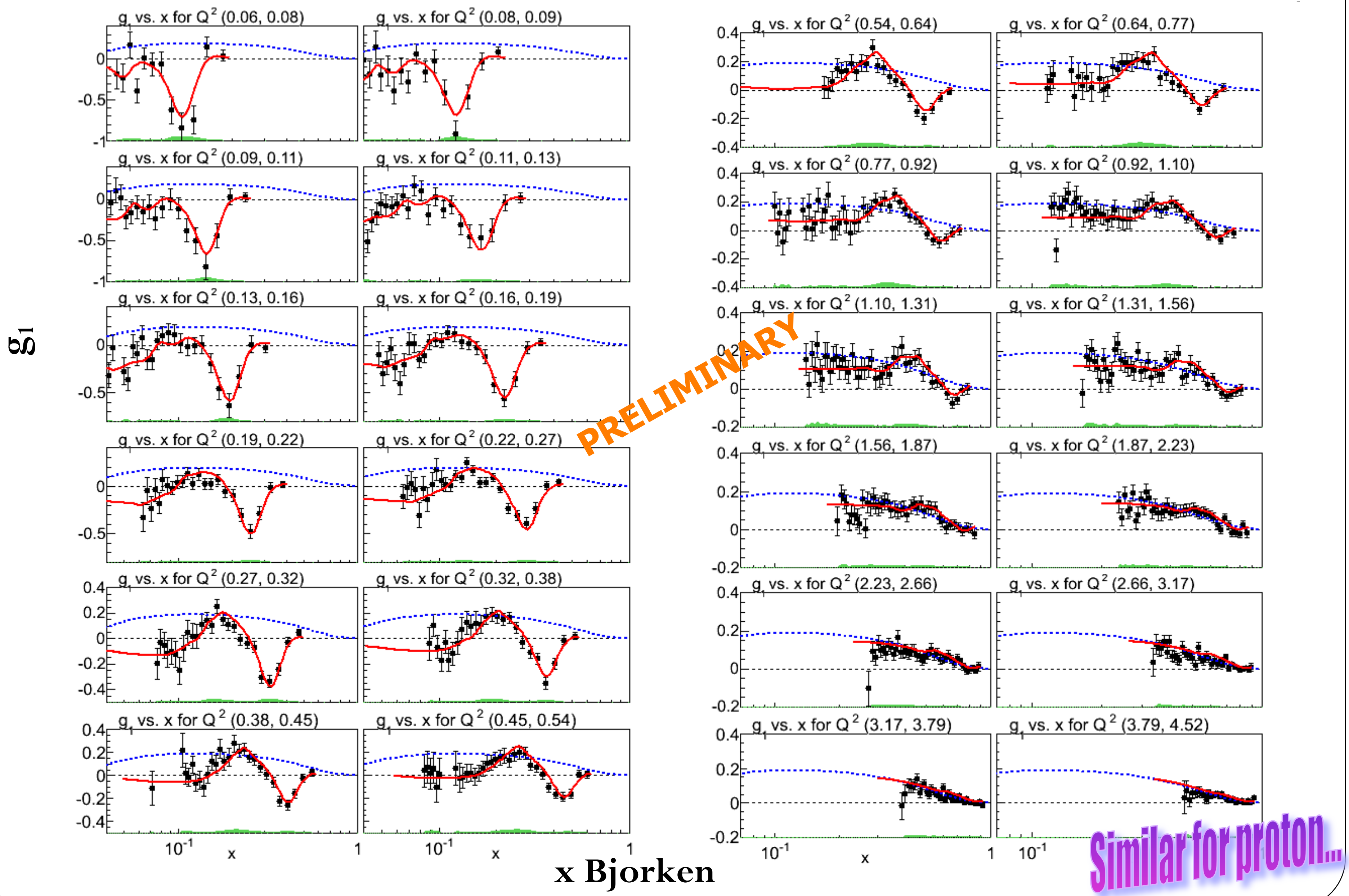
World data on the proton before JLab (without COMPASS)

World data on the proton including EG1

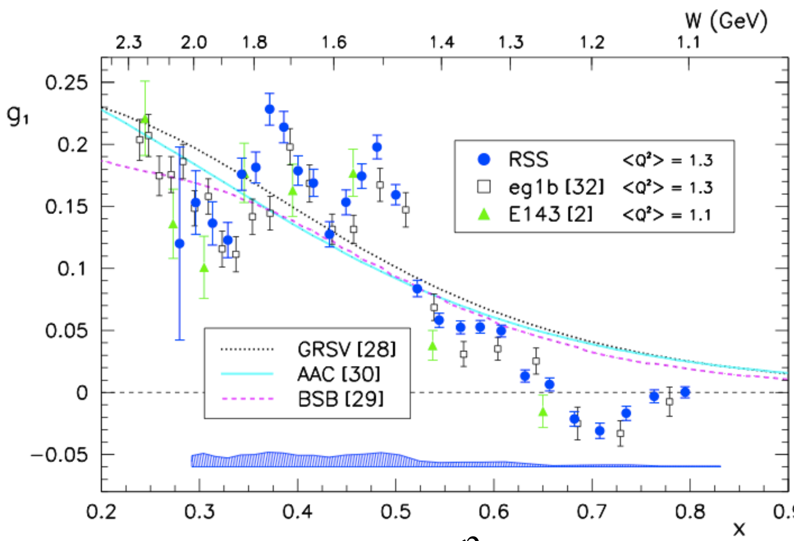
…including resonance region data!

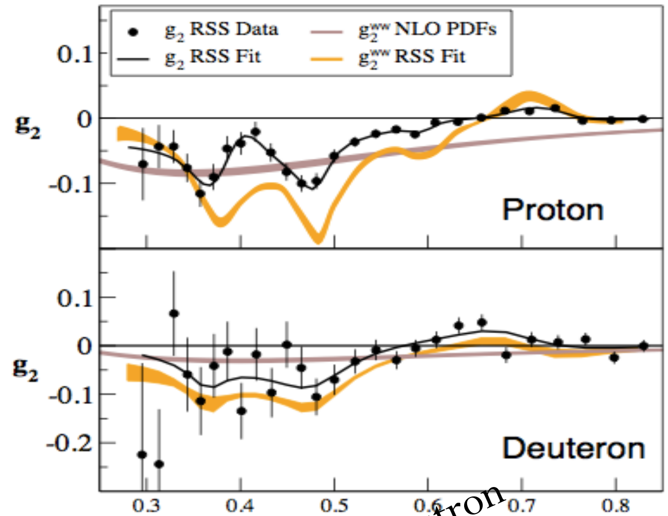


$g_1(x,Q^2)$ proton for different Q^2 bins – eg1

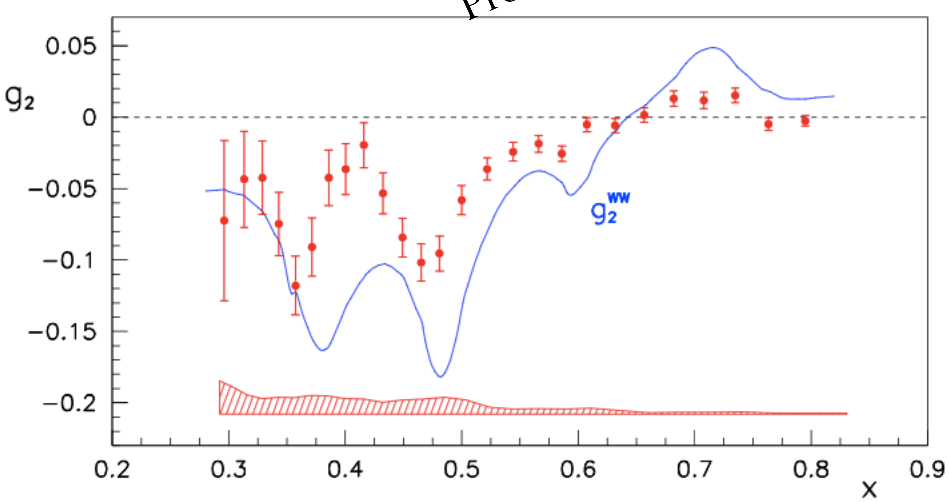


g_1 and g_2 for p and d

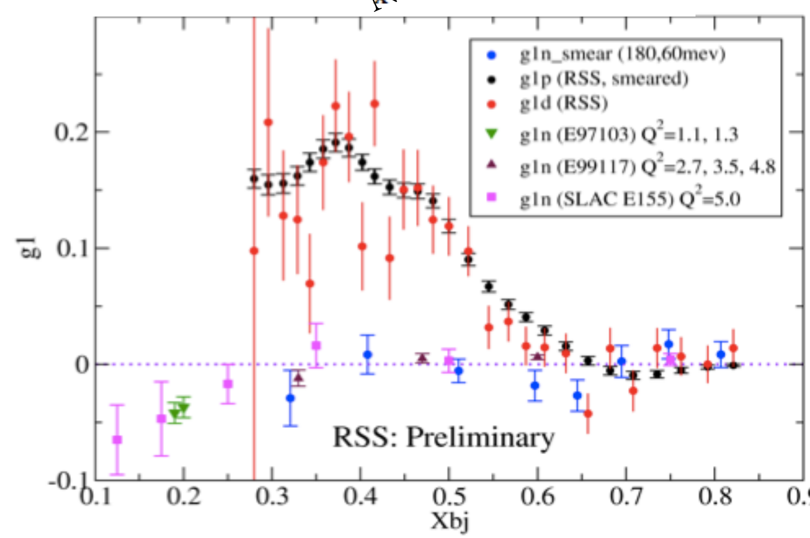




Proton



Neutron

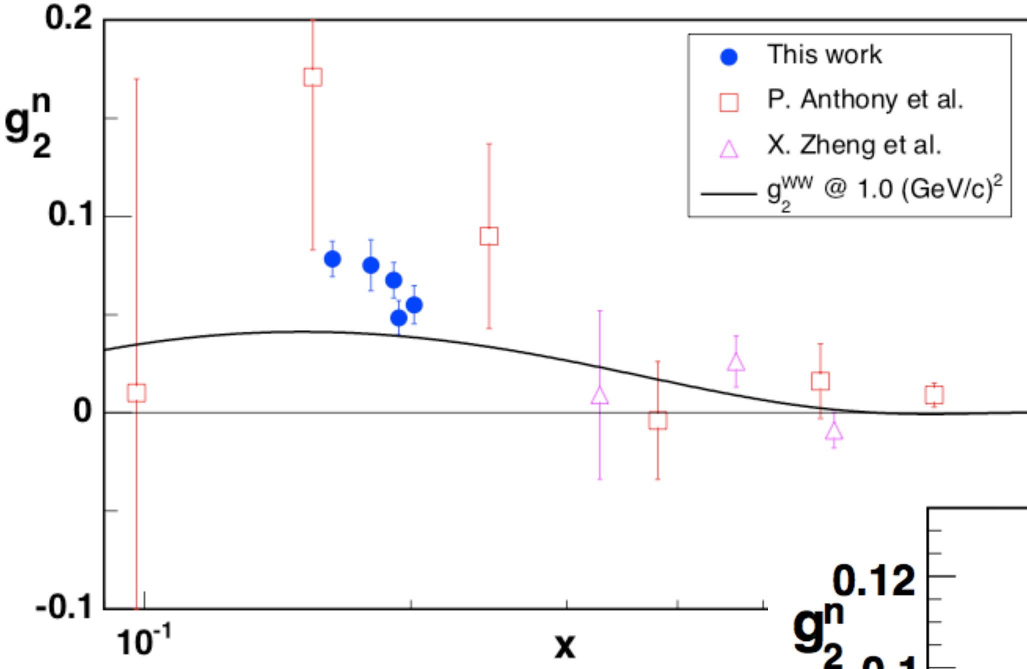


$Q^2 = 1.3\ \mathrm{GeV}^2$

Hall C RSS, PRL 98, 132003 (2007)

Hall C RSS, arXiv:0812.0031 (2008)

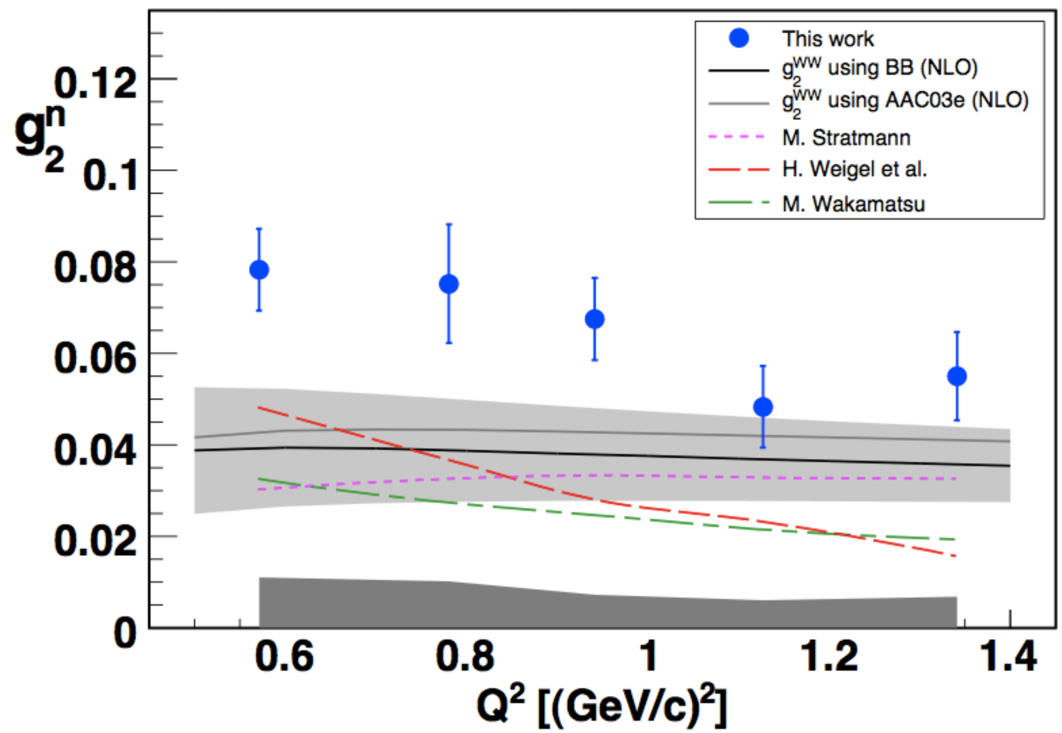
g_2 for neutron – Hall A



Hall A, E97-103 K. Kramer et al.,
PRL 95, 142002 (2005)

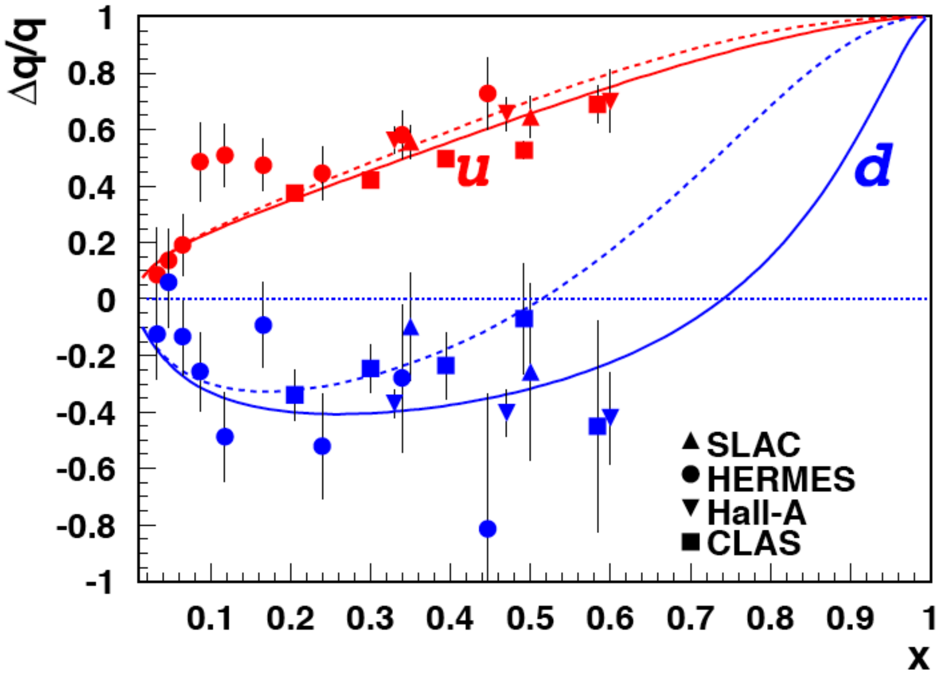
E97-103:

- Q^2 from 0.58 to 1.36 GeV^2
- $x \approx 0.2$
- Dedicated exp g_2^n in DIS region at low Q^2

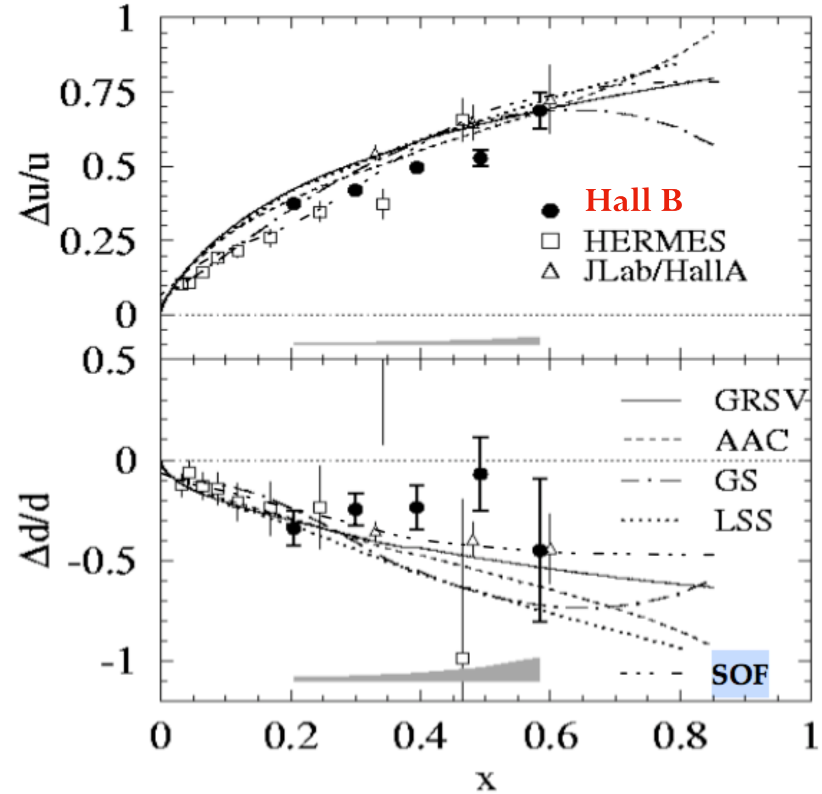


- Measure higher twist → quark-gluon correlations.
- Positive deviation from g_2^{WW} → higher twist contributions

Polarized quark distribution functions



Avakian et al., Phys.Rev.Lett.99:082001,2007



Dharmawardane et al., Phys.Rev.Lett. B641,2006

Assuming the naïve parton model with no sea contribution, quark polarizations in the valence region can be estimated directly from the data:

$$\frac{\Delta u}{u} \approx \frac{5g_1^p - 2g_1^d/(1-1.5\omega_D)}{5F_1^p - 2F_1^d}$$

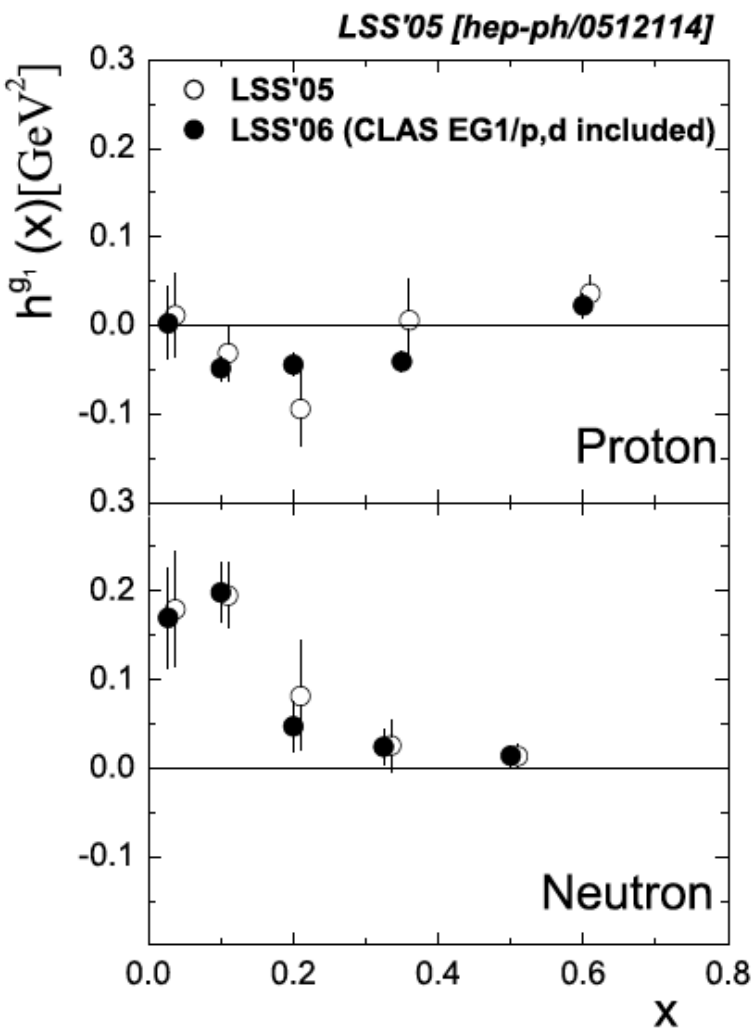
$$\frac{\Delta d}{d} \approx \frac{8g_1^d/(1-1.5\omega_D) - 5g_1^p}{8F_1^d - 5F_1^p}$$

•Also NLO analysis on this data

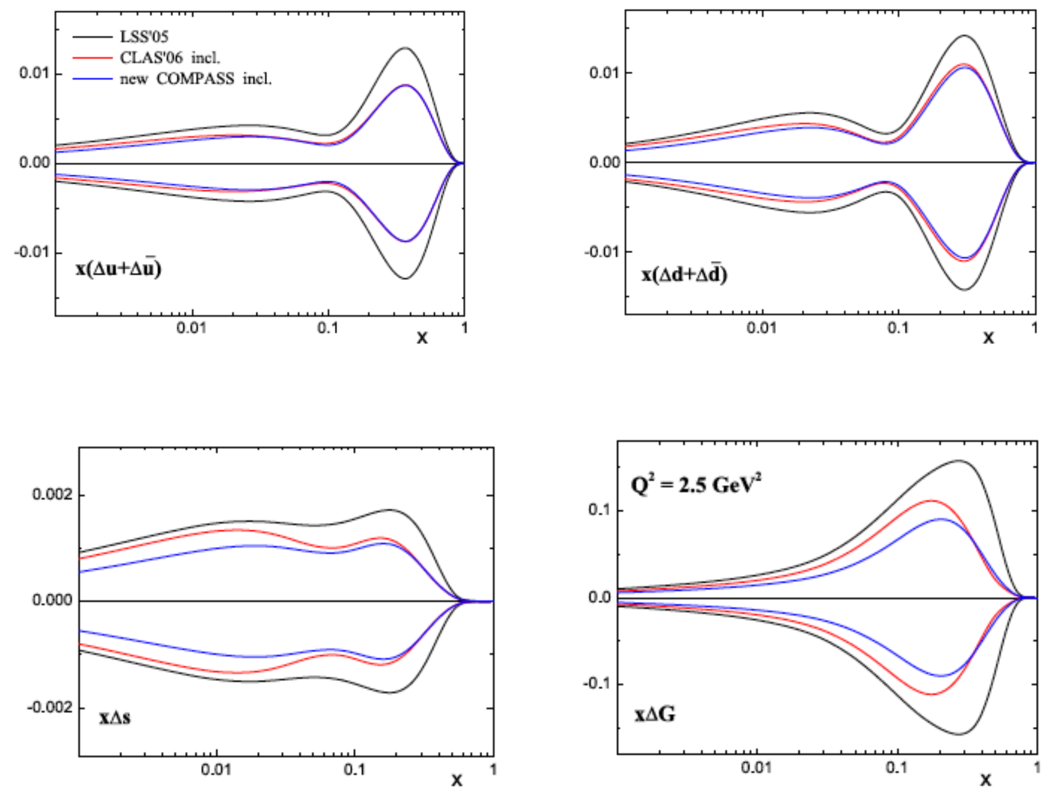
•New results for recent data coming soon!

Orbital angular momentum may change this picture

Effect of CLAS data on NLO fits of PDFs



Higher Twist contribution to g_1



$$g_1(x,Q^2)_{\exp} = g_1(x,Q^2)_{LT} + h^{g_1}(x)/Q^2$$

NLO fit by Leader, Stamenov and Siderov, including both CLAS data and new COMPASS data on the deuteron

First moment Γ_1 and GDH

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

Net Quark Spin

At high Q² - QPM $\quad g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$

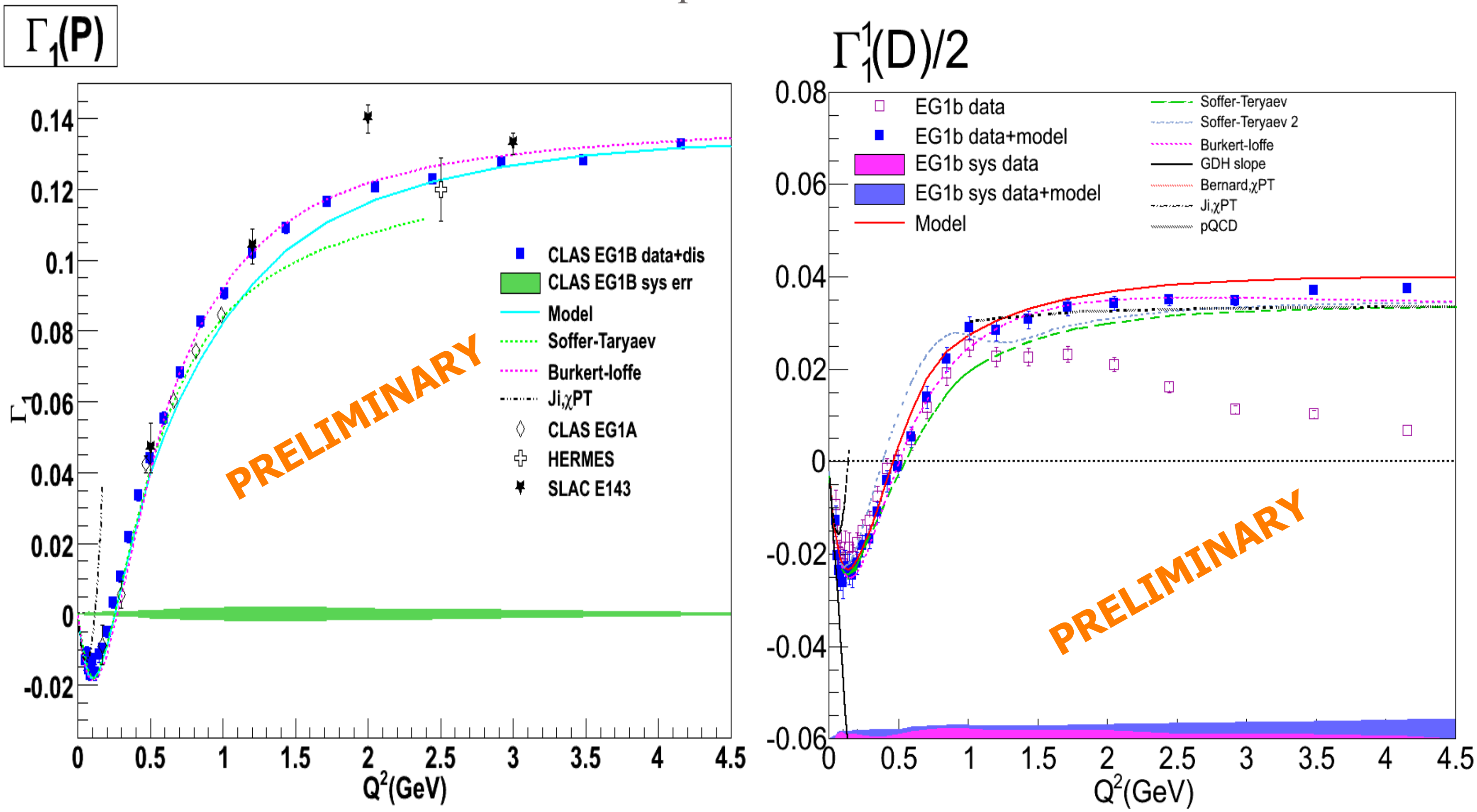
$$\Gamma_1^p = \frac{1}{9}\left(\frac{3}{4}a_3 + \frac{1}{4}a_8 + a_0\right) \qquad a_0 = \Delta\Sigma$$

Q²→0 - GDH $\quad \Gamma_1 = \int g_1\left(x,Q^2\right)\,dx \xrightarrow[Q^2\to 0]{} \frac{Q^2}{2M^2} I_{GDH}$

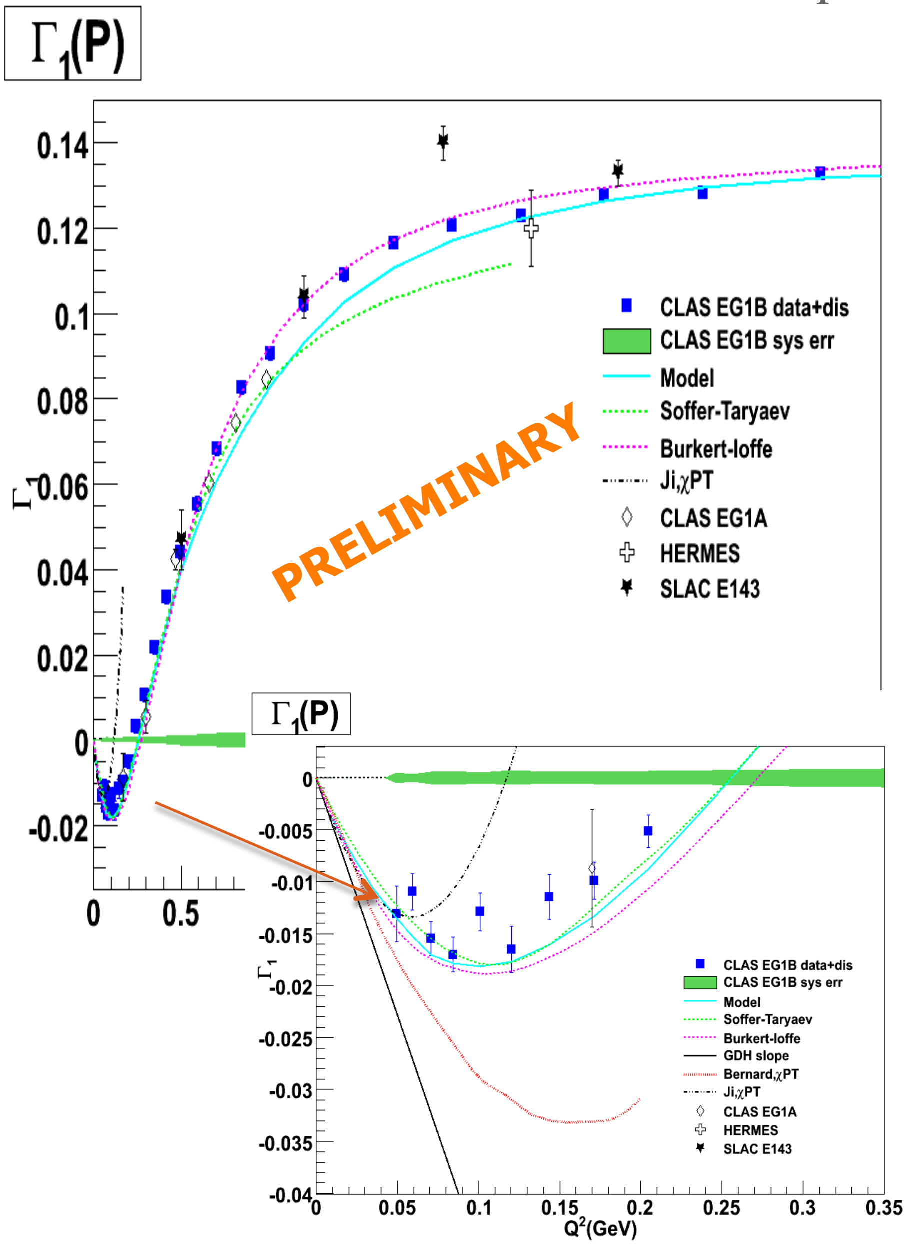
$$I_{GDH} = \frac{M^2}{8\alpha\pi^2}\int_{thr}^{\infty}\left(\sigma_{1/2} - \sigma_{3/2}\right)\frac{d\nu}{\nu} = -\frac{1}{4}\kappa^2$$

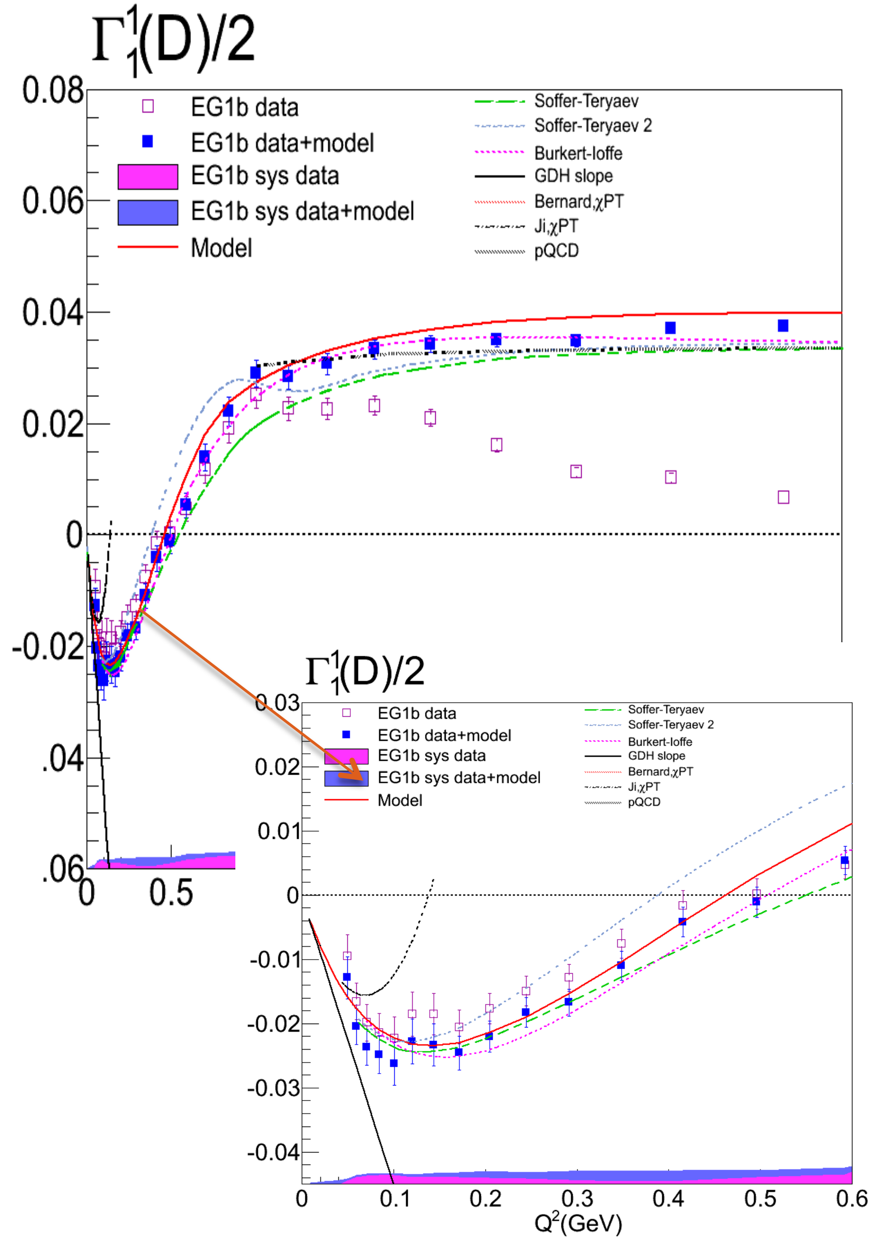
A connection between dynamic and static properties.

First moment Γ_1 and GDH - CLAS



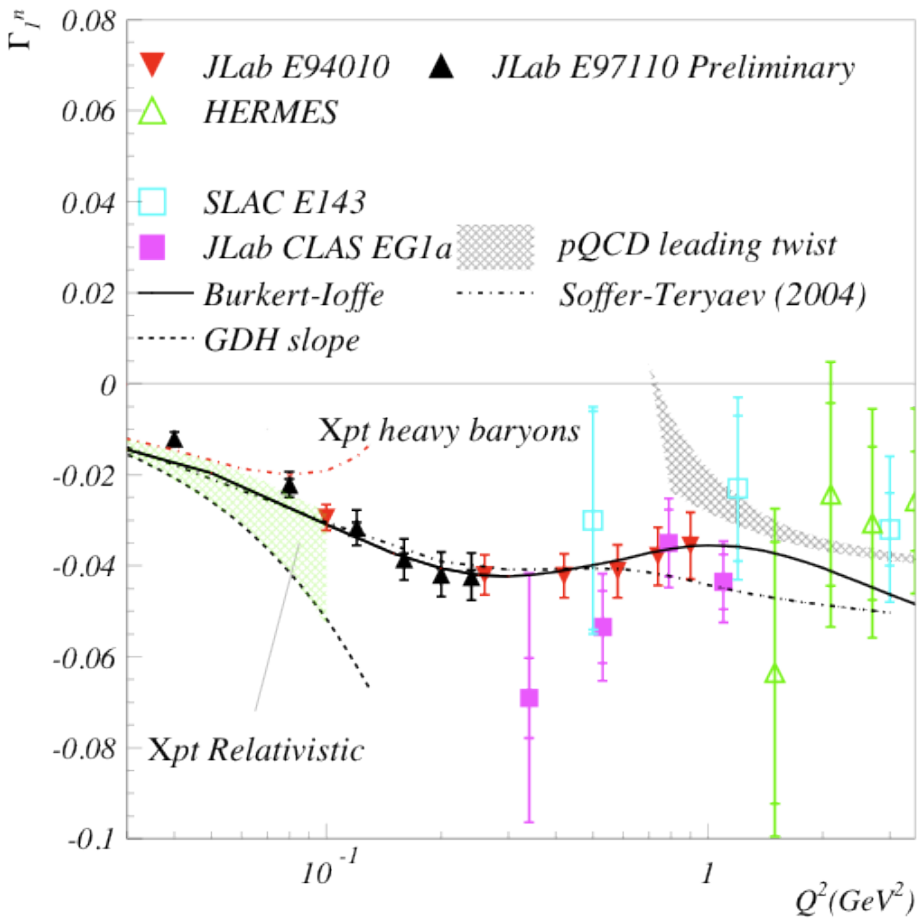
First moment Γ_1 and GDH - CLAS



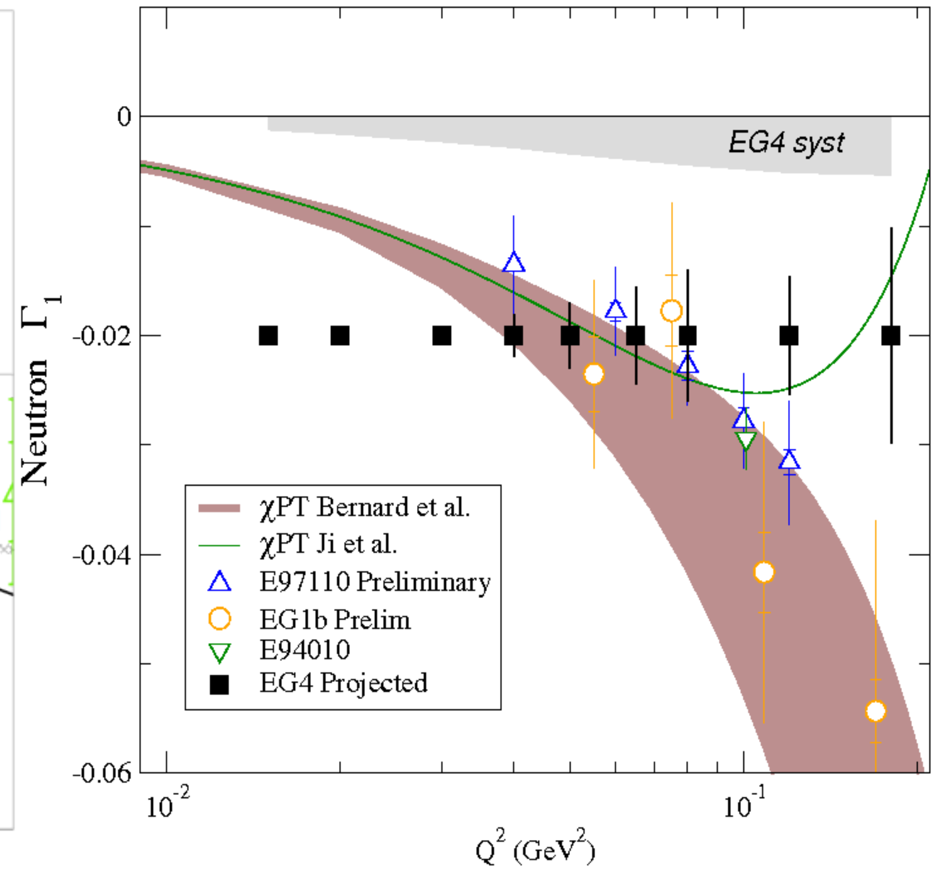


First moment Γ_1 and GDH – low Q^2

Neutron



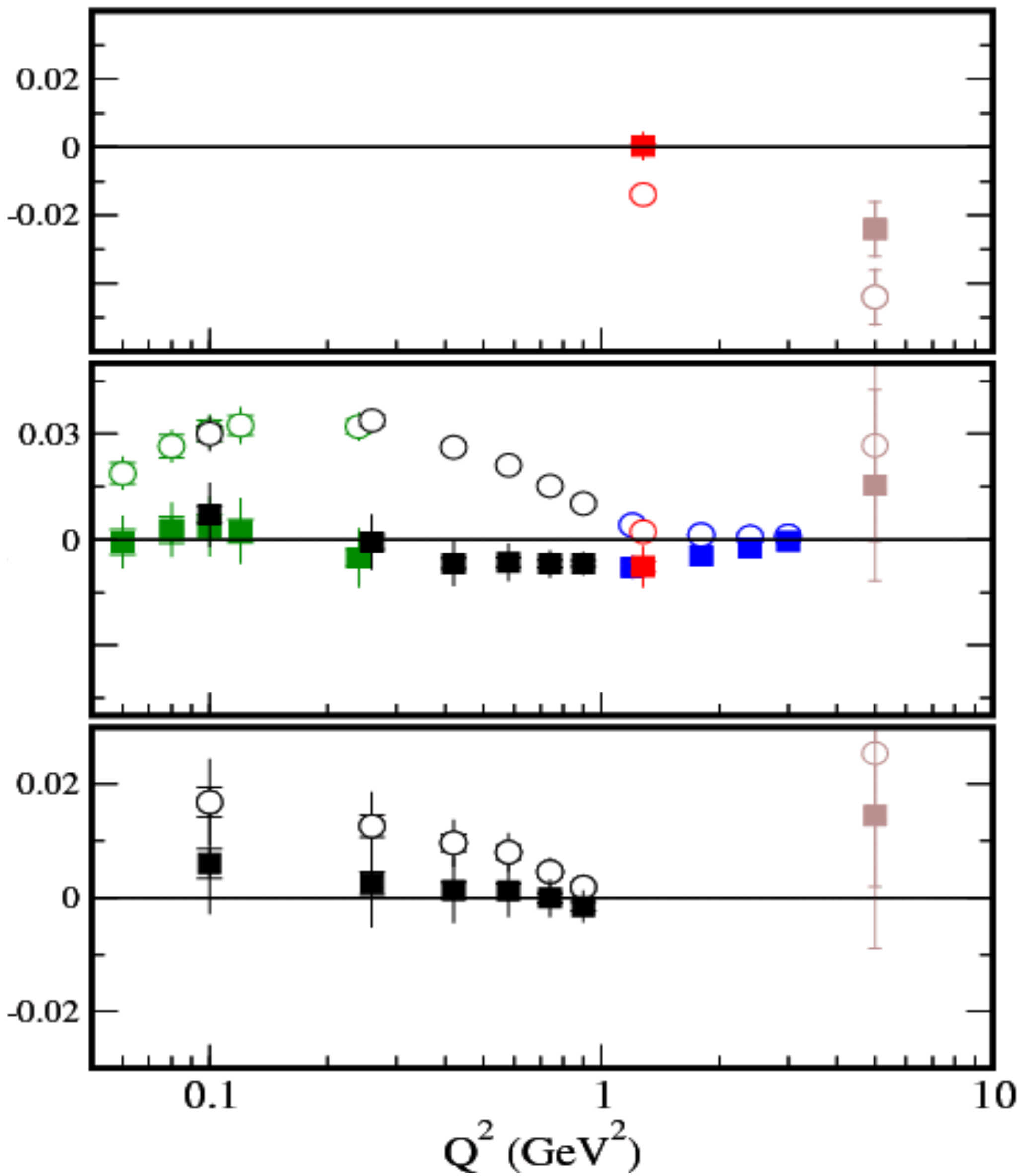
Hall A



EG4 (expect results)

Hall A, E94-010 M. Amarian et al.,
PRL 92, 022301(2004)

Burkhardt - Cottingham Sum Rule



$$\Gamma_2 = \int_0^1 g_2(x)dx = 0$$

Brown: SLAC E155x
Red: Hall C RSS
Black: Hall A E94-010
Green: Hall A E97-110 (preliminary)
Blue: Hall A E01-012 (very preliminary)

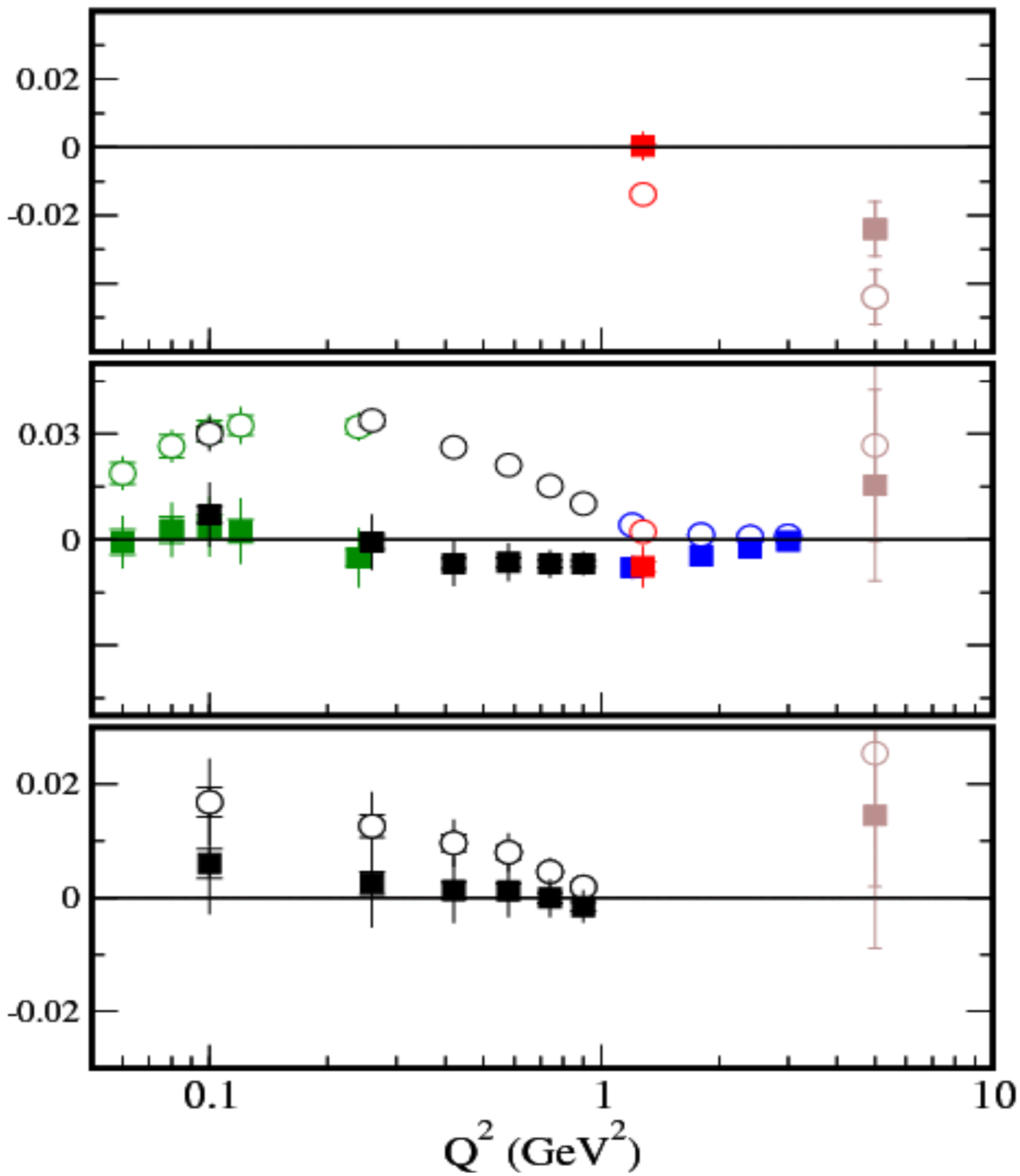
BC = Meas+low_x+Elastic

"Meas": Measured x-range

"low-x": refers to unmeasured low x part of the integral.
Assume Leading Twist Behaviour

Elastic: From well know FFs (<5%)

Burkhardt - Cottingham Sum Rule

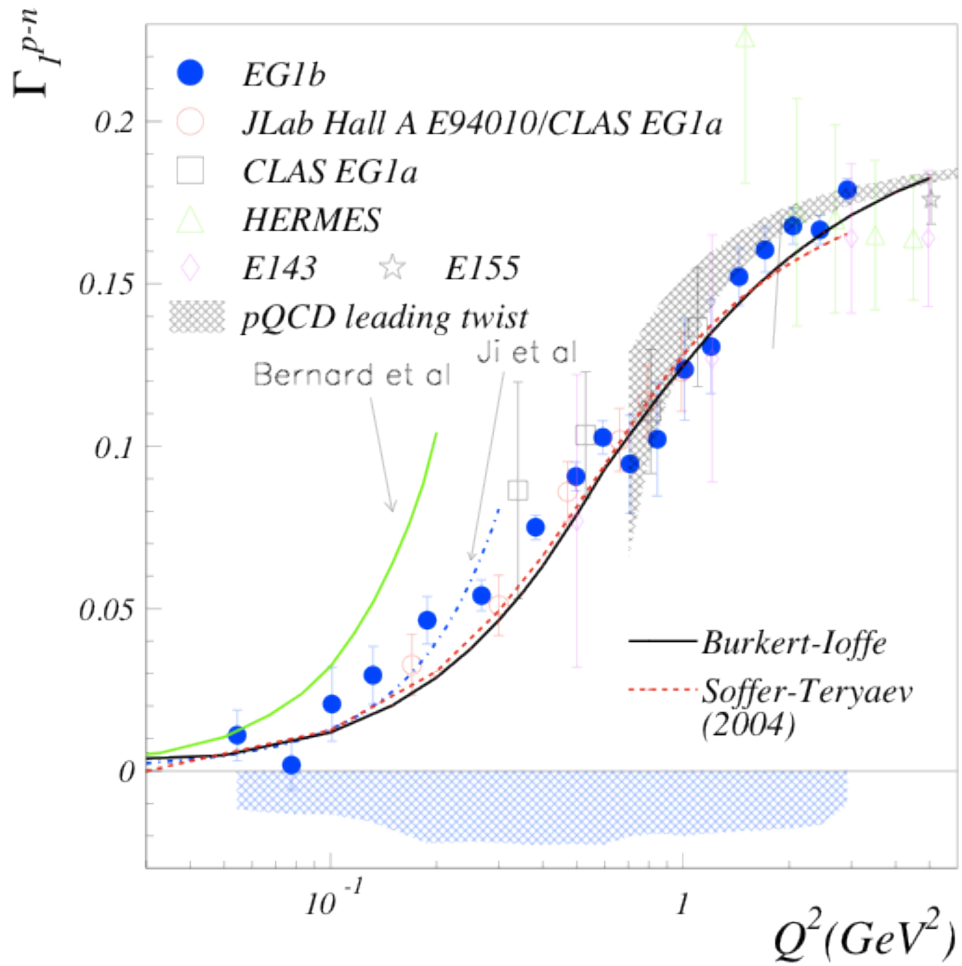


BC satisfied w/in errors for JLab Proton
2.8σ violation seen in SLAC data

BC satisfied w/in errors for Neutron
(But just barely in vicinity of Q^2=1!)

BC satisfied w/in errors for ^3He

Γ_1 of p-n – Bjorken integral

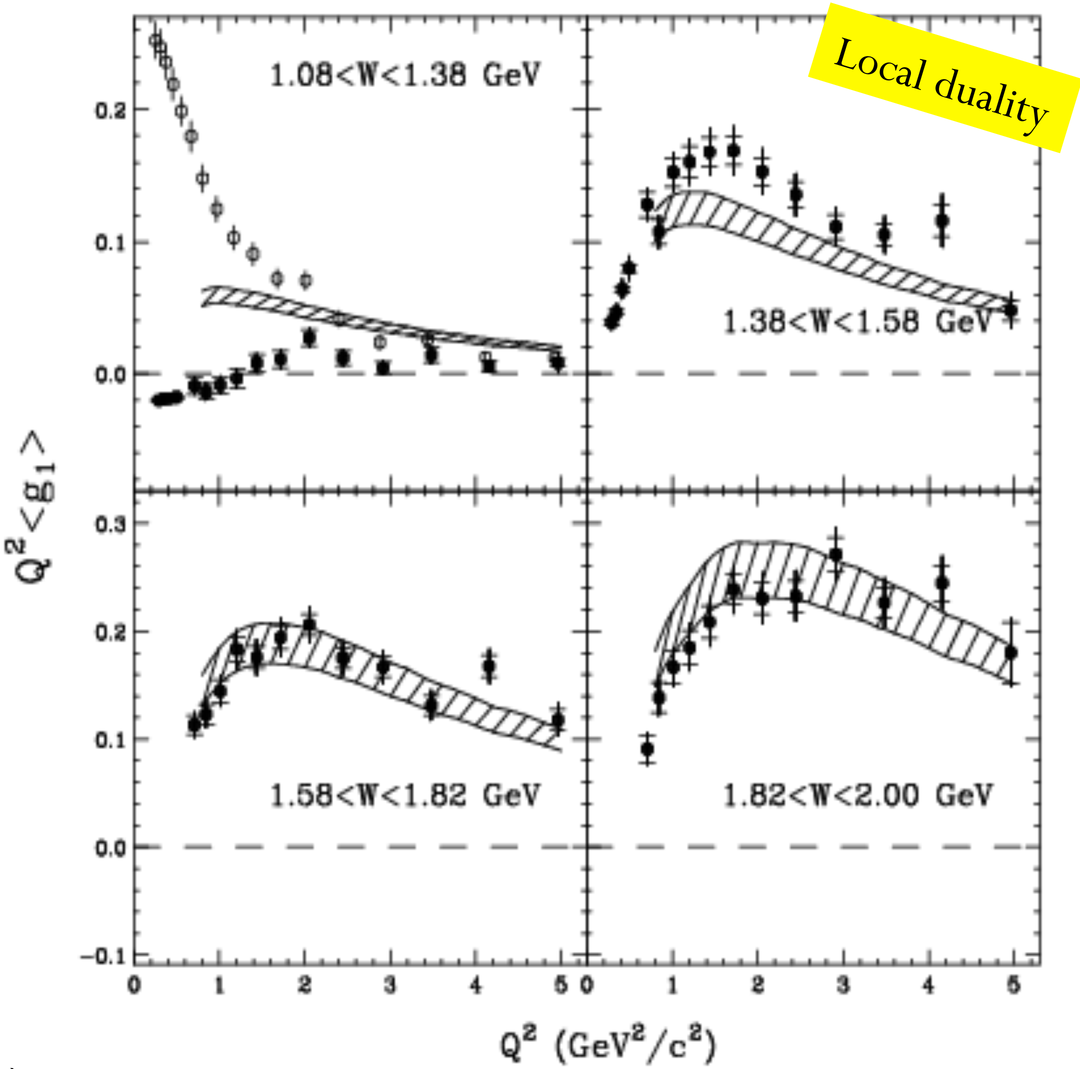


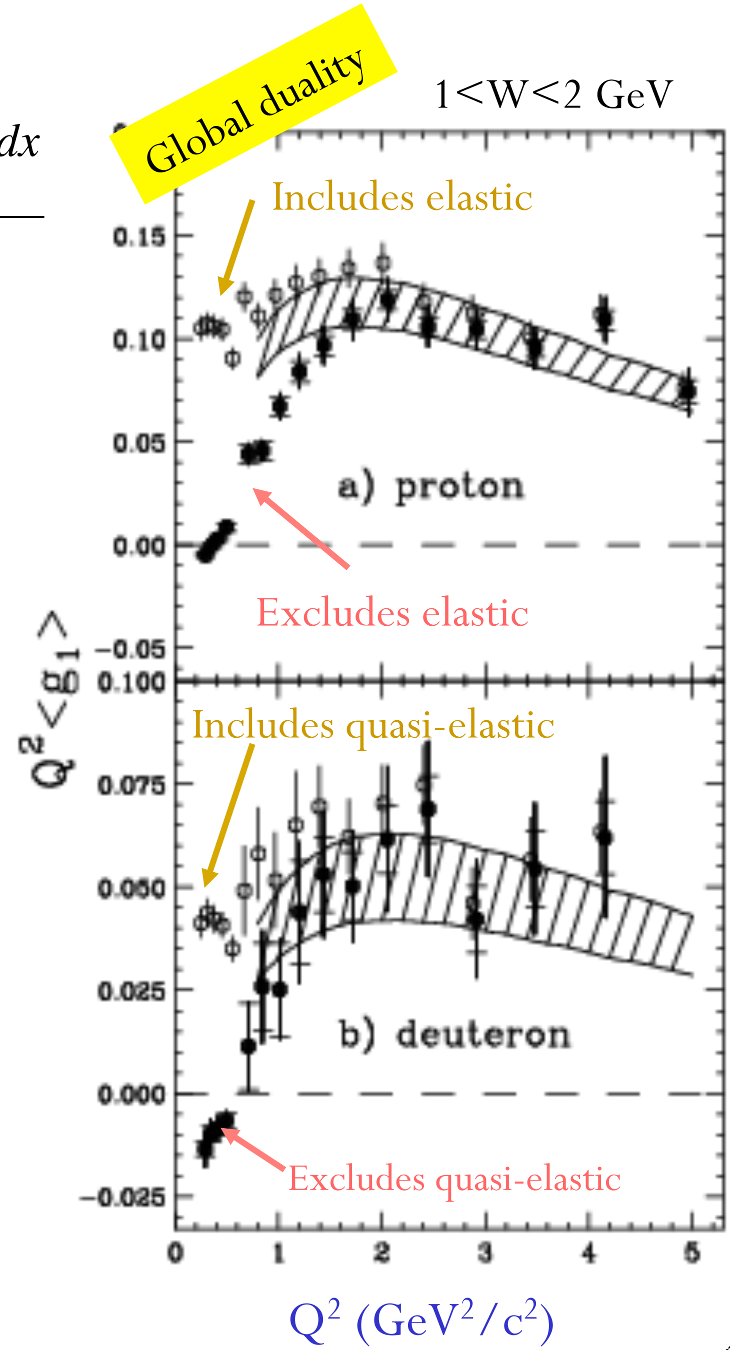
- EG1b, PRD 78, 032001 (2008)
- E94-010 + EG1a: PRL 93 (2004) 212001

Duality

Structure functions averaged over resonances behave like DIS

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



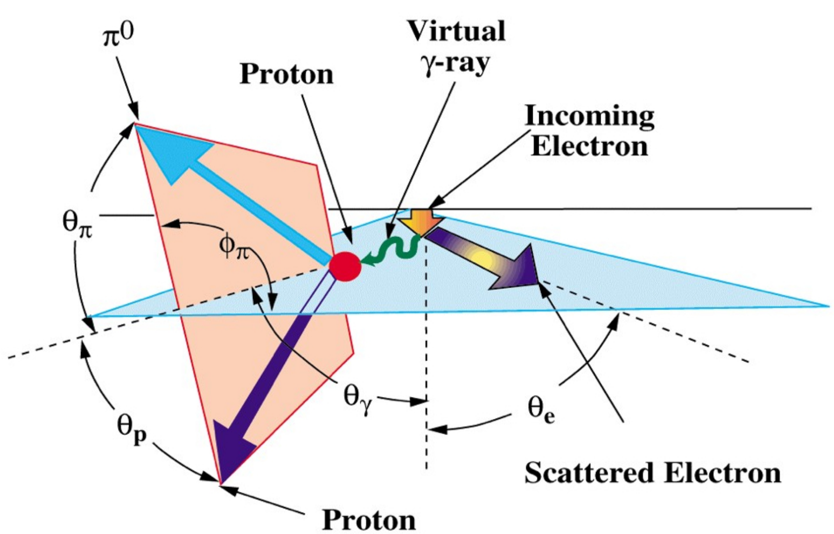


2 particles final state

H(e,e'π^0)p
H(e,e'π^+)n
D(e,e'pπ^-)p
rho production
eta production

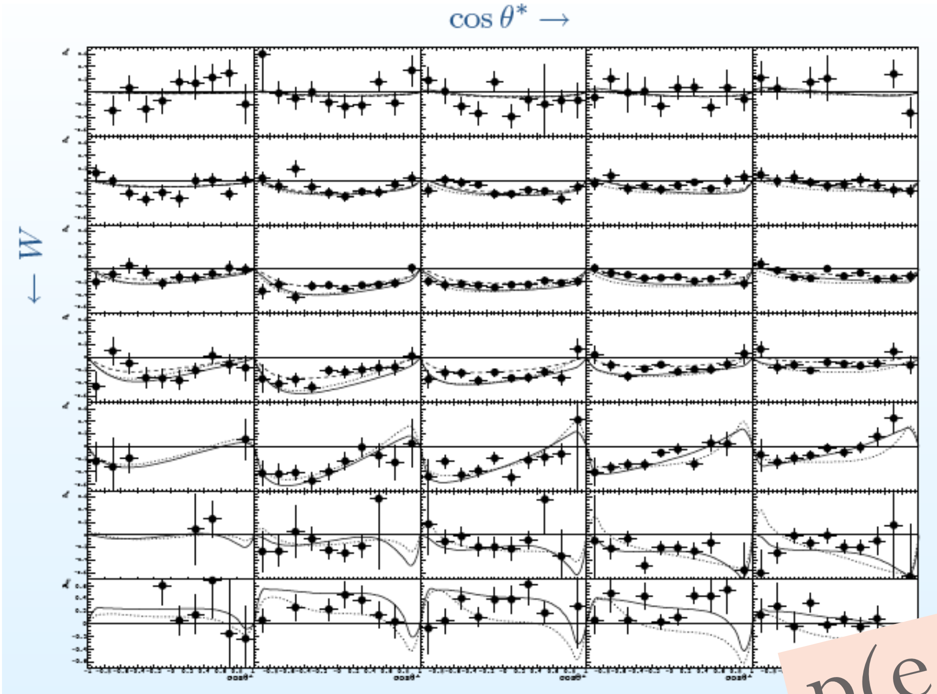
$$\sigma(W, Q^2, \vartheta^*, \phi^*) \propto \sigma_o + P_e\sigma_e + P_t\sigma_t + P_eP_t\sigma_{et}$$

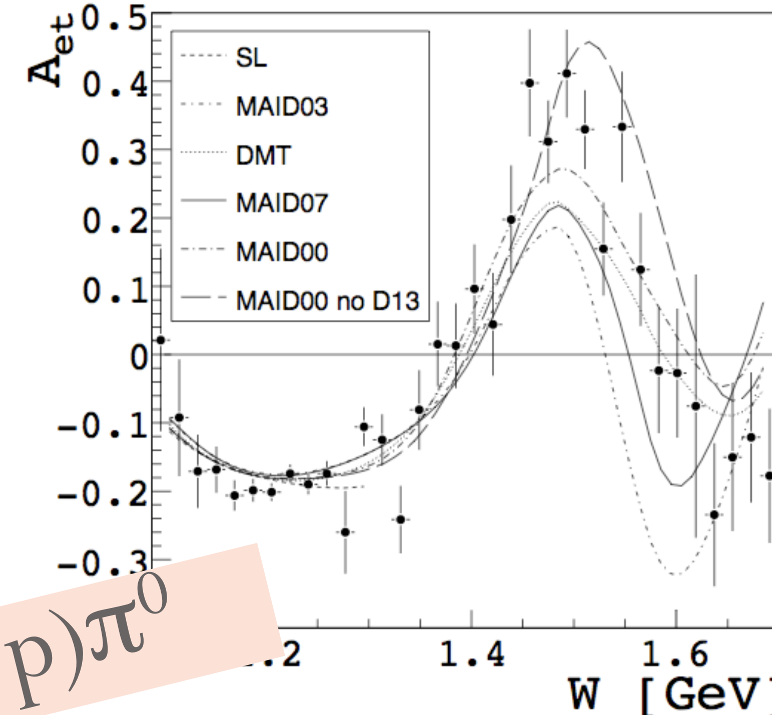
- Different sensitivities to resonant and non resonant contributions for the double (σ_{et}) and target (σ_t) polarization terms
- Polarized measurements to provide new constraints to phenomenological models which are based on previous unpolarized photo- and electro-production data



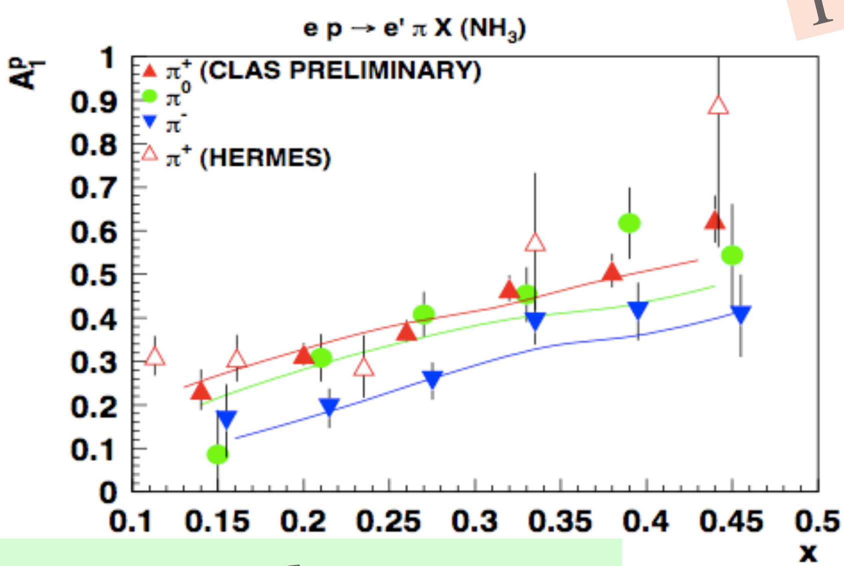
Semi-inclusive

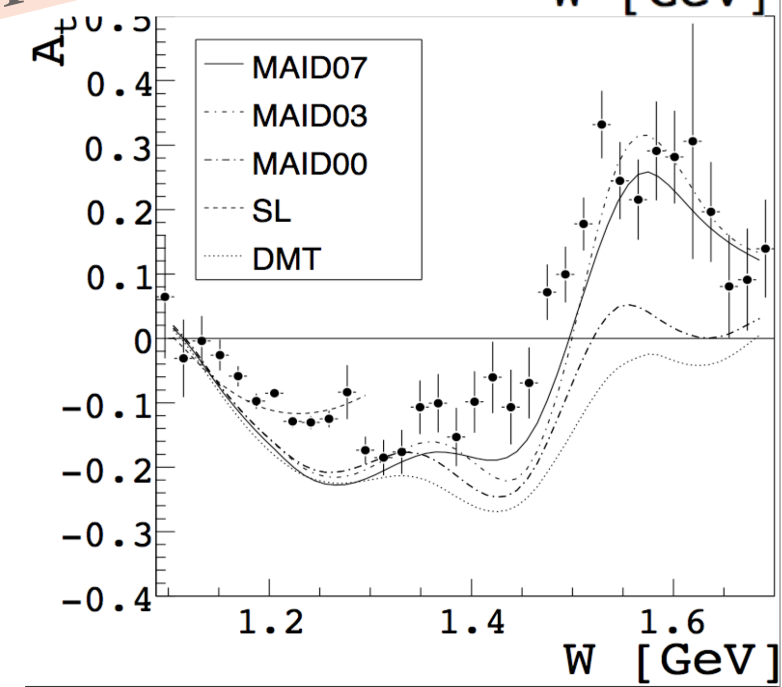
- e p $\longrightarrow$ e' p X
- Struck quark of different flavors produce the hadron with different probabilities $\longrightarrow$ SIDIS can help to separate contributions from quark flavors
- Access to orbital angular momentum of quarks
- Transverse momentum distributions





$p(e,e'p)\pi^0$



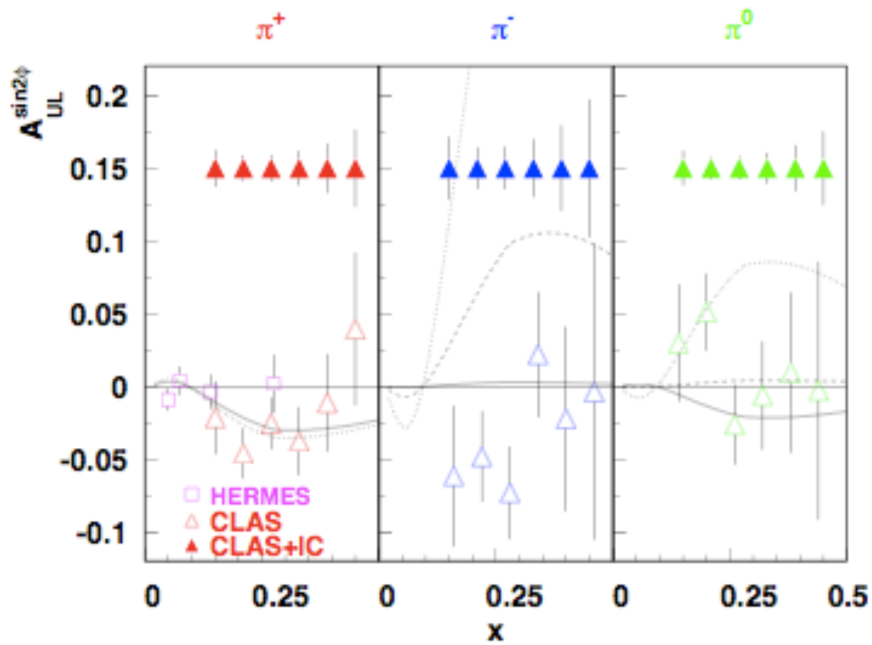


Semi-inclusive

Study of the semi-inclusive pion production (E05-113)

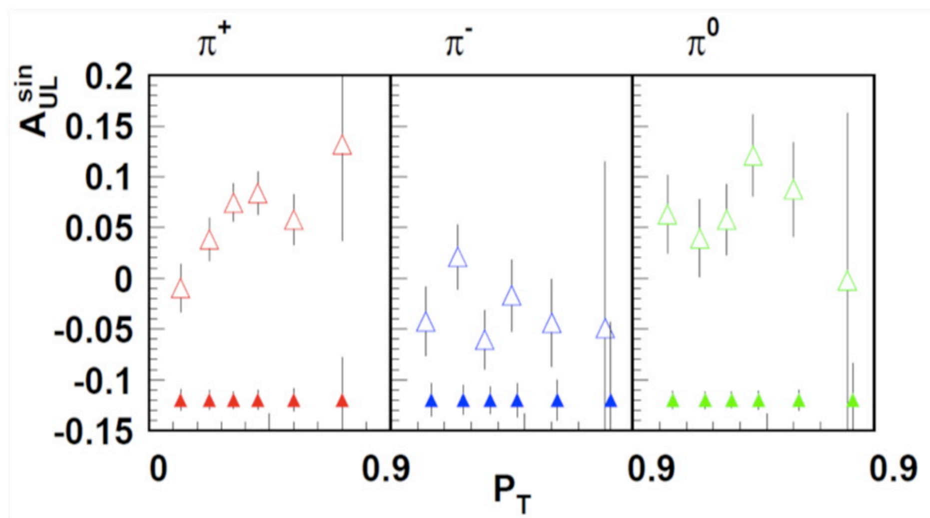
Completed in Fall 2009

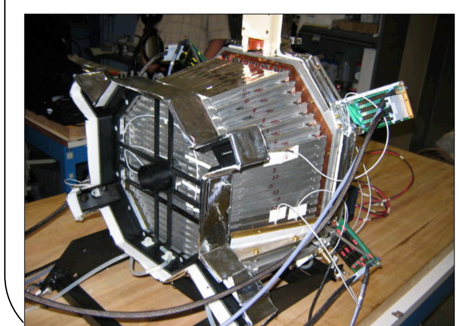
TMDs and Collins fragmentation function as well as DVCS



Expected Precision for $\sin\phi$ and $\sin 2\phi$ moments of target SSA

$E_{beam} = 6$ GeV



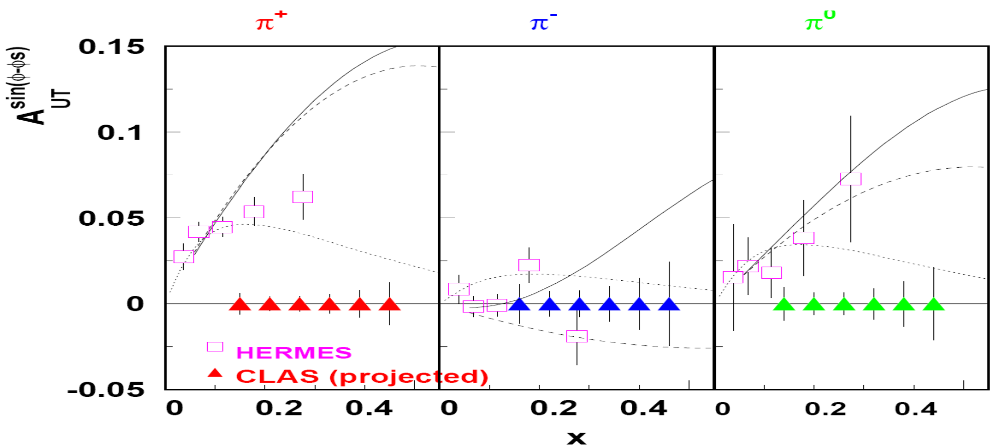


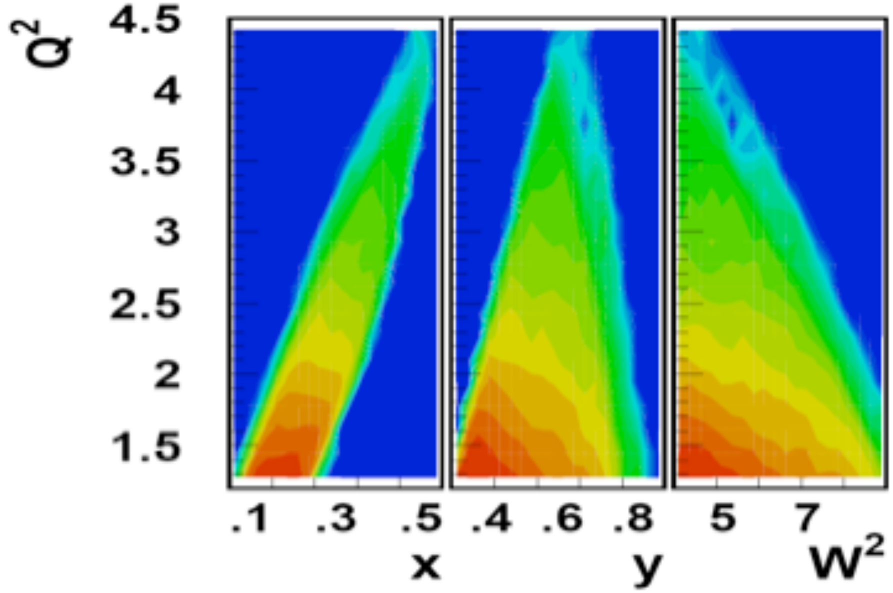
60 days (P_H=75%)

uses 2π inner calorimeter for γ/π^0 coverage

Study of spin orbit correlations in semi inclusive DIS and Sivers distribution function (E08-015)

HD target





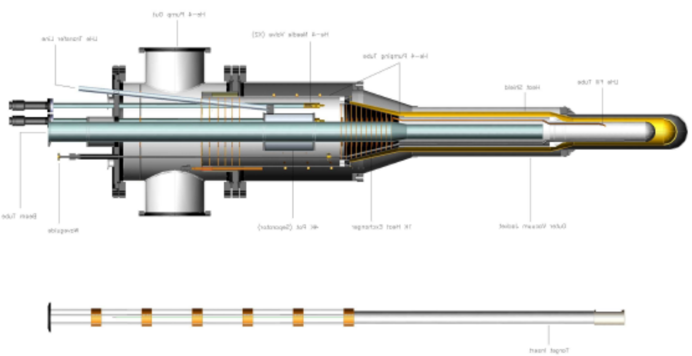
E_{beam} = 6 GeV

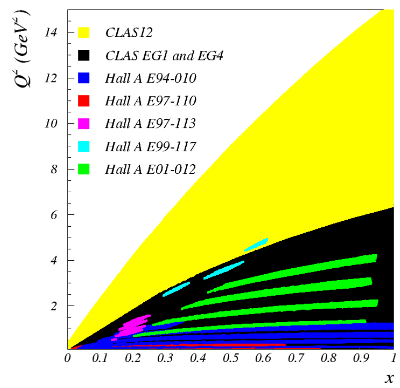
25 days (P_H=75% P_D=25%)

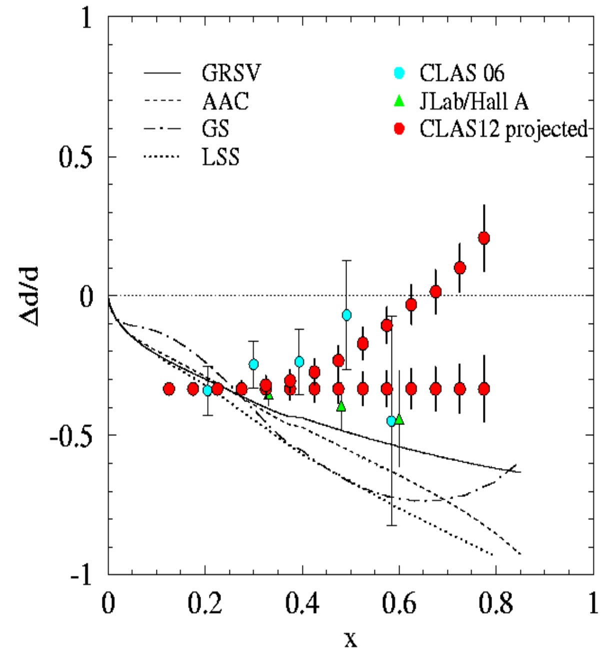
Potential to add to world data on g_2 and A_2

12 GeV program

CLAS12



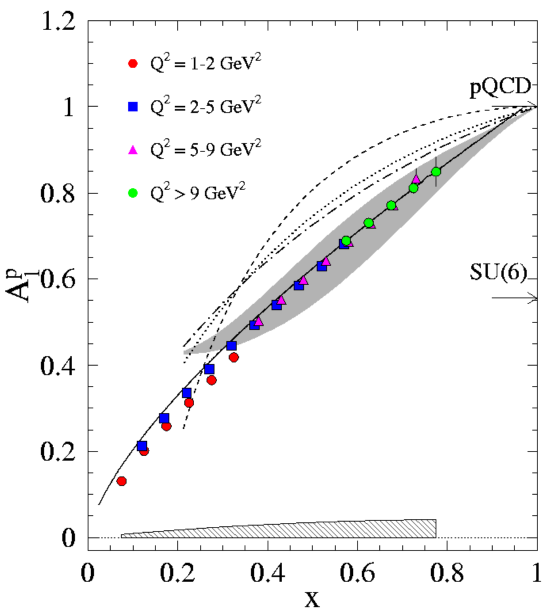


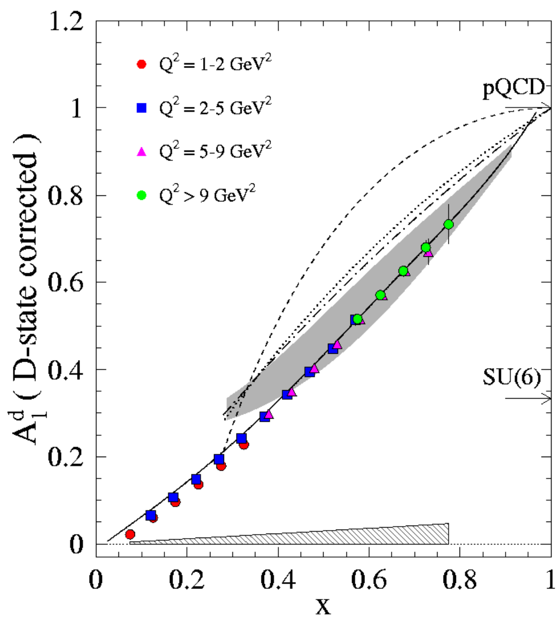


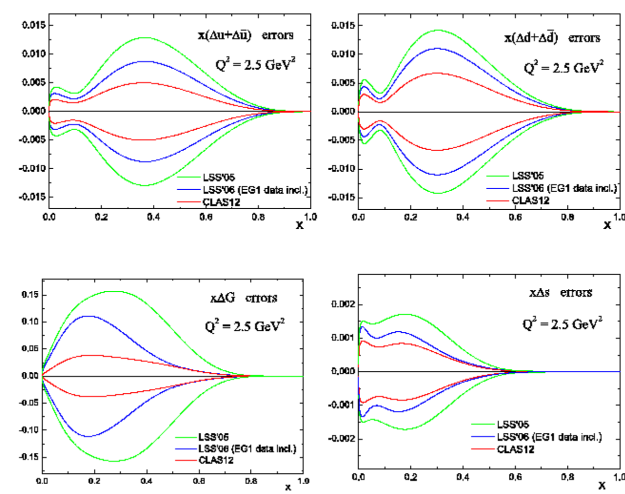
Proton

W > 2; Q^2 > 1

Deuteron







Also semi-inclusive proposals!

Conclusions

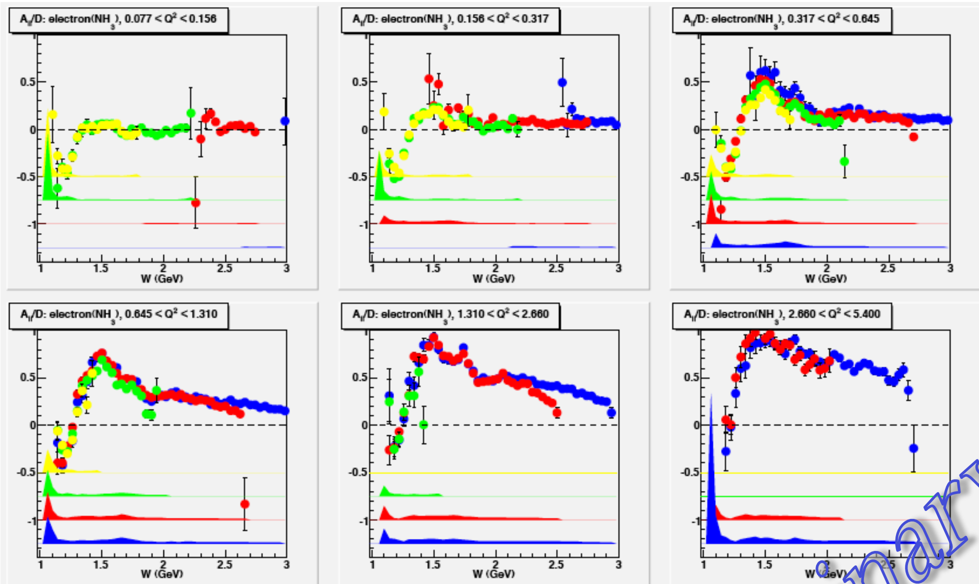
- Broad spin program at Jefferson Lab.
- Complex look at the structure of the nucleon.
- Many observables asymmetries, structure functions, sum rules, moments
- New information to understand the transition between hadron and partonic degrees of freedom
- Plenty results from Jefferson Lab, large acceptance and access to resonance region
- Much more to come COMPASS+RHIC, Spring8, **JLab @ 12 GeV**, J-PARC, FAIR, … EIC?

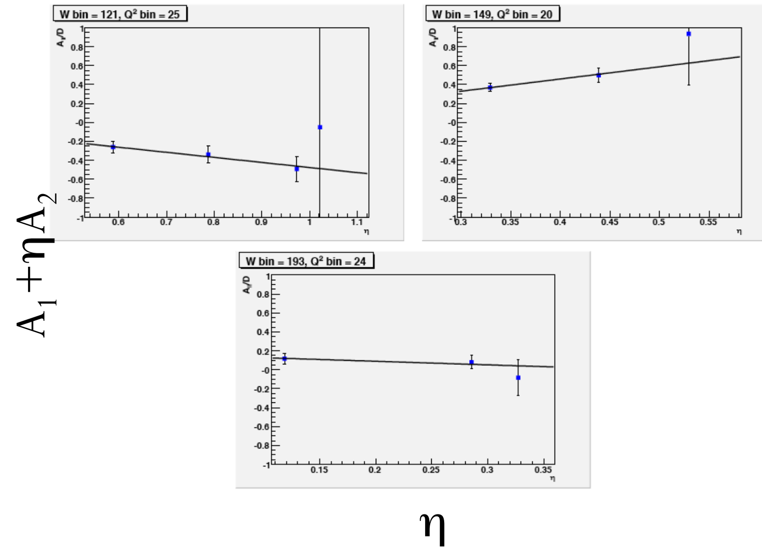
Thanks to Sebastian Kuhn, Nevtzat Guler, Yelena Prok, Keith Griffioen, Jiang-Peng, Karl Slifer, Narbe Kalantarians, Oscar Rondon, K. Adhikari

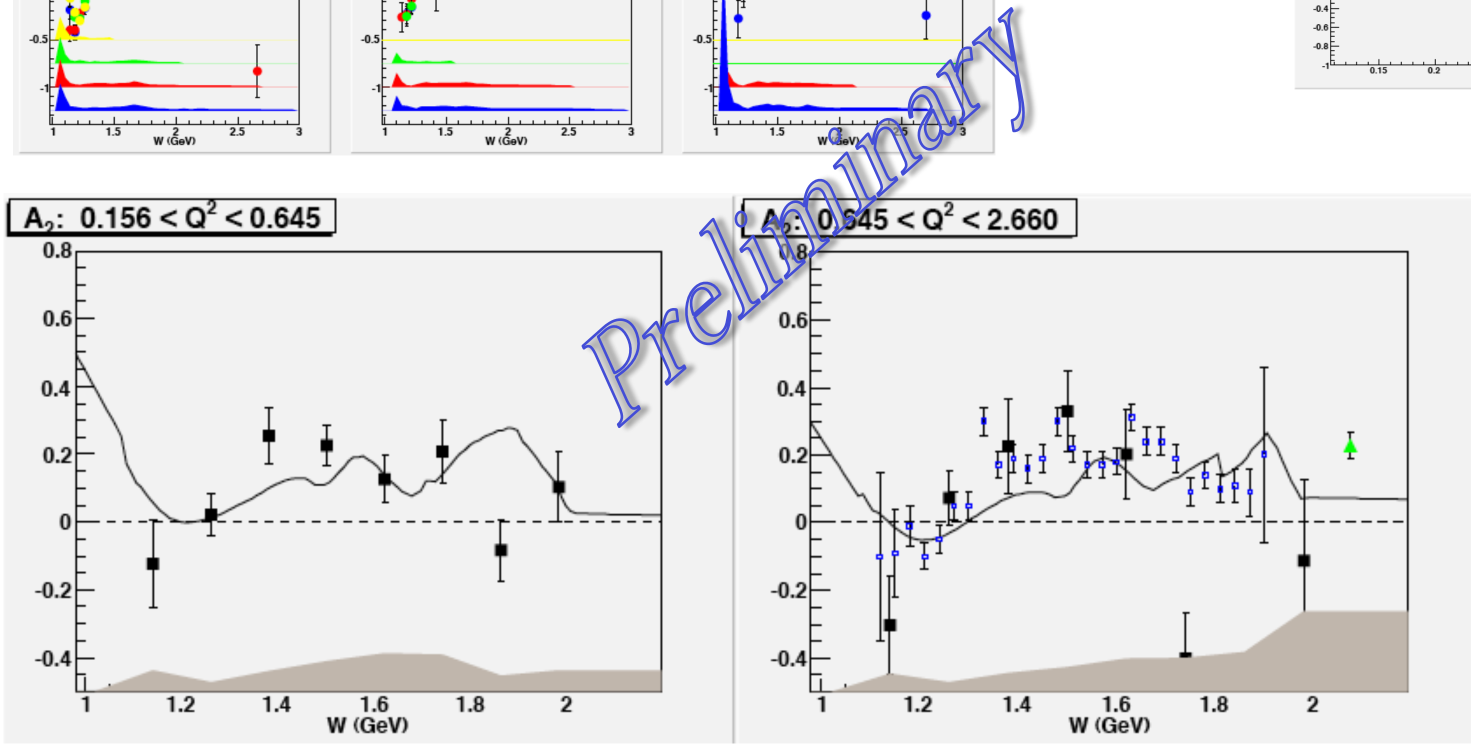
Overview

- Spin Physics
- Experiments at JLab
- Nucleon Structure Functions results
- Future experiments
- Summary

Extracting A_2 / g_2 - CLAS





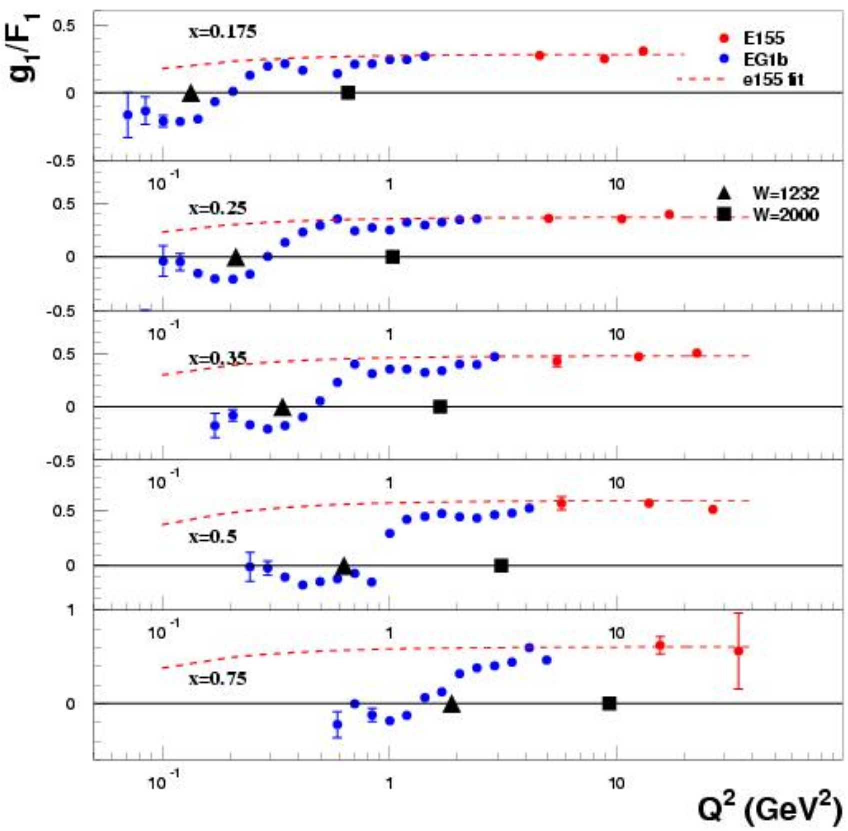


Black points: EG1b data

Blue points: RSS data

Line: EG1b model for A_2

g_1/F_1



•g_1/F_1 falls below the DIS extrapolation at low Q2 (dashed curve)

Large-x behavior of the A_1 asymmetry

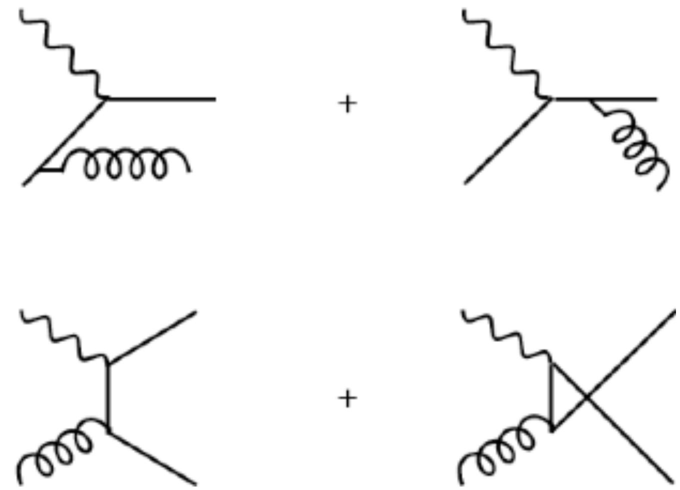
Large x region dominated by valence quarks→ can test quark models

- SU(6) QM: Exact SU(6) symmetry
  Equal probability for S=0 and S=1 di-quark configuration
- Hyperfine perturbed QM **Isgur, PRD 59, 034013 (2003)**
  makes S=1 pairs more energetic than S=0 pairs
- Duality **Close and Melnitchouk, PRC 68, 035210 (2003)**
  Suppress transitions to specific resonances (56^+ and 70^-)
- In DIS, pQCD: Minimal gluon exchanges
  Spectator pair: quarks have opposite helicities **Farrar and Jackson, PRL 35, 1416 (1975)**

Model for x --> 1	A_1^p	A_1^n	d/u	$\Delta u/u$	$\Delta d/d$
SU(6)	5/9	0	1/2	2/3	-1/3
w/ hyperfine ($E_{S=0} < E_{S=1}$)	1	1	0	1	-1/3
One gluon exchange	1	1	0	1	-1/3
Suppressed symmetric WF	1	1	0	1	-1/3
S=1/2 dominance	1	1	1/14	1	1
$\sigma_{1/2}$ dominance	1	1	1/5	1	1
pQCD (conserved helicity)	1	1	1/5	1	1

Parton Distributions Functions and NLO pQCD

- Two effects modify simple parton picture:
  - pQCD evolution makes PDFs Q^2-dependent (NLO DGLAP equations) – mild logarithmic dependence
  - (Gluon) radiative corrections change elementary cross section generating a contribution to g1 due to the gluon polarization



$$g_1^{NLO}(x,Q^2) = g_1^{LO} + \frac{1}{2}\langle e^2\rangle \sum_q e_q^2 [\Delta q(x,Q^2)\otimes C_q + \Delta g(x,Q^2)\otimes C_g]$$

we can extract information on the gluon from DIS

Jefferson Laboratory and CLAS

CEBAF
Large
Acceptance
Spectrometer

- Six individually instrumented sectors
- Toroidal magnetic field
- Multi-particle final state
- Large acceptance

CEBAF is a superconductive electron accelerator

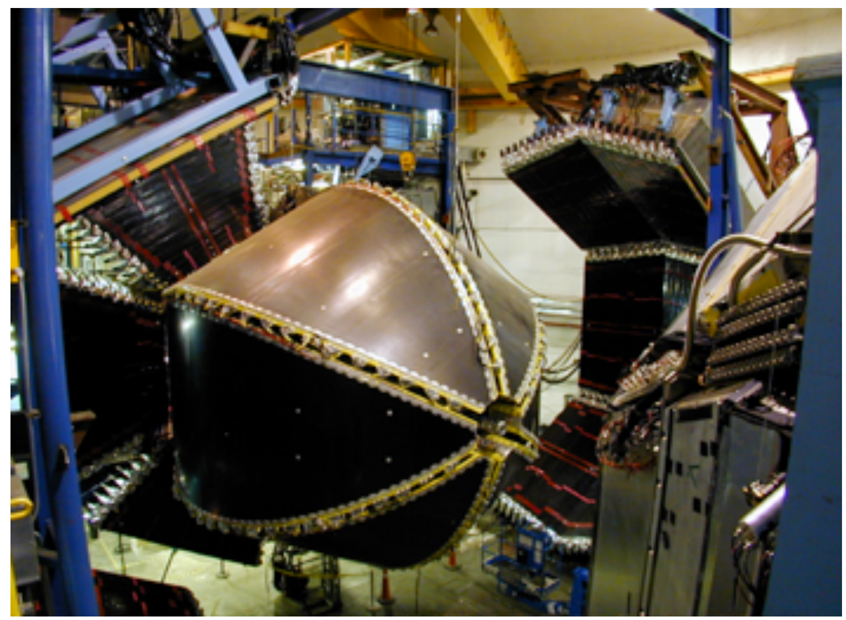
→ **continuous beam**

→ **high longitudinal polarization**

→ **energy range → 0.75 –5.9 GeV**

→ **current range → 0.1 nA –200mA**

→ **Beam polarization 80-90%**

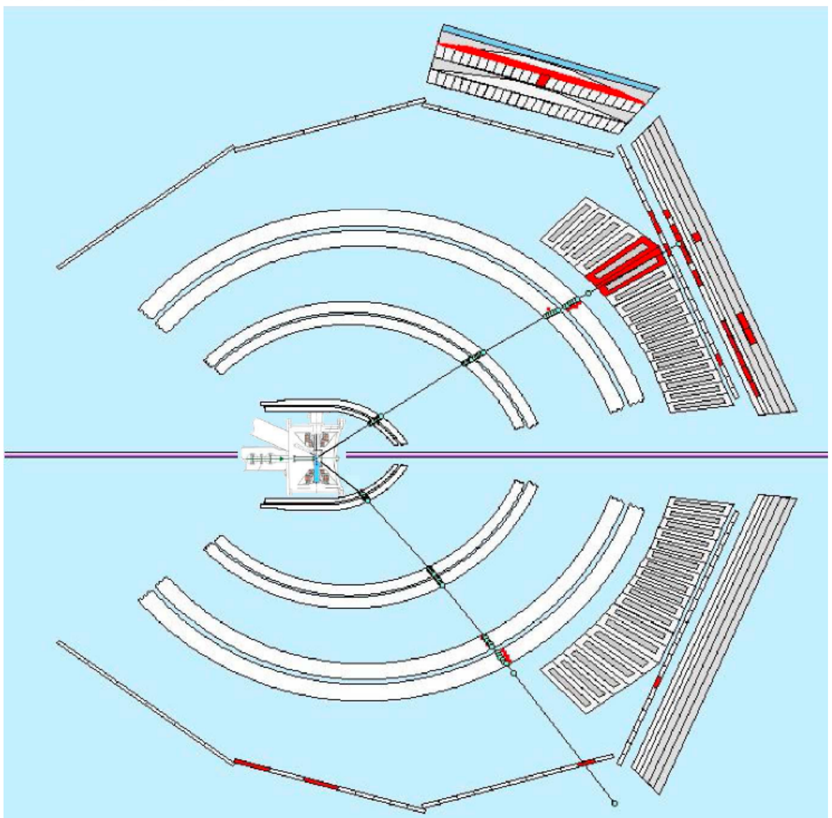


Experiments EG1 and EG4 with CLAS

EG1: $Q^2 = 0.05\ldots5\ \mathrm{GeV}^2$

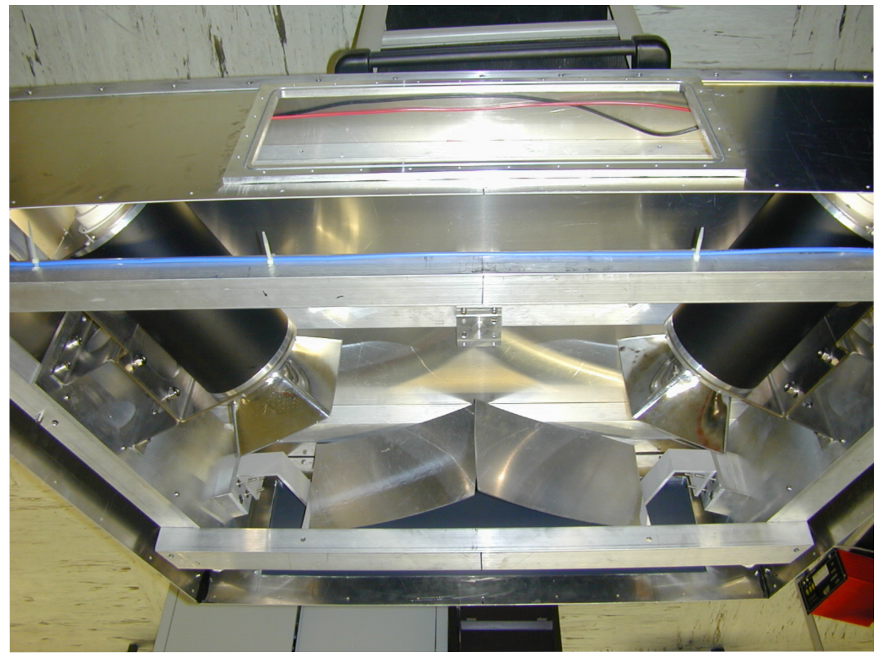
Largest possible kinematic coverage
→ inbending and outbending configuration, E = 1.6…5.8 GeV

1998 - 2001



EG4: Q^2_{min}=0.015 GeV^2

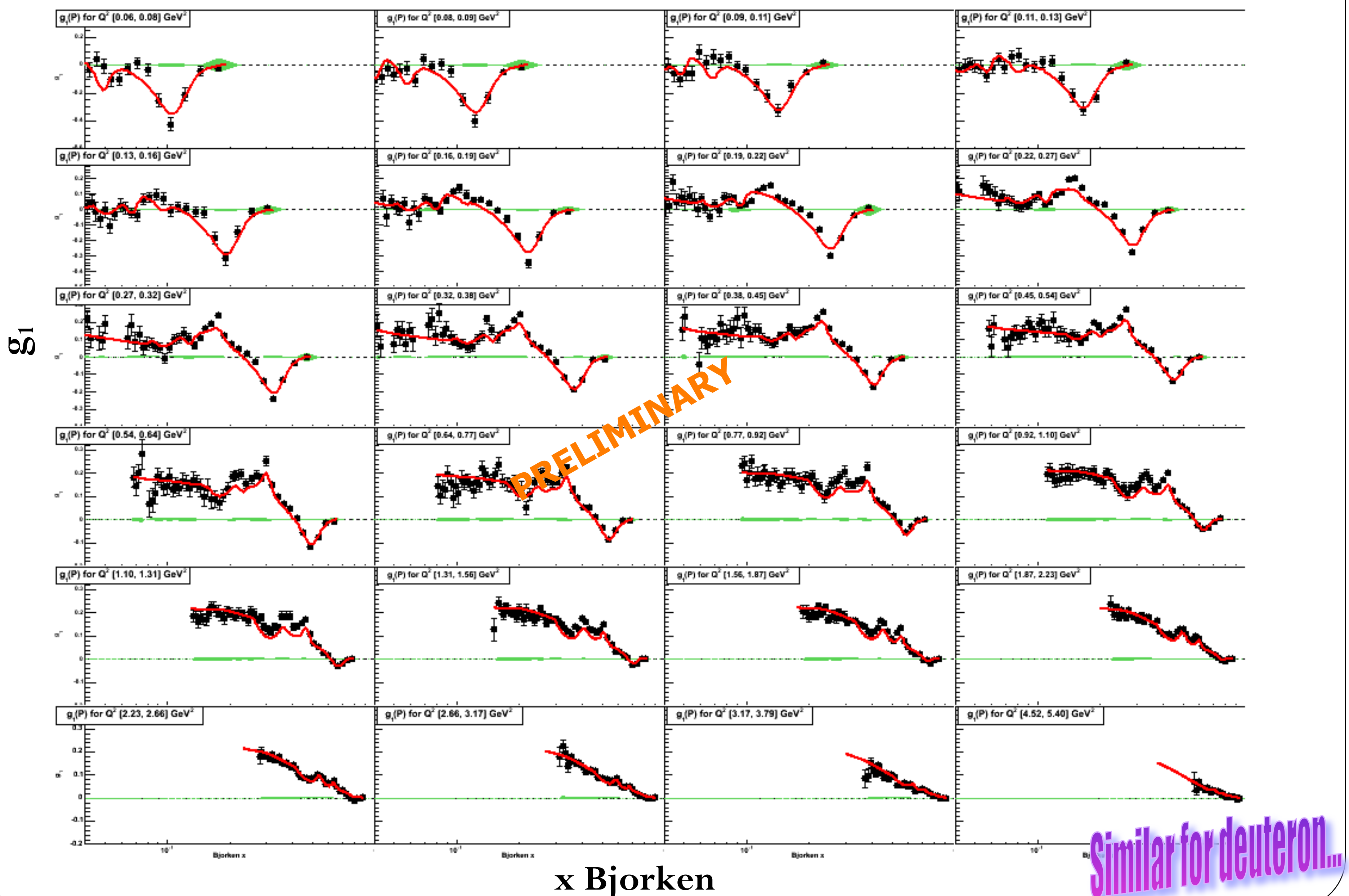
note: $m_\pi^2 = 0.02\ \mathrm{GeV}^2$



Focus on low Q^2 (GDH, χPT) => lower beam energies (up to 3 GeV), new Cherenkov for optimal acceptance in outbending configuration, θ_e as small as 6 degrees

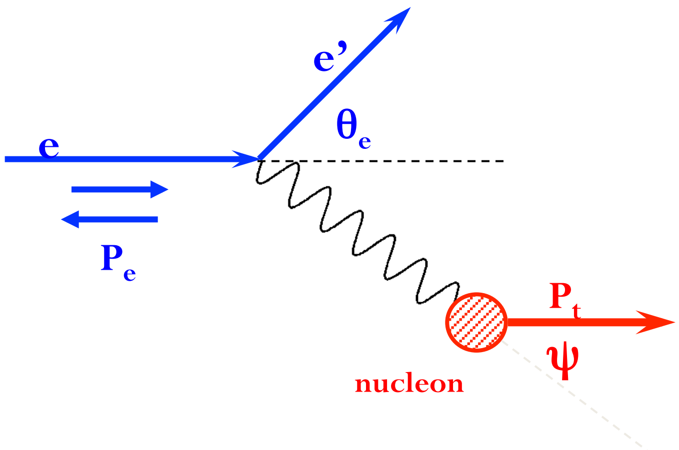
2006

$g_1(x,Q^2)$ proton for different Q^2 bins



Virtual photon asymmetries

$$\frac{d\sigma}{dE'\,d\Omega} = \Gamma_v\left[\sigma_T + \varepsilon\sigma_L + P_e P_t\left(\sqrt{1-\varepsilon^2}A_1\sigma_T\cos\psi + \sqrt{2\varepsilon(1-\varepsilon)}A_2\sigma_T\sin\psi\right)\right]$$



$$\mathbf{A_1} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_T} \qquad \mathbf{A_2} = \frac{\sigma_{LT'}}{\sigma_T}$$

the asymmetries A_1 and A_2 can be extracted by varying the *direction of the nucleon polarization* or by varying the *beam energy* at fixed Q^2, ν

$$A_{\parallel} = D(A_1 + \eta A_2)$$
$$A_{\perp} = d(A_1 + \zeta A_2)$$

[where D, η, d, ζ are functions of Q^2, E′, E, R, e.g.:

$$D = \frac{1-\varepsilon E'/E}{1+\varepsilon R}$$

$$\eta = \frac{\varepsilon\sqrt{Q^2}}{E-\varepsilon E'} \qquad R = \frac{\sigma_L}{\sigma_T} \quad]$$

$$A_1 \approx \frac{\sum_i e_i^2 \Delta q_i(x)}{\sum_i e_i^2 q_i(x)}$$

EG1 used parameterization of world data on A_2 to extract A_1 (η is usually small)

The asymmetry analysis

$$A_{raw} = \frac{N^-/Q^- - N^+/Q^+}{N^-/Q^- + N^+/Q^+}$$

- $N^{+/-}$ Yield for electron/target spins
- antiparallel (-) or parallel (+)
- $Q^{+/-}$ gated FC

Physics asymmetry $A_{||}$

$$A_{\parallel,\perp} = \frac{C_{back} A_{raw}}{P_e P_t \times DF}$$

- P_e Beam polarization
- P_t Target polarization
- DF Dilution factor
- C_{back} Background processes

(pion contamination & pair symmetric)

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

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

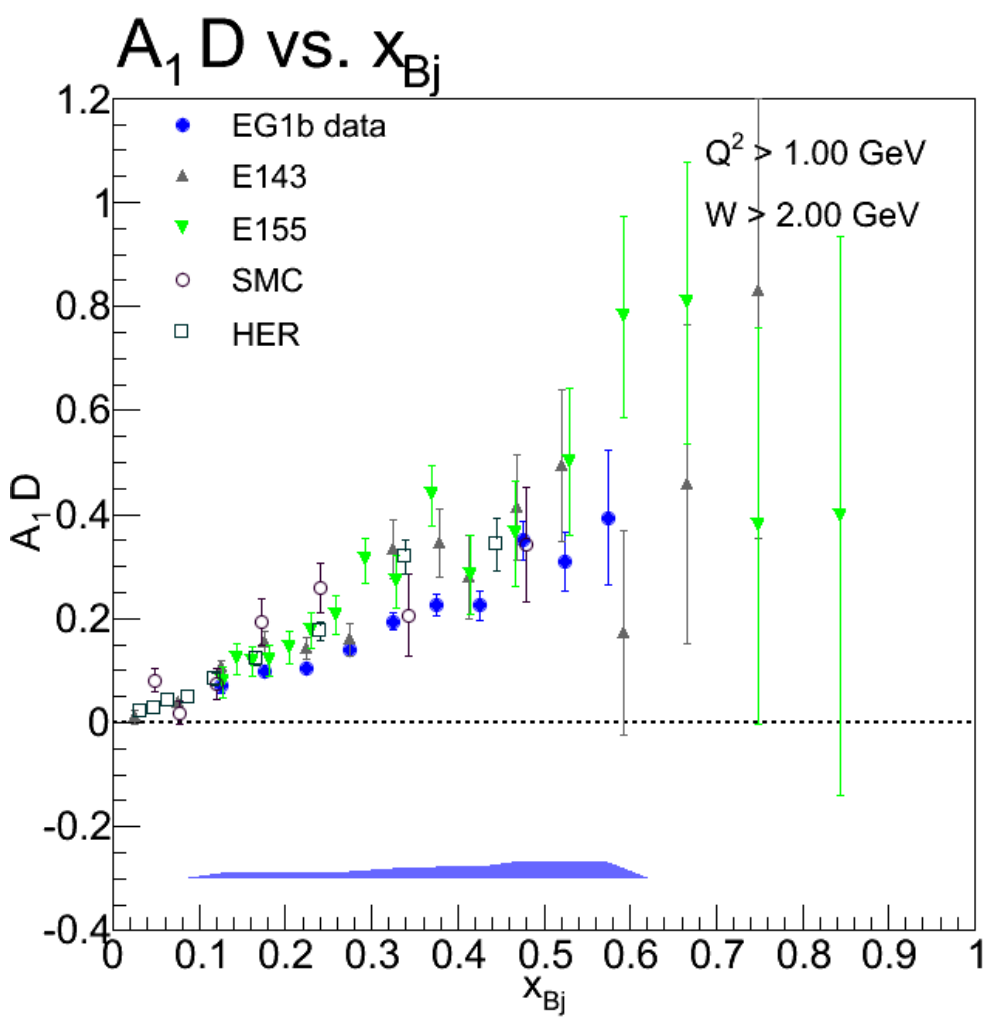
A_1, g_1 can be extracted

the structure functions g_1 and g_2 are linear combinations of A_1 and A_2

$$g_1(x,Q^2) = \frac{\tau}{1+\tau}\left(A_1 + \tfrac{1}{\sqrt{\tau}} A_2\right)F_1 = \frac{\tau}{1+\tau}\left(\frac{A_\parallel}{D} + \left(\tfrac{1}{\sqrt{\tau}} - \eta\right)A_2\right)F_1$$

$$g_2(x,Q^2) = \frac{\tau}{1+\tau}\left(\sqrt{\tau}A_2 - A_1\right)F_1$$

$$\tau = \frac{\nu^2}{Q^2}$$



A1 D vs. xBj
EG1b data
E143
E155
SMC
HER
Q2 > 1.00 GeV
W > 2.00 GeV
A1D
xBj
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Outlook: The Future at JLab

- Remaining experiments at 6 GeV
  - Hall A
    - E-06-010: Transverse target single spin asymmetry in n↑(e,e'π^-)
    - E-06-011: Transverse target single spin asymmetry in n↑(e,e'π^+)
    - E-06-014: Precision measurement of d_2 on the neutron
    - E-08-027: g_{2p} and δ_{LT}
  - Hall B
    - E-05-113: Semi-inclusive pion production (and DVCS) on p→
    - E-08-015: Semi-inclusive pion production (and DVCS) on p↑
  - Hall C
    - E-07-011: High precision g_{1d} in DIS region
    - E-07-003: SANE (SSFs on p, with emphasis on g_2)

Running now!

- Approved experiments for 12 GeV
  - Hall A/C
    - E12-06-122: A_{1n} at high x with 8.8 GeV and 6.6 GeV beam in Hall A
    - E12-06-121: Precision measurement of g_2 and d_2 on the neutron
  - Hall B
    - E12-06-10: SSFs on longitudinal target with CLAS12
    - E12-07-107: Semi-inclusive pion production on p→