Revealing the nucleon's spin structure using inclusive electron scattering at Jefferson Lab

Jefferson Lab, Newport News, VA

Hall D

Hall A

Hall B

Hall C

12 GeV linear
Electron accelerator

Mark K Jones, Jefferson Lab

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Revealing the nucleon's spin structure using inclusive electron scattering at Jefferson Lab

- Newly published results from 6 GeV experiments
  - Proton and neutron g_2 and d_2.
  - Test of chiral perturbation theory at low Q^2
- Upcoming 12 GeV experiments
  - In Hall B measure parallel beam-target spin asymmetry with polarized proton and deuteron (polarized ammonia targets)
    - Extract x-dependence of proton A_1 as x goes to 1.
    - Measure Q^2 dependence of g_1/F_1 in x-bins.
  - In Hall C measure parallel and perpendicular beam-target spin asymmetry with polarized neutron (polarized 3He target)
    - Extract x-dependence of neutron A_1 as x goes to 1.
    - Measure broad range of x at near Q^2 = 3,4,5 and 6 to extract d_2

Mark K Jones, Jefferson Lab

12 GeV era has started at Jlab

6 GeV Experimental equipment

- Beam polarization at 85% with beam currents of 80-200 uA.
- Polarized proton (70-90%) and neutron targets (50%)
- Hall A had high luminosity, small acceptance spectrometers (HRS) and moderate acceptance spectrometer (BigBite).
- Hall B had moderate luminosity and large acceptance spectrometer (CLAS) detector
- Hall C had had high luminosity, small acceptance spectrometer(HMS) and moderate acceptance non-magnetic detector (BETA).

12 GeV Experimental equipment

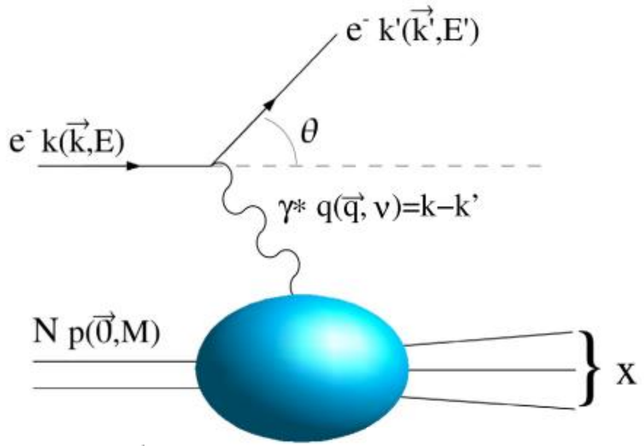
- Beam polarization at 85% with beam currents of 80uA.
- Polarized proton (70-90%) and neutron targets (improved polarization to 60%)
- New Large acceptance detector (CLAS12) in Hall B.
- New moderate acceptance spectrometer (SBS) in Hall A.
  - Proposed large acceptance solenoid magnet, SoLID.
- New high momentum spectrometer (SHMS) in Hall C.
- New Hall D with 4pi acceptance GLUEX detector

Polarized Deep Inelastic Scattering

Inclusive polarized electron scattering on polarized target.

Beam spin parallel $\longrightarrow$
or anti-parallel $\longleftarrow$
to beam direction

Target spin is parallel $\Rightarrow$
or perpendicular $\Uparrow$
to beam direction



$k = (E, \vec{k})$

$k' = (E', \vec{k}')$

$Q^2 = -(k - k')^2 = -q^2$

$\nu = E - E'$

$y = q \cdot P / k \cdot P$

$x_B = Q^2 / 2q \cdot P$

$$A_{\parallel} \equiv \frac{d\sigma^{\overset{\rightarrow}{\Leftarrow}} - d\sigma^{\overset{\rightarrow}{\Rightarrow}}}{2\, d\sigma_{unpold}} \qquad A_{\perp} \equiv \frac{d\sigma^{\rightarrow\Uparrow} - d\sigma^{\rightarrow\Downarrow}}{2 d\sigma_{unpold}}$$

$$\frac{d^2\sigma_{unpold}}{dx\, dy} = \frac{4\pi\alpha^2}{x\, y\, Q^2}\left\{xy^2\left(1 - \frac{2m^2}{Q^2}\right)F_1 + \left[1 - y - \frac{M^2x^2y^2}{Q^2}\right]F_2\right\}. \qquad R \equiv [1+\gamma^2]\left(\frac{F_2}{2xF_1}\right) - 1$$

$$\frac{d^2\sigma^{\overset{\rightarrow}{\Leftarrow}}}{dx\, dy} - \frac{d^2\sigma^{\overset{\rightarrow}{\Rightarrow}}}{dx\, dy} = \frac{16\pi\alpha^2}{Q^2}\left[\left(1 - \frac{y}{2} - \frac{y^2(M^2x^2 + m^2)}{Q^2}\right) g_1 - \frac{2M^2x^2y}{Q^2} g_2\right]$$

$$\frac{d^2\sigma^{\rightarrow\Uparrow}}{dx\, dy} - \frac{d^2\sigma^{\rightarrow\Downarrow}}{dx\, dy} = -\frac{16\alpha^2}{Q^2}\left(\frac{2Mx}{Q}\right)\sqrt{1 - y - \frac{M^2x^2y^2}{Q^2}}\left[\frac{y}{2}\left(1 + \frac{2m^2y}{Q^2}\right)g_1 + g_2\right]$$

Spin Asymmetries and structure functions

Extract photon-nucleon asymmetries A_1 and A_2 from measured $A_{\parallel}$ and $A_{\perp}$

$$A_{\parallel} = D\,(A_1 + \eta A_2) \qquad\qquad A_{\perp} = d(A_2 - \xi A_1)$$

η,d,ξ,D are kinematic functions D also depends on R

Extract spin structure functions, g_1 and g_2

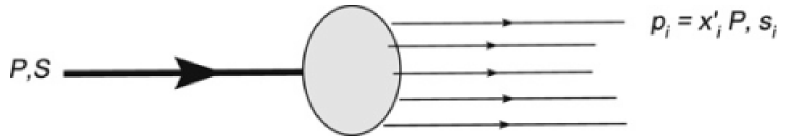
$$A_1 = \frac{g_1 - \gamma^2 g_2}{F_1} \qquad A_2 = \gamma\left[\frac{g_1 + g_2}{F_1}\right] \qquad \gamma^2 = \frac{4M^2x^2}{Q^2}$$

Ideally measure both $A_{\parallel}$ and $A_{\perp}$, but some only measure $A_{\parallel}$

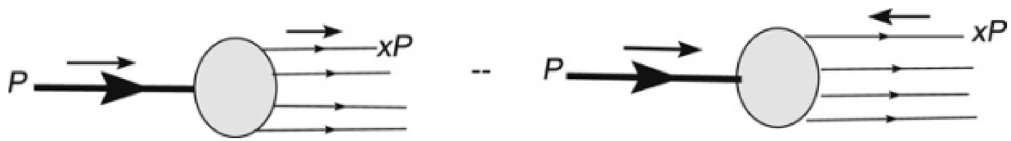
$$\frac{A_{\parallel}}{D} = (1+\gamma^2)\left[\frac{g_1}{F_1}\right] + (\eta - \gamma)\,A_2 \qquad\qquad |A_2| \leq \sqrt{R\,(1 + A_1)/2}$$

$$A_1 \approx \frac{A_{\parallel}}{D} \approx (1+\gamma^2)\left[\frac{g_1}{F_1}\right]$$

Partonic picture of nucleon (Longitudinal picture)



$$F_1(x, Q^2) = \frac{1}{2} \sum_i e_j^2 \, [\, q_j(x) + \bar{q}_j(x)] \qquad F_2(x) = 2xF_1(x).$$



$$g_1(x) = \frac{1}{2} \sum_i e_j^2 \, [\Delta q_j(x) + \Delta \bar{q}_j(x)]$$

No simple interpretation of g_2

Need to understand the transverse structure of nucleon

Measurement of g_2: Access to Higher twist

Twist-2 and Twist-3 contribute at leading order to g_2

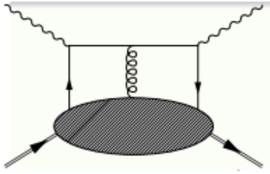
$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

Wandura-Wilczek relation

Twist-2

$$g_2^{WW}(x,Q^2) = -g_1^{LT}(x,Q^2) + \int_x^1 g_1^{LT}(y,Q^2)\mathrm{d}y/y$$

Twist-3



$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M} h_T(y,Q^2) + \xi(y,Q^2)\right)\frac{dy}{y}$$

ξ the quark-gluon correlation function

h_T denotes the transversity distribution

Dynamical twist-3 d_2

Cornwall-Norton moments of g_1 and g_2 connected by OPE to twist-2 a_n and twist-3 d_n matrix elements

$$\Gamma_1^{(n)} = \int_0^1 x^n g_1(x, Q^2)\,dx = \frac{1}{2} a_n + O(M^2/Q^2)$$

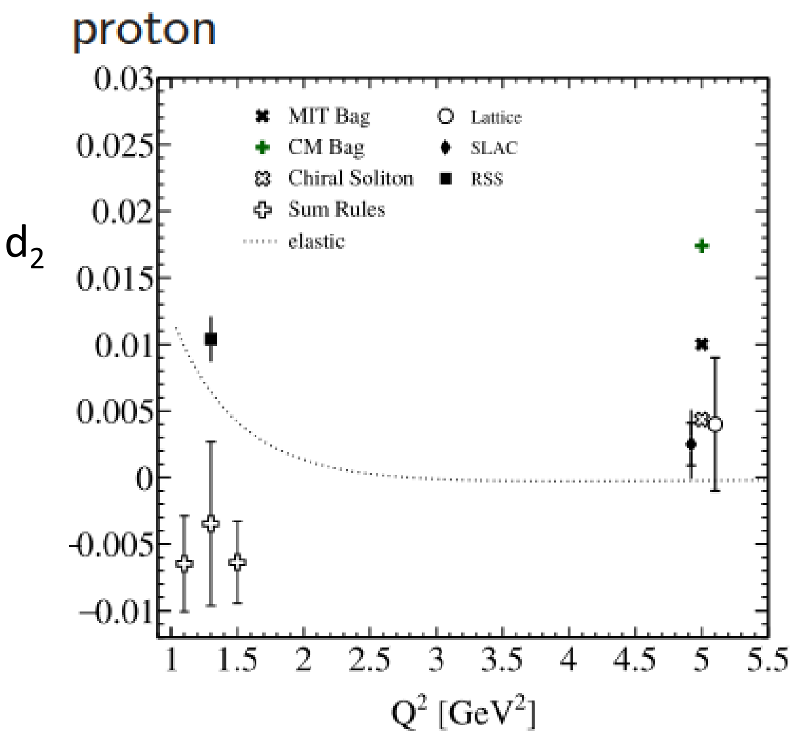
$$\Gamma_2^{(n)} = \int_0^1 x^n g_2(x, Q^2)\,dx = \frac{n}{2(n+1)} (d_n - a_n) + O(M^2/Q^2)$$

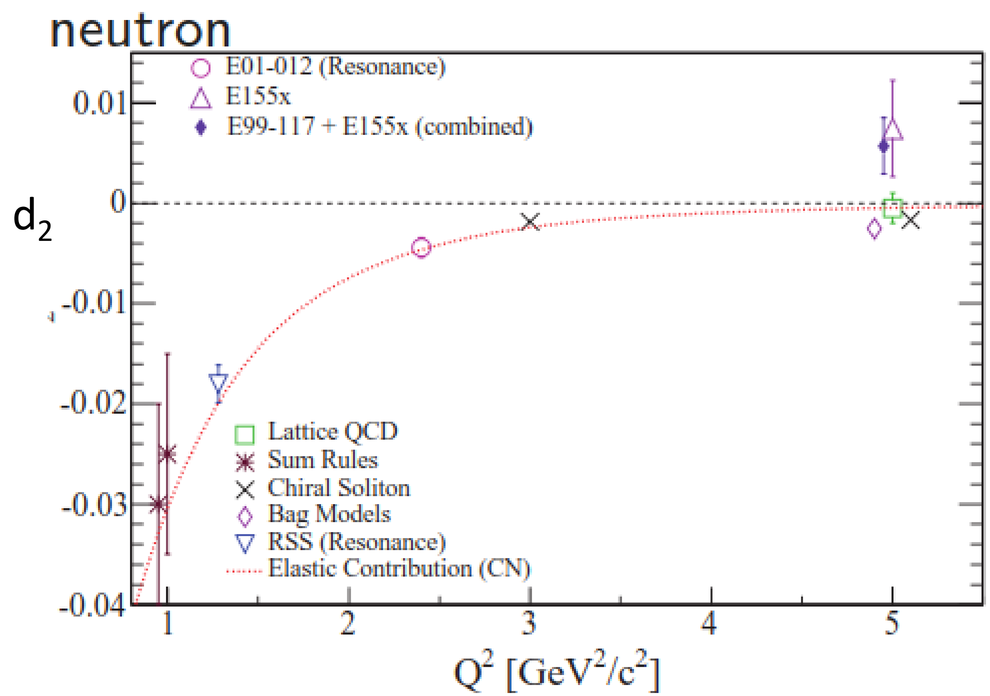
At lower Q^2, Nachtmann moments are needed to obtain clean dynamic twist-3 matrix elements (no target mass corrections to order M^8/Q^8)

$$d_2(Q^2) = \int_0^1 dx\, \xi^2 \left(2\frac{\xi}{x} g_1 + 3\left(1 - \frac{\xi^2 M^2}{2Q^2}\right) g_2 \right) \Rightarrow_{Q^2 \to \infty} \int_0^1 dx\, x^2 (2 g_1 + 3 g_2)$$

JLab is a perfect place to measure d_2 with the x^2 weight of the integral

Previous proton and neutron d_2 measurements

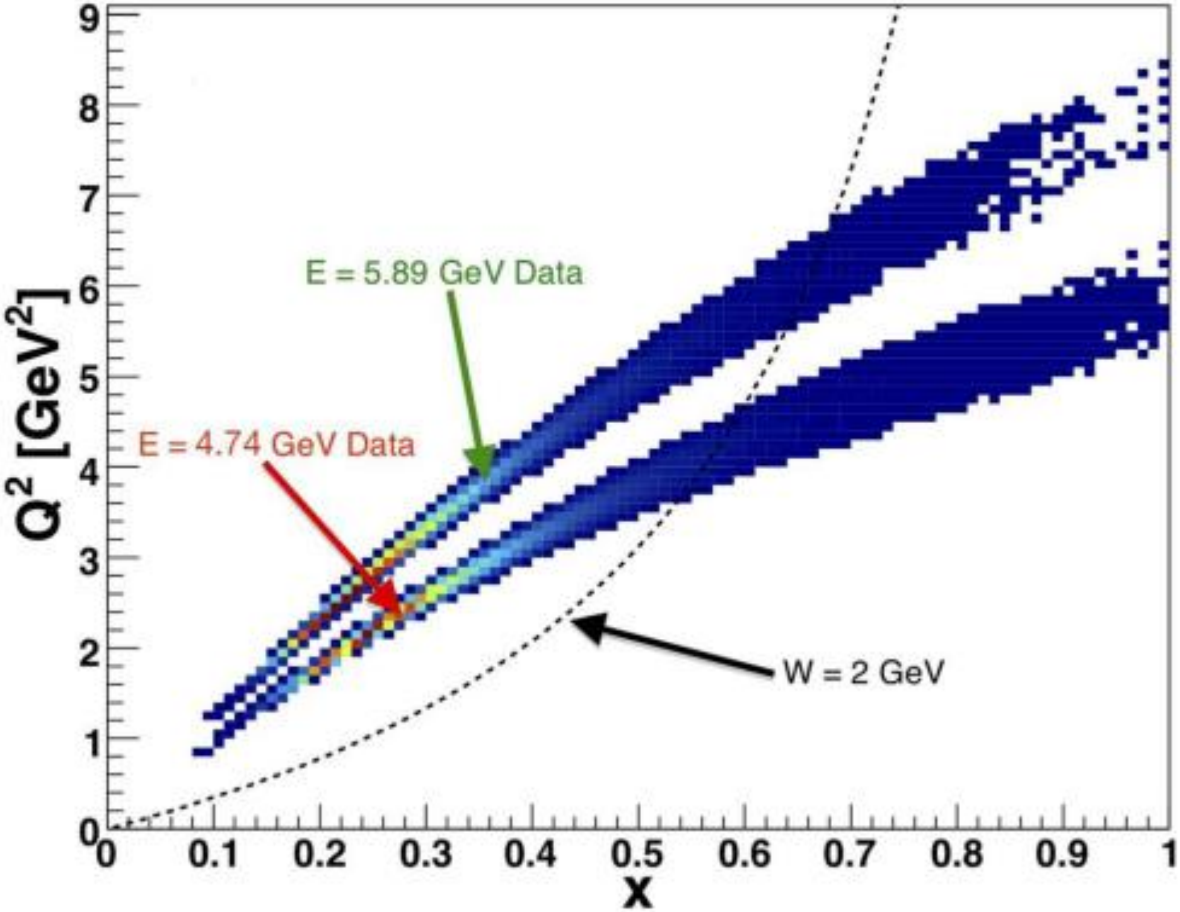




- At $Q^2 = 5$, SLAC 155x measured proton and neutron d_2.
- At $Q^2 = 1.3$, RSS (Resonance Spin Structure) experiment in Hall C detected electrons in HMS to measured g_1 and g_2 for polarized proton and deuteron. Extract neutron by subtracted proton from deuteron
- At $Q^2 = 2.5$, E01-012 experiment in Hall A detected electrons in the HRSs to measured g_1 and g_2 for polarized 3He (neutrons).

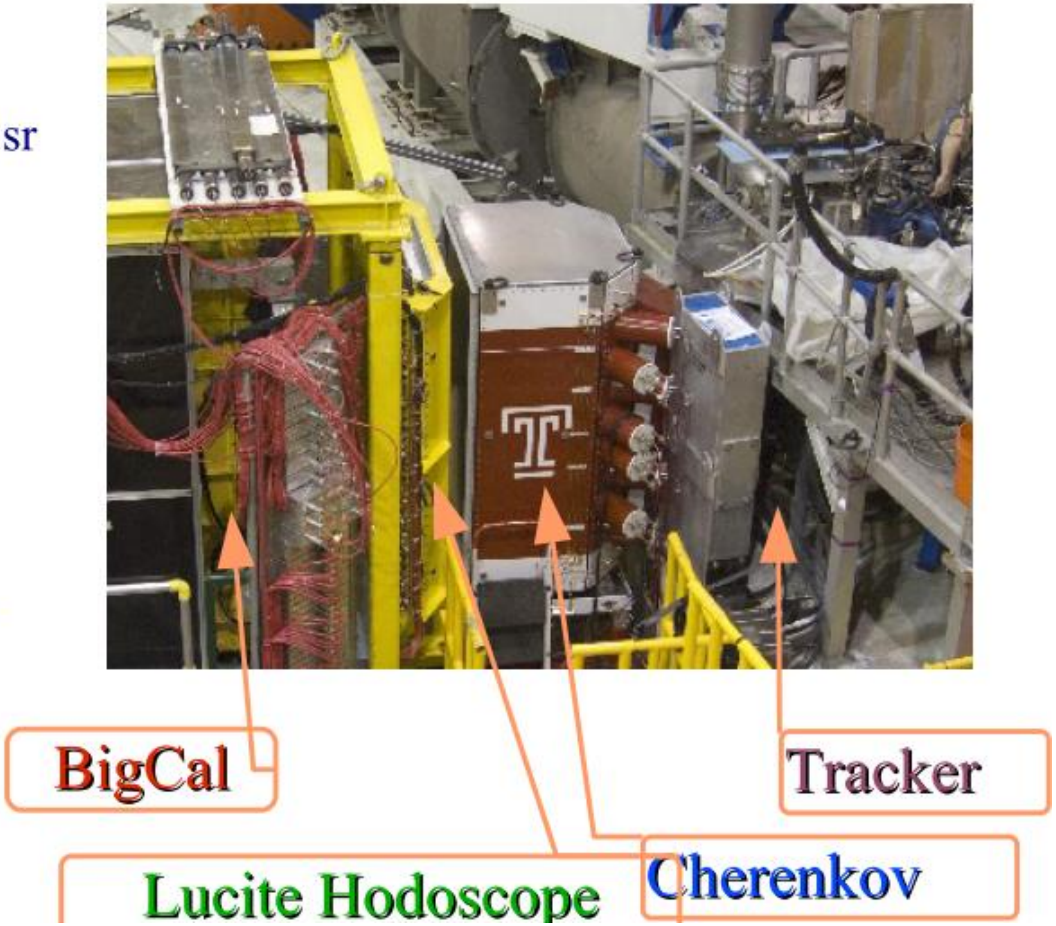
JLab Experiments to measure proton and neutron d_2

- Hall C measured proton d_2
- Hall A measured neutron d_2
- Beam energies of 4.7 and 5.9 GeV
- Covered similar x, Q^2 and W kinematics
- Parallel and perpendicular target polarization directions



Hall C Proton d_2 experiment

- BETA specs
  - Effective solid angle 0.194 sr
  - Energy resolution $10\%/\sqrt{E(\mathrm{GeV})}$
  - 1000:1 pion rejection
  - angular resolution ~ 1 mr
- Non-magnetic detector
  - detects DIS e and e^+e^- pairs: need to cut on minimum E'
  - Target field helps sweep lowest E background (180 MeV/c cutoff)



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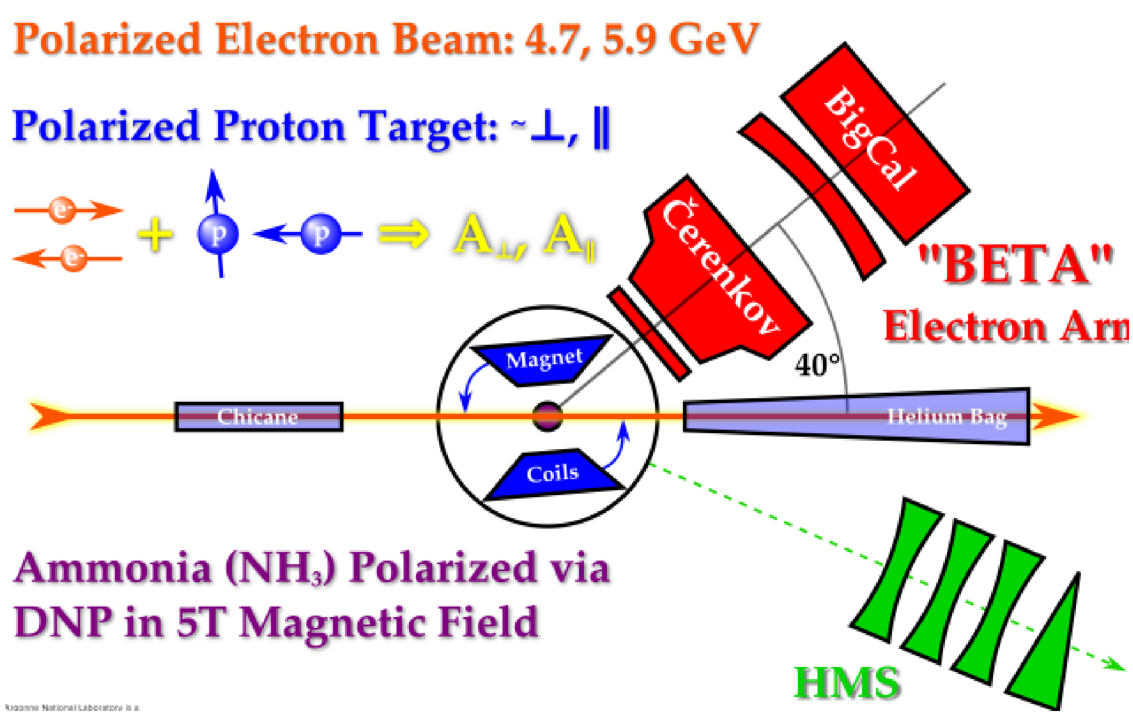
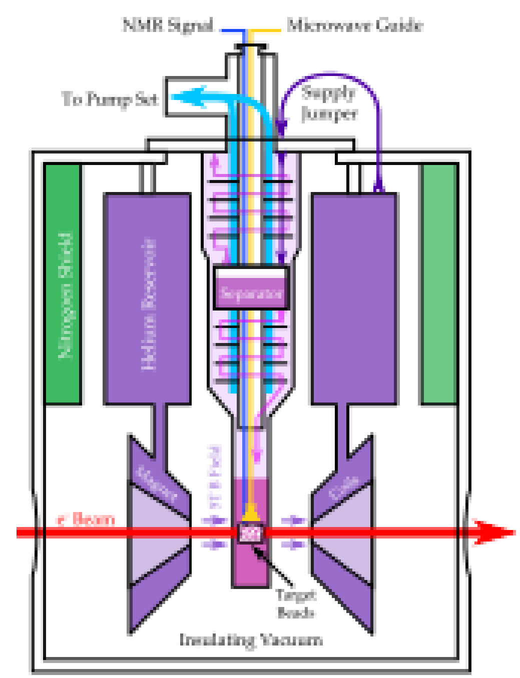
Hall C Proton d_2 experiment

Spin Asymmetries of the Nucleon Experiment (SANE)



Average target polarization of 68%



Dynamically polarized ammonia target

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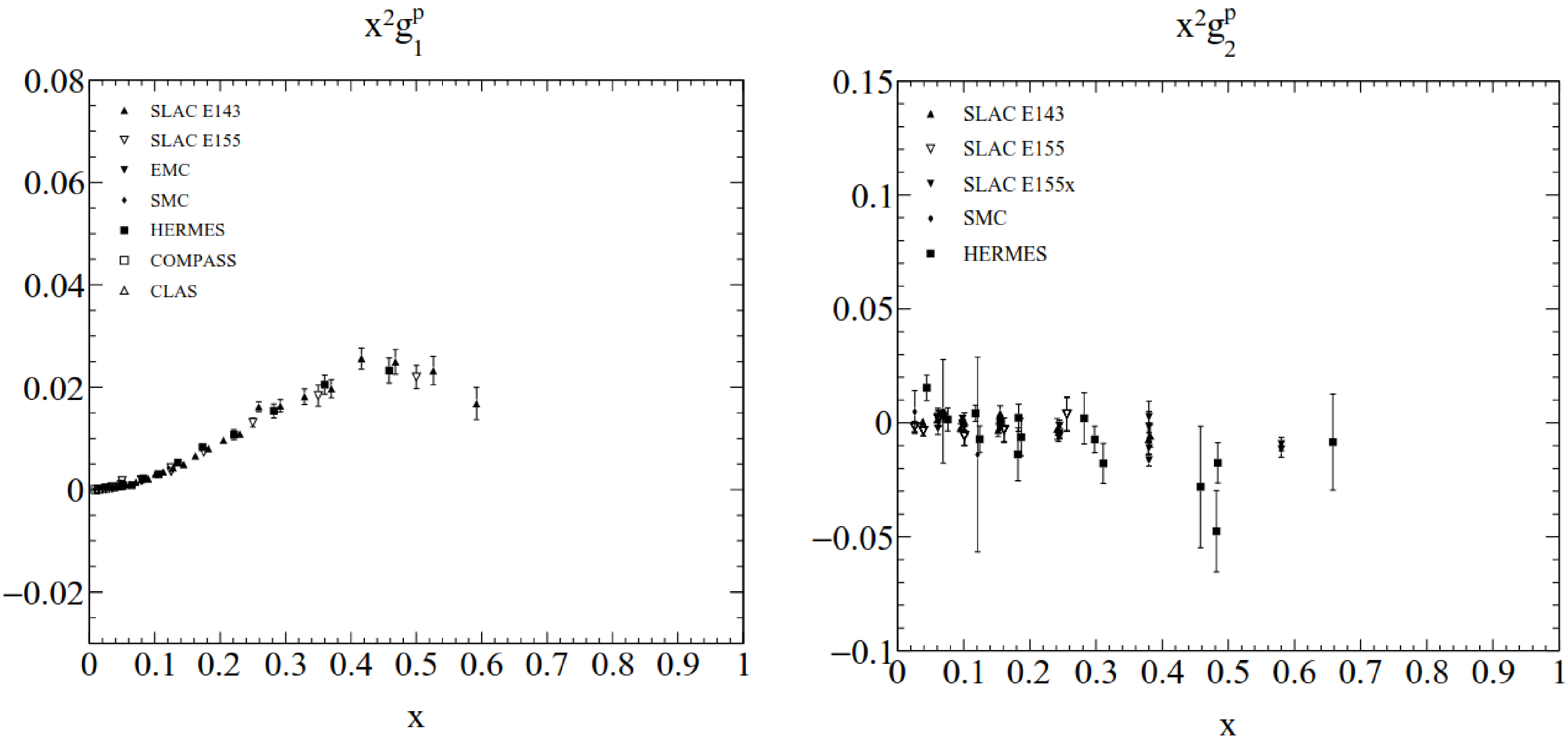
Previous proton g_1 and g_2 measurements



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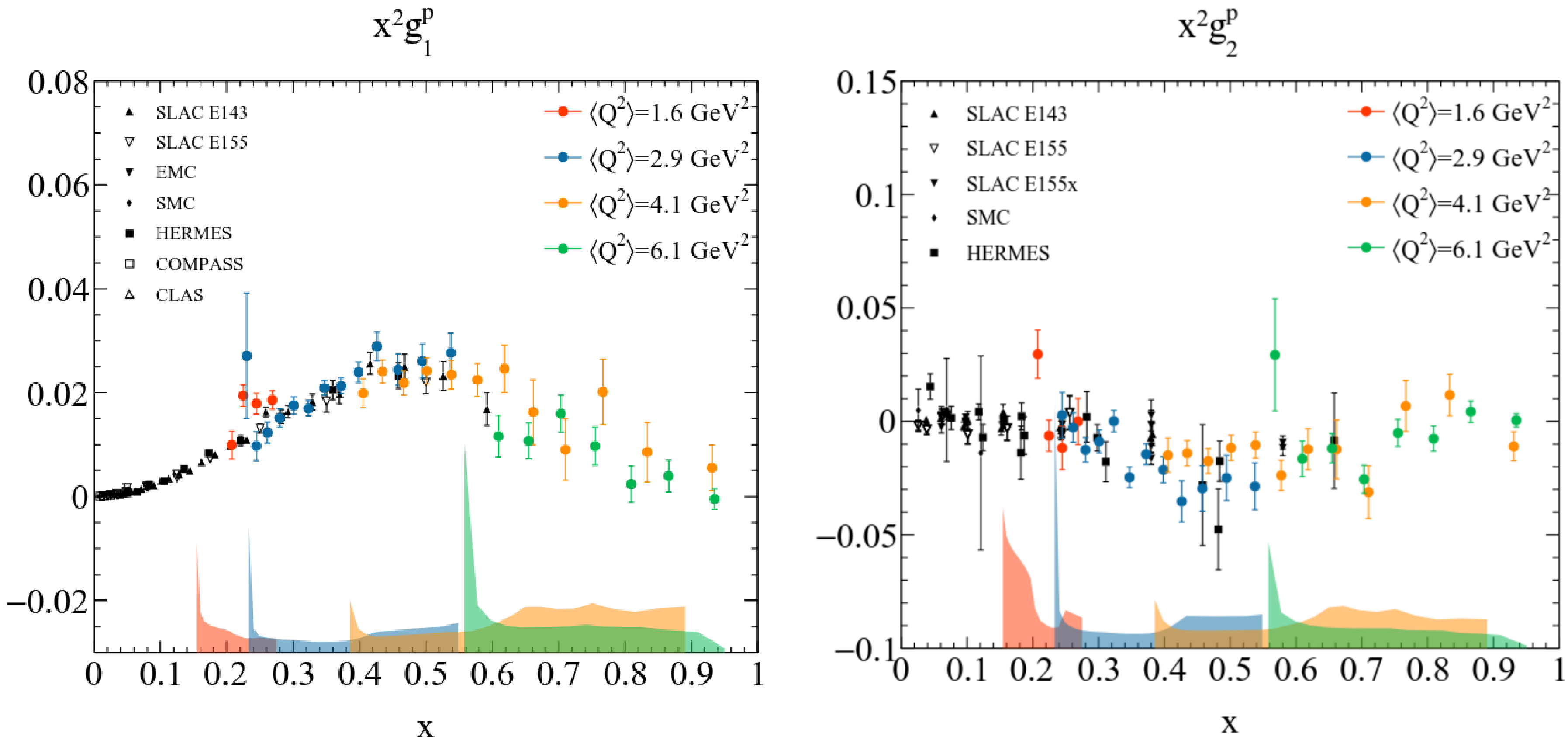
Recent Hall C SANE g1p and g2p results

W. Armstrong et al. Phys. Rev. Lett. 122, 022002 (2019)



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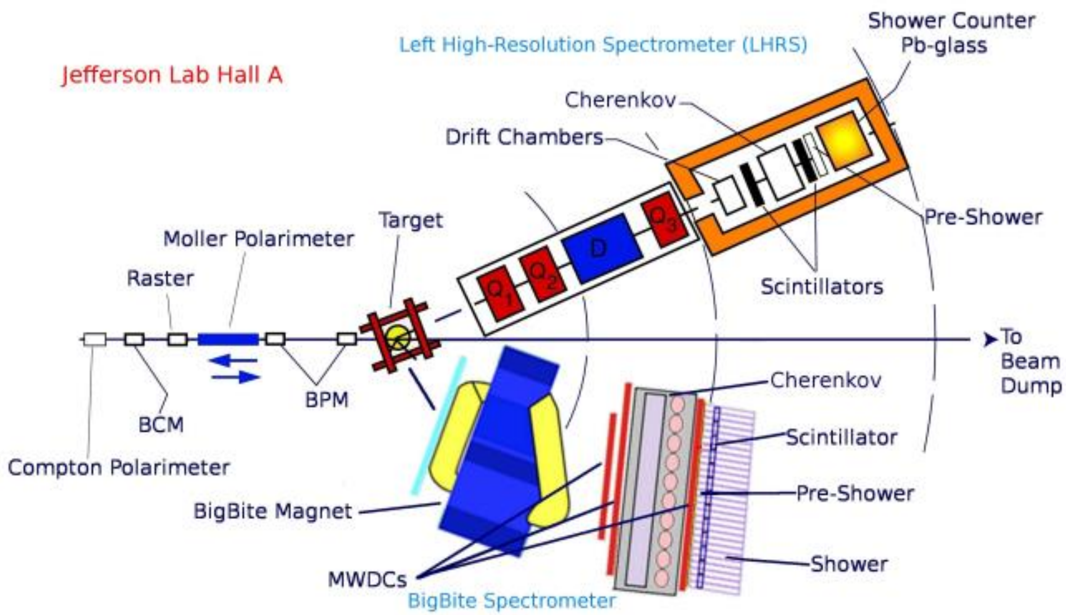
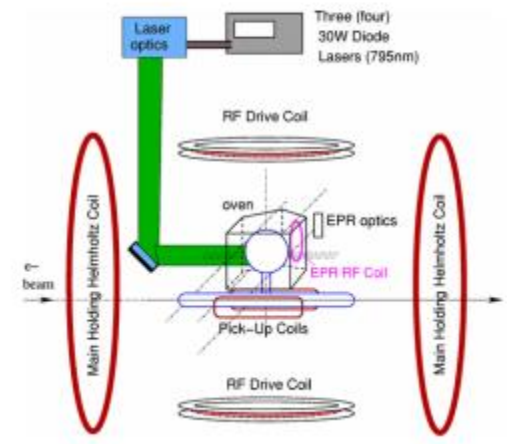
Hall A neutron d_2 experiment (E06-014)

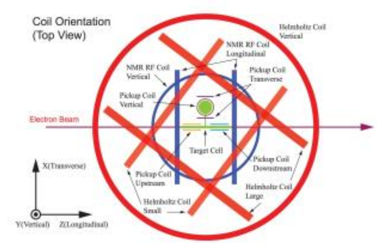
- Detected electrons in BigBite and HRSL
- Target polarization parallel and perpendicular
  - Target cell is 40cm long
  - Typical polarization around 50% at 15uA



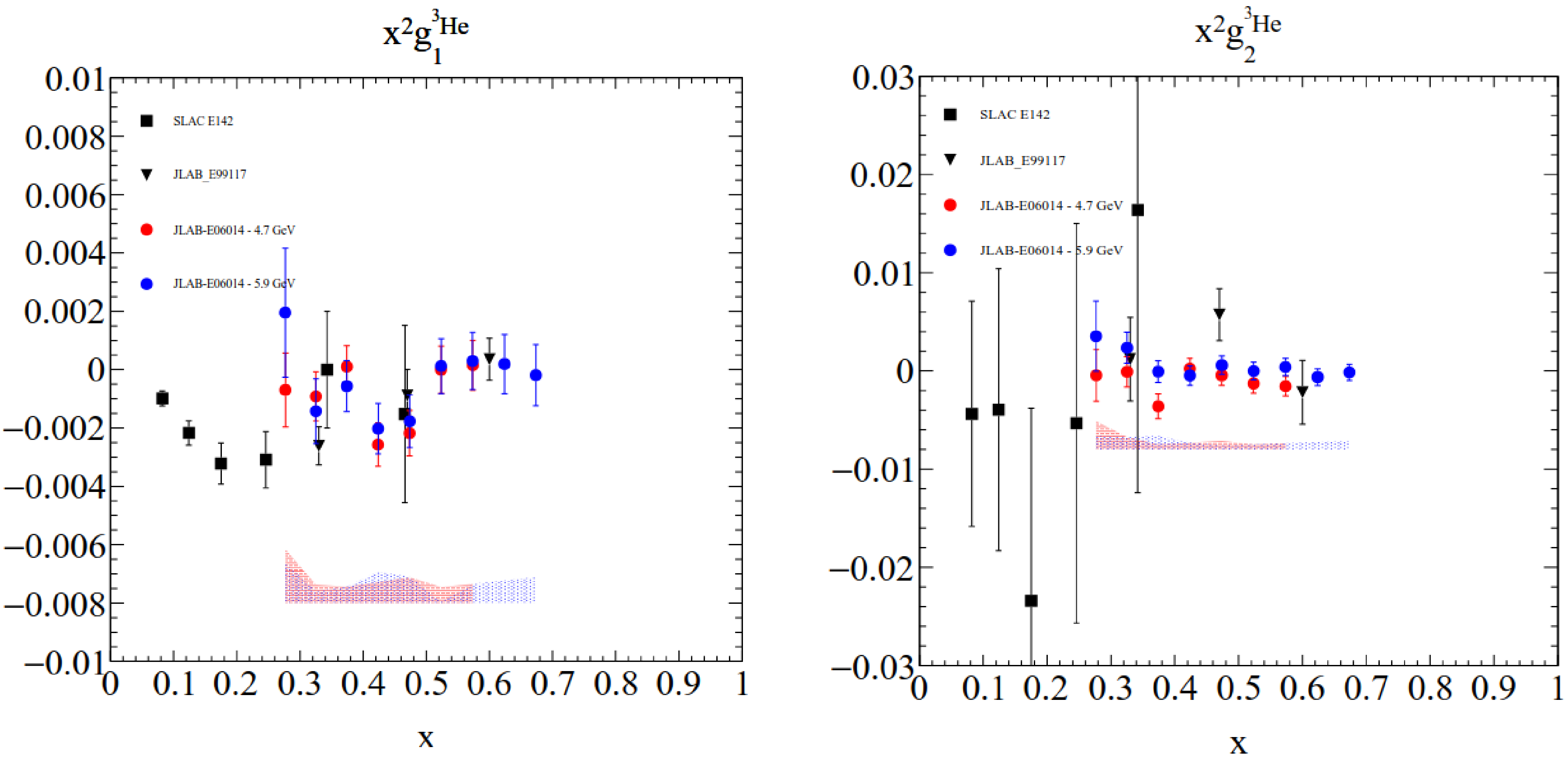
Polarized 3He target



Coil configuration rotates the polarization direction

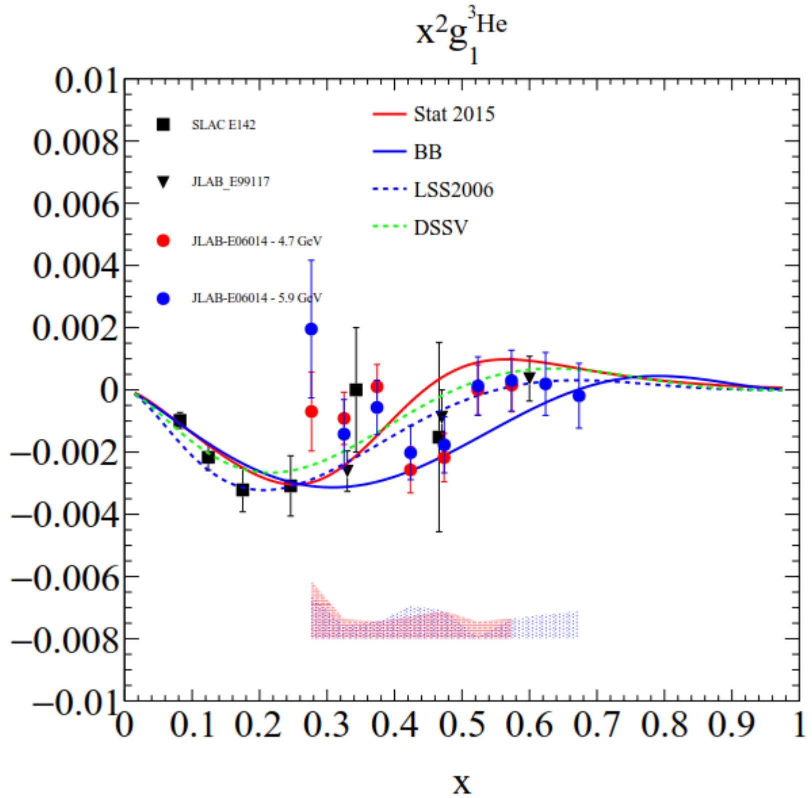


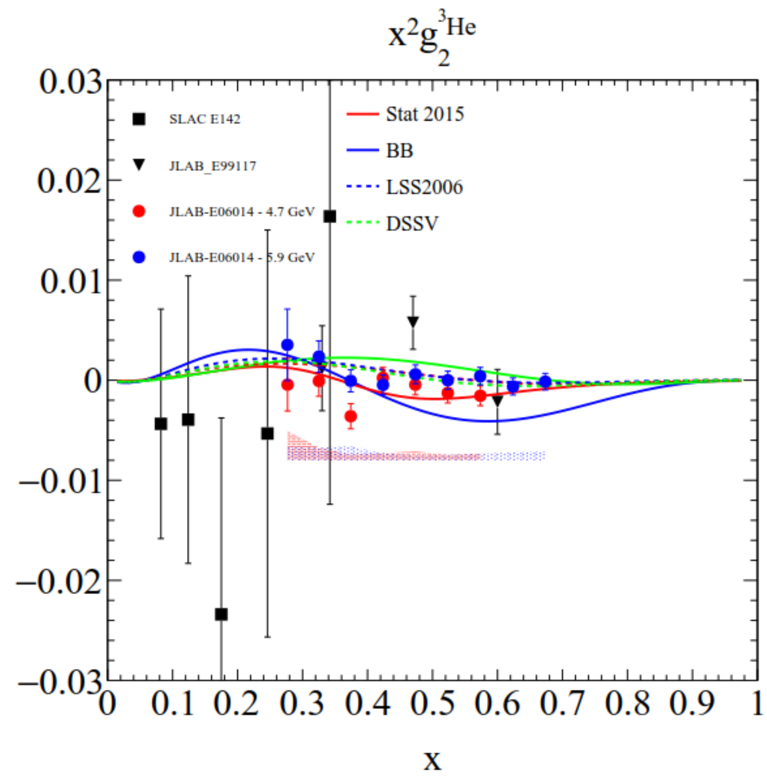
Recent Hall A Neutron g_1 and g_2 results



D. Flay et al. Phys. Rev. D 94, 052003 (2016)

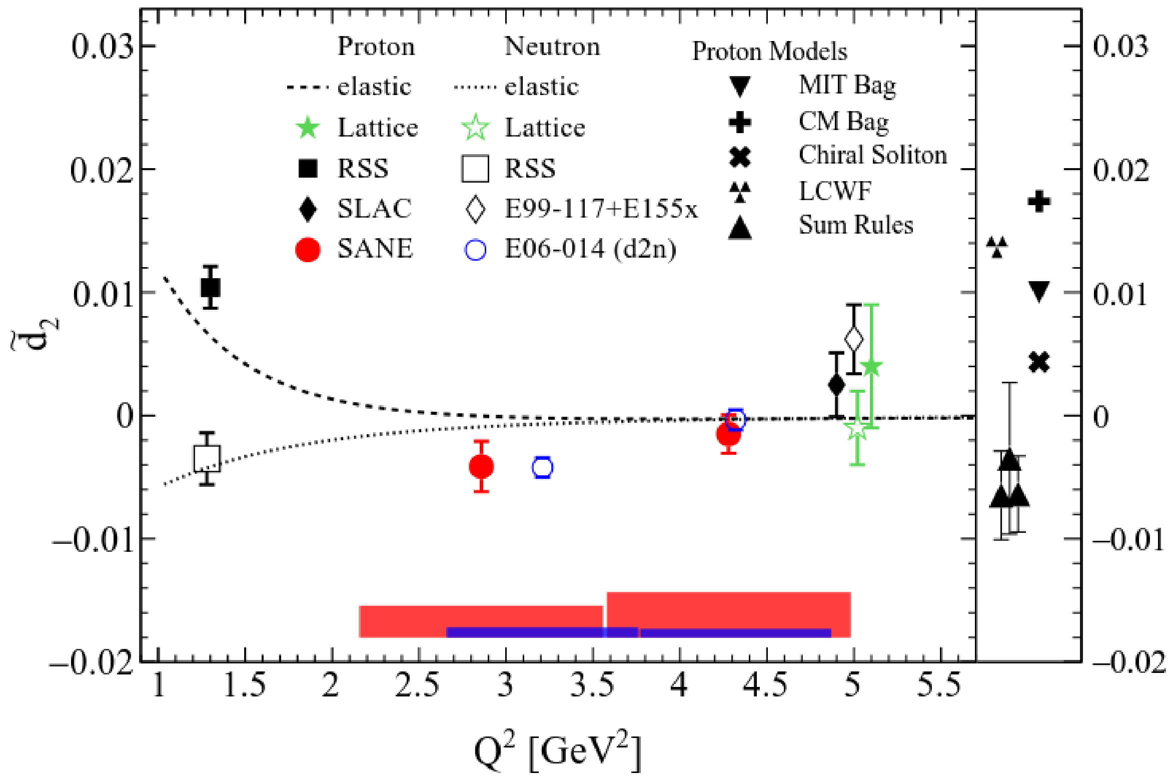
Comparison of neutron results to theory





D. Flay et al. Phys. Rev. D 94, 052003 (2016)

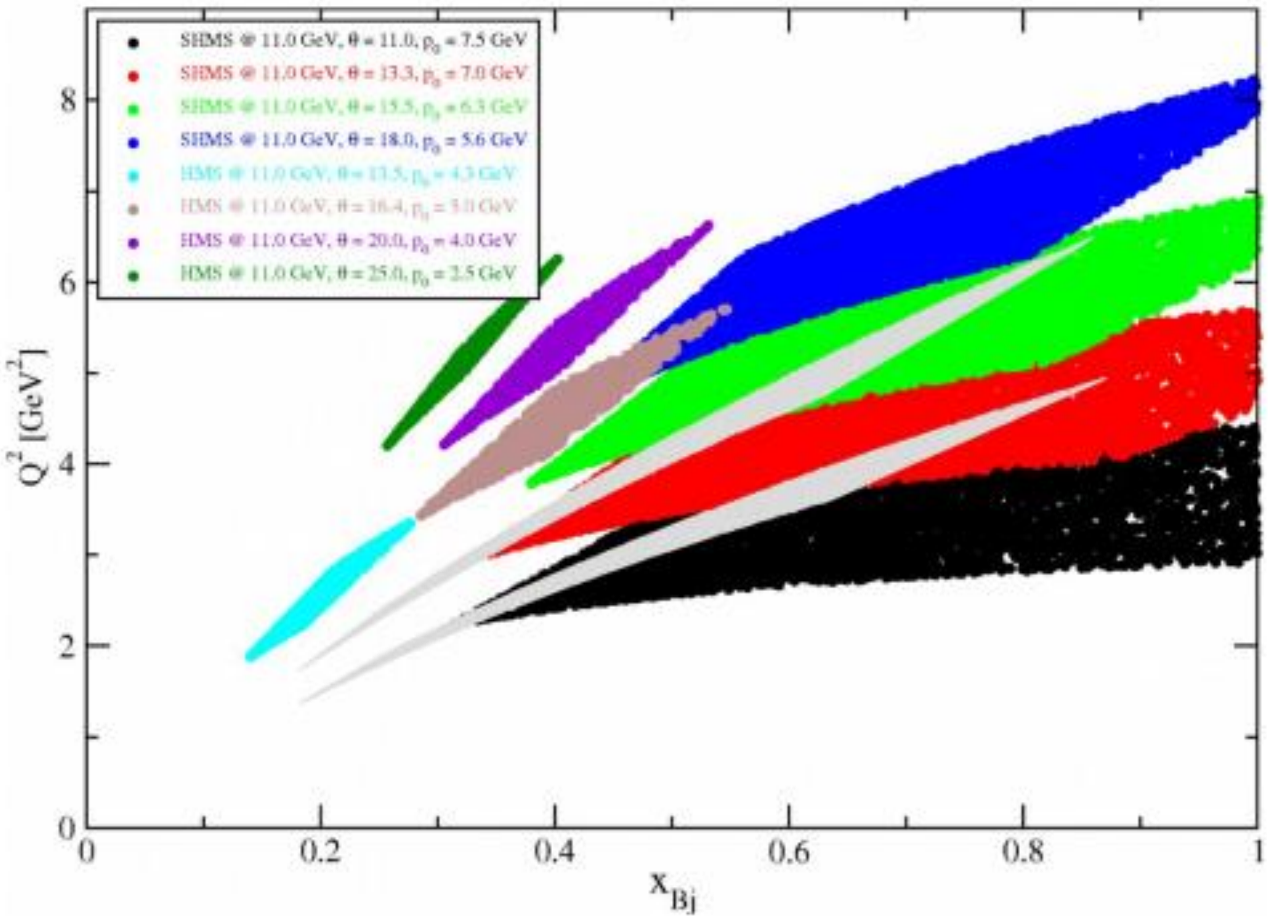
Direct comparison of neutron and proton d_2



- Lattice calculations at $Q^2 = 5$ in the quenched approximation (PRD 63, 074506)
    - Proton calculations agree with SLAC data.
    - Neutron calculations disagree with SLAC data.
- New lattice calculations needed.

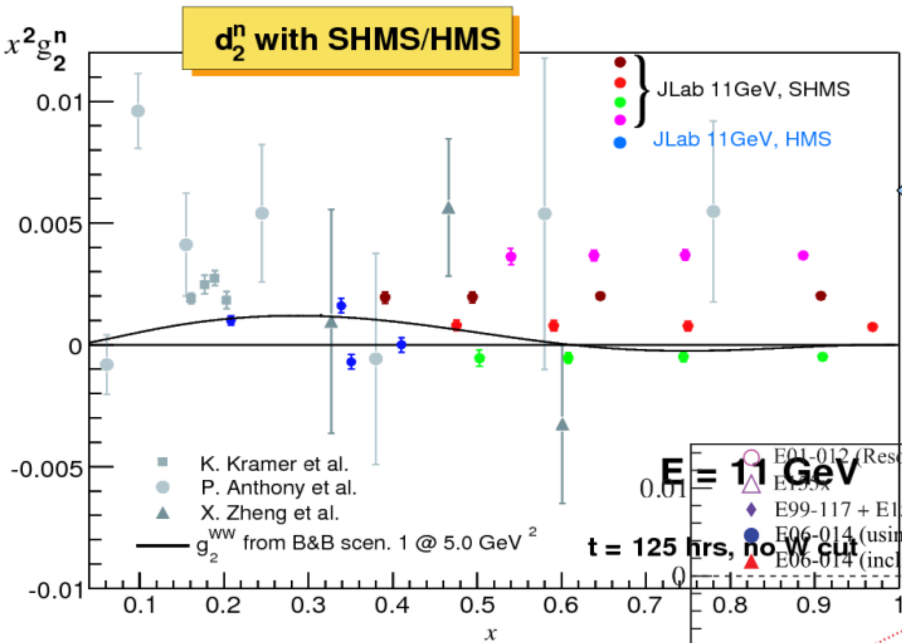
Upcoming Hall C Measurement of neutron d_2

- Run in Spring 2020
- Detect electrons in the HMS and SHMS

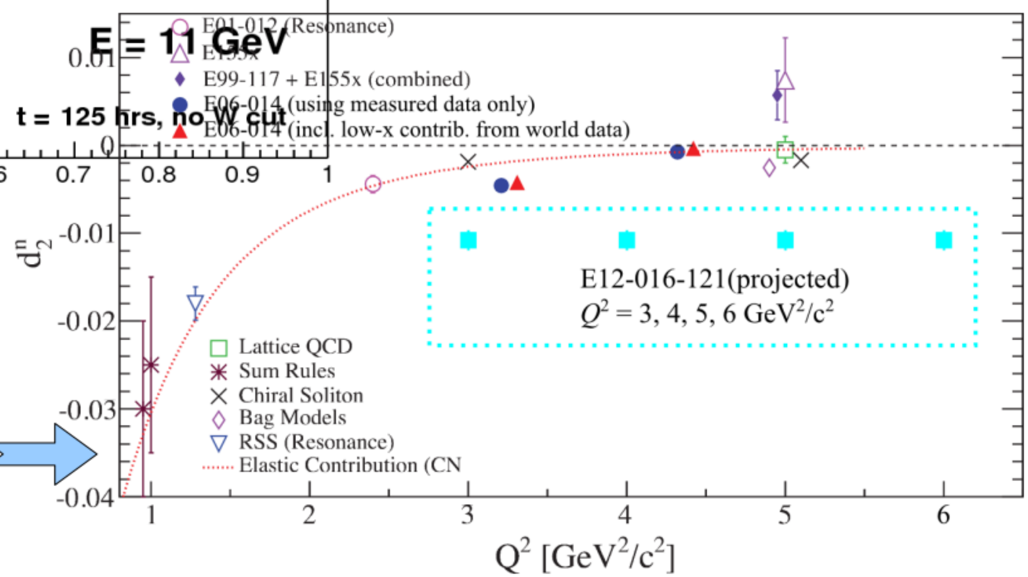


Upcoming Hall C Measurement of neutron d_2

Projected results for E12-06-121



Projected g_2^n points are vertically offset from zero along lines that reflect different (roughly) constant Q^2 values from 2.5—7 GeV^2.



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

Direct overlap with 6 GeV Hall A measurements.

Large x dependence of valence quark distributions

At leading order $$A_1(x,Q^2) = \frac{\sum e_i^2 \Delta q_i(x,Q^2)}{\sum e_i^2 q_i(x,Q^2)}$$

Different models predict different large x behavior for proton and neutron A_1 and for the spin dependent *u* and *d*-quarks

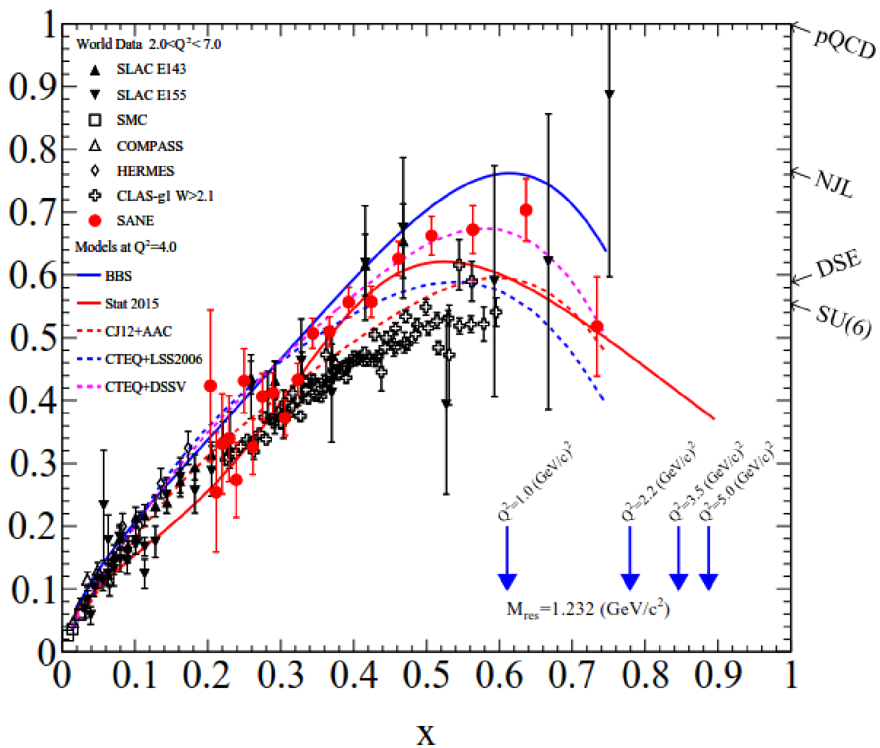
Exact SU(6) $$A_1^p = \frac{5}{9}; \quad A_1^n = 0; \quad \frac{d}{u} = \frac{1}{2}; \quad \frac{\Delta u}{u} = \frac{2}{3}; \quad \frac{\Delta d}{d} = -\frac{1}{3}$$

Hyperfine perturbation of SU(6) $$A_1^{n,p} \to 1; \quad \frac{d}{u} \to 0; \quad \frac{\Delta u}{u} \to 1; \quad \frac{\Delta d}{d} \to -\frac{1}{3}.$$

pQCD, helicity conservation $$A_1^{n,p} \to 1; \quad \frac{d}{u} \to \frac{1}{5}; \quad \frac{\Delta u}{u} \to 1; \quad \frac{\Delta d}{d} \to 1.$$

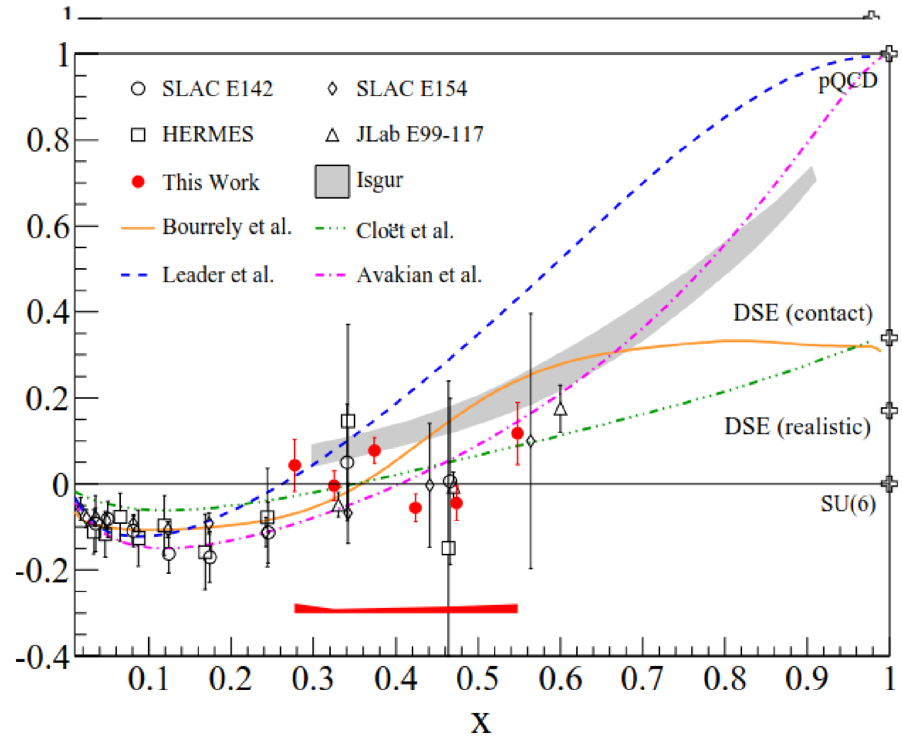
Proton and Neutron A_1

Proton A_1



CLAS extraction of A_1 needs model of g_2

Neutron A_1



Bourrely : Statistical quark model
Leader : NLO QCD analysis
Avakian : pQCD inspired fit
Cloet : Modified NJL

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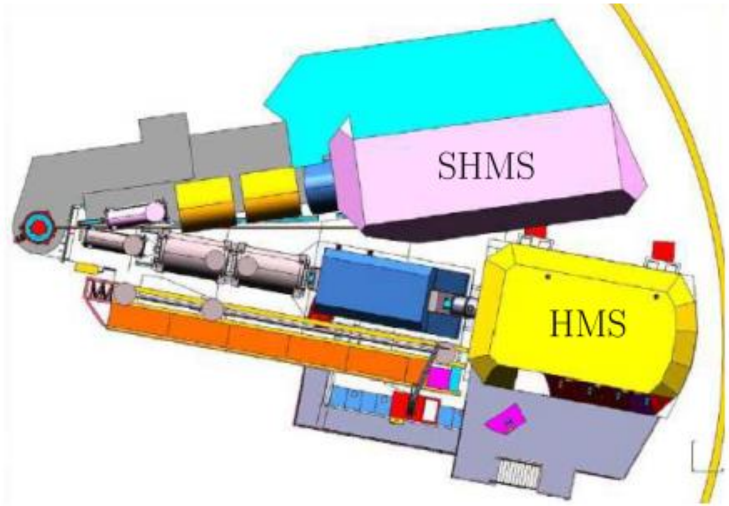
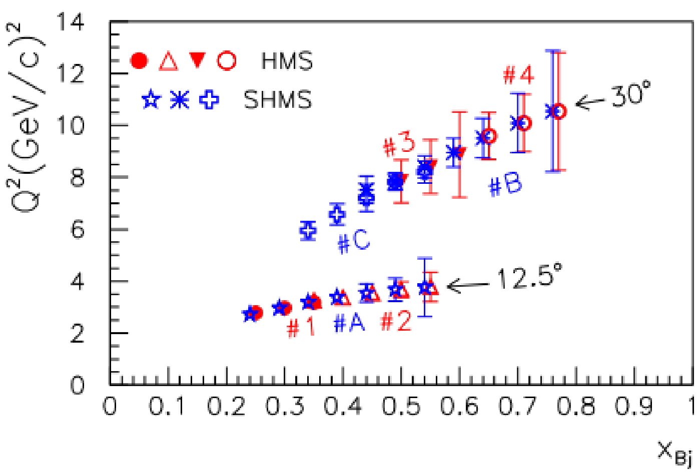
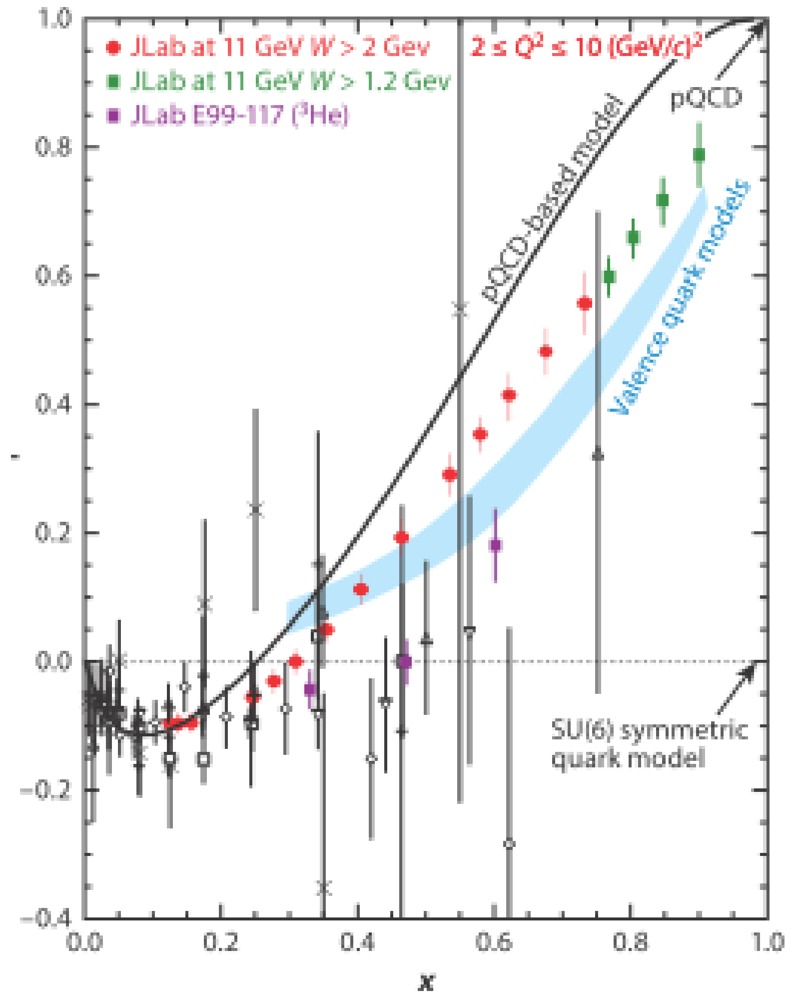
Proposed measurement of neutron A_1 in Hall C

- Run in Fall 2019
- Detect electrons in HMS and new Super High Momentum Spectrometer (SHMS)





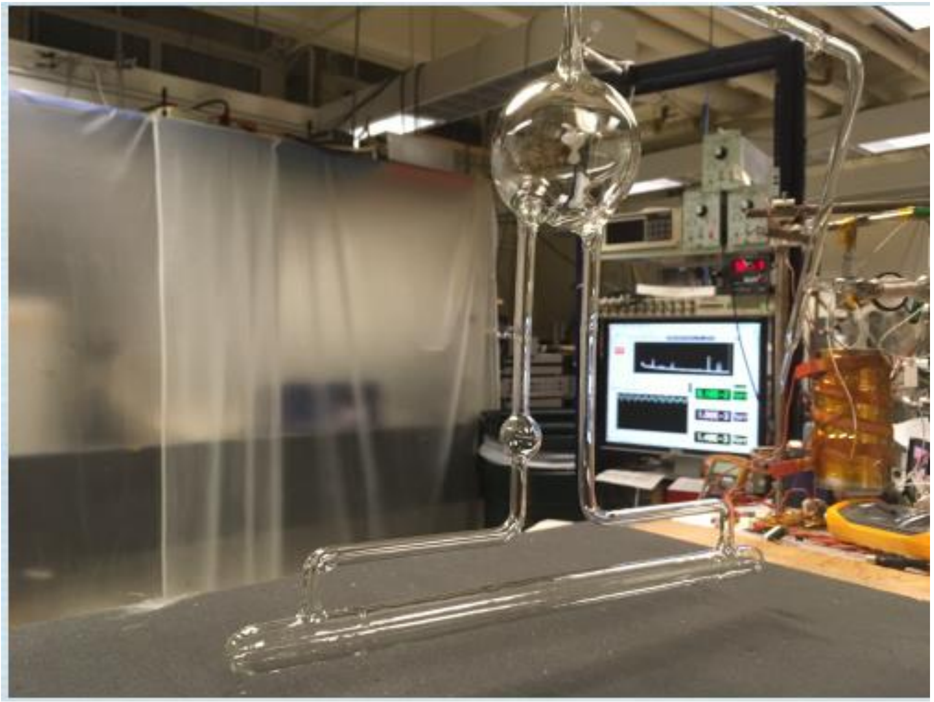


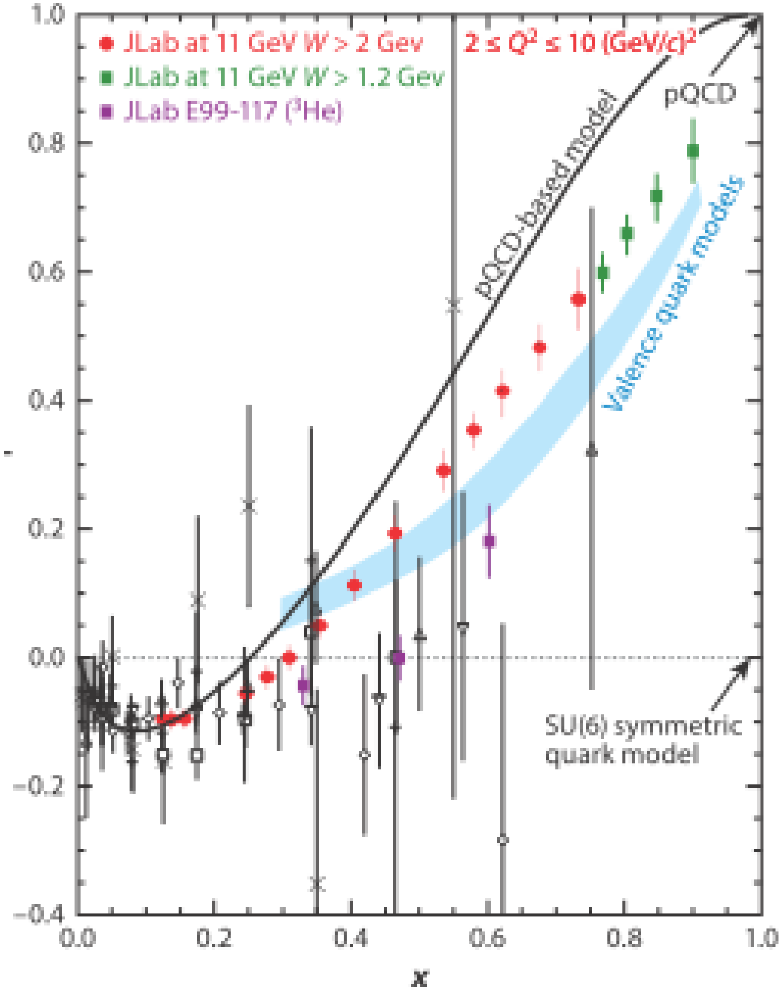
PR12-06-110 J.-P. Chen, G. Cates, Z. E. Meziani and X. Zheng.

Proposed measurement of neutron A_1 in Hall C

New polarized 3He convection cell

Expect 60% polarization at 30uA





PR12-06-110 J.-P. Chen, G. Cates, Z. E. Meziani and X. Zheng.

Large x dependence of proton A_1

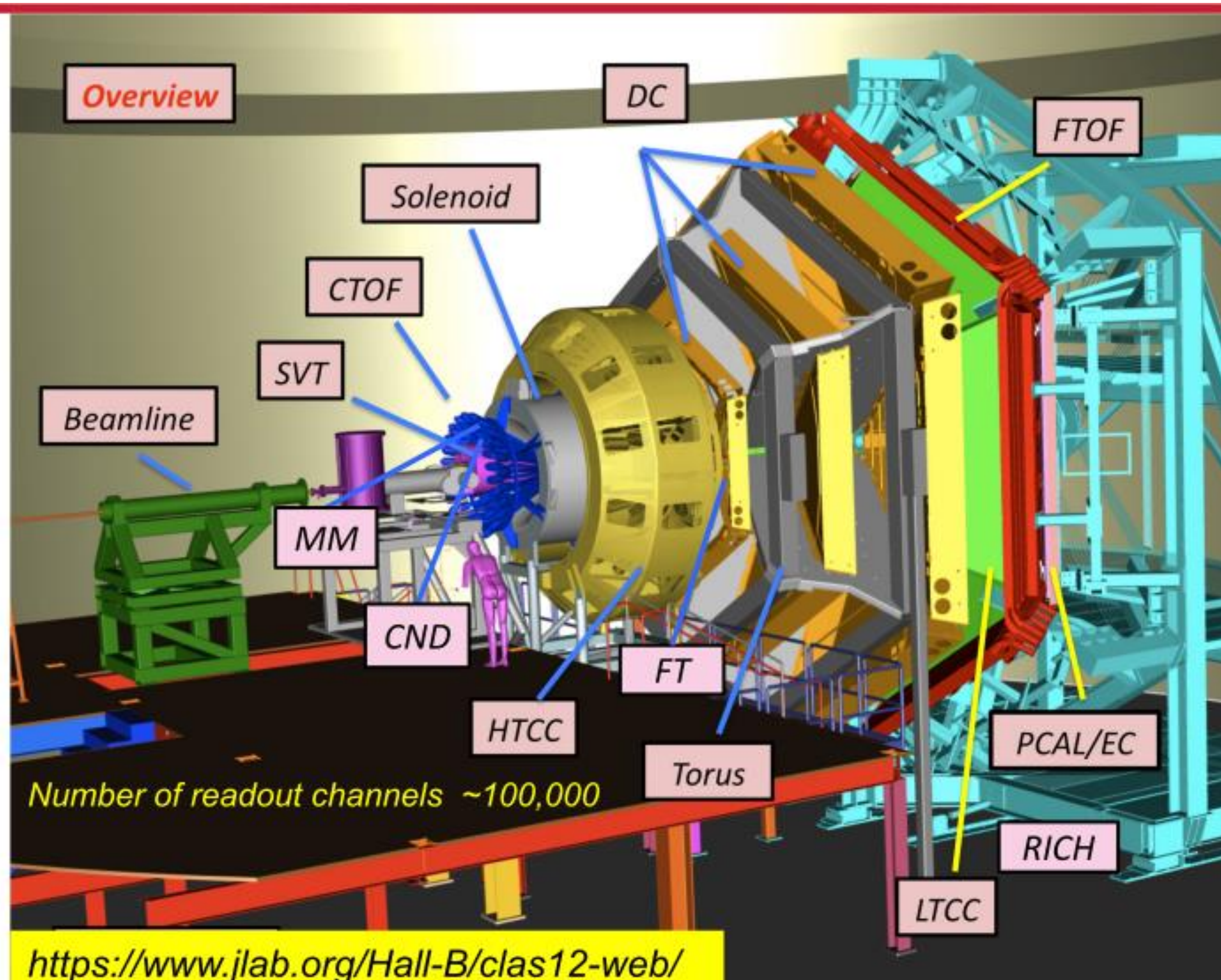
Upcoming measurement of parallel asymmetry with polarized proton and deuteron with CLAS12. PR12-06-109 Contact: S. Kuhn

Forward Detector:

- *TORUS magnet*
- *HT Cherenkov Counter*
- *Drift chamber system*
- *LT Cherenkov Counter*
- *RICH detector*
- *Forward ToF System*
- *Pre-shower calorimeter*
- *E.M. calorimeter (EC)*
- *Forward Tagger*

Central Detector:

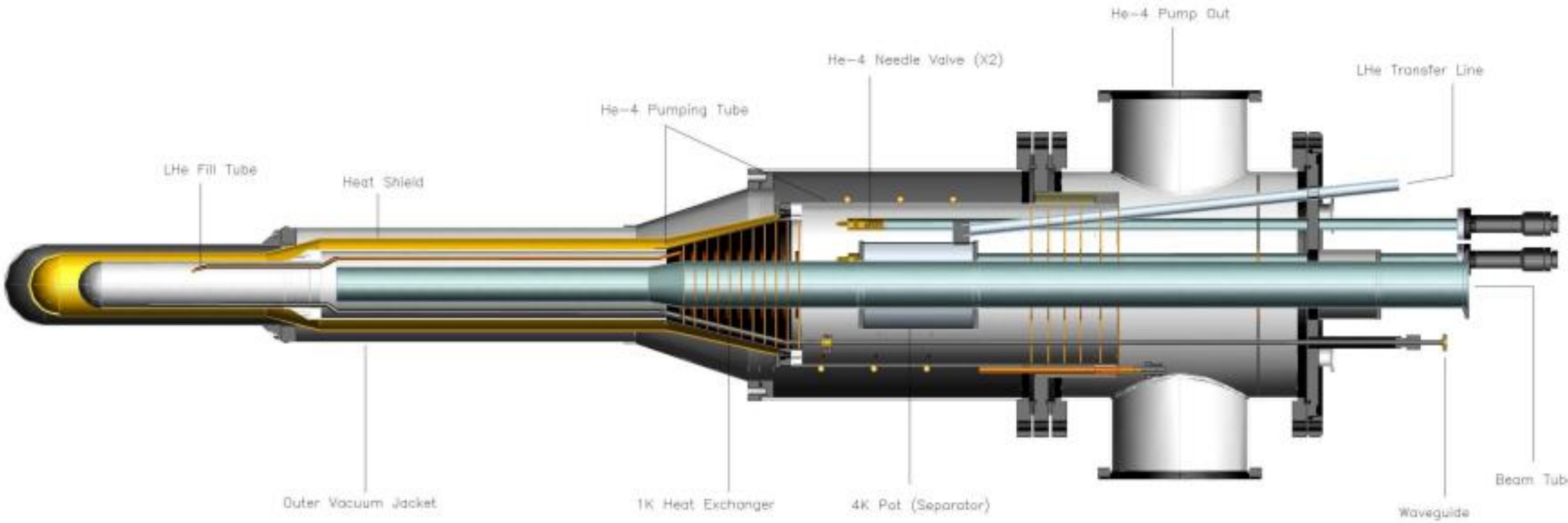
- *SOLENOID magnet*
- *Barrel Silicon Tracker*
- *Micromegas*
- *Central ToF system*
- *Neutron detector*
- *Backward Angle Neutron detector*



Large x dependence of proton A_1

Upcoming measurement of parallel asymmetry with polarized proton and deuteron with CLAS12. PR12-06-109 Contact: S. Kuhn

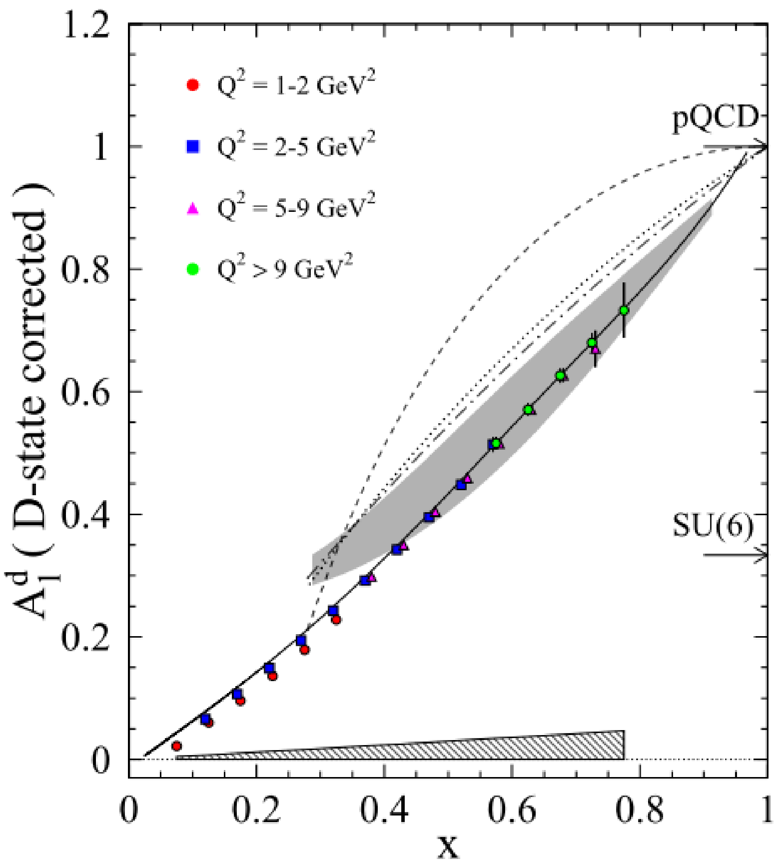
Longitudinally polarized proton and deuteron using dynamic nuclear polarization (DNP) on ammonia targets.



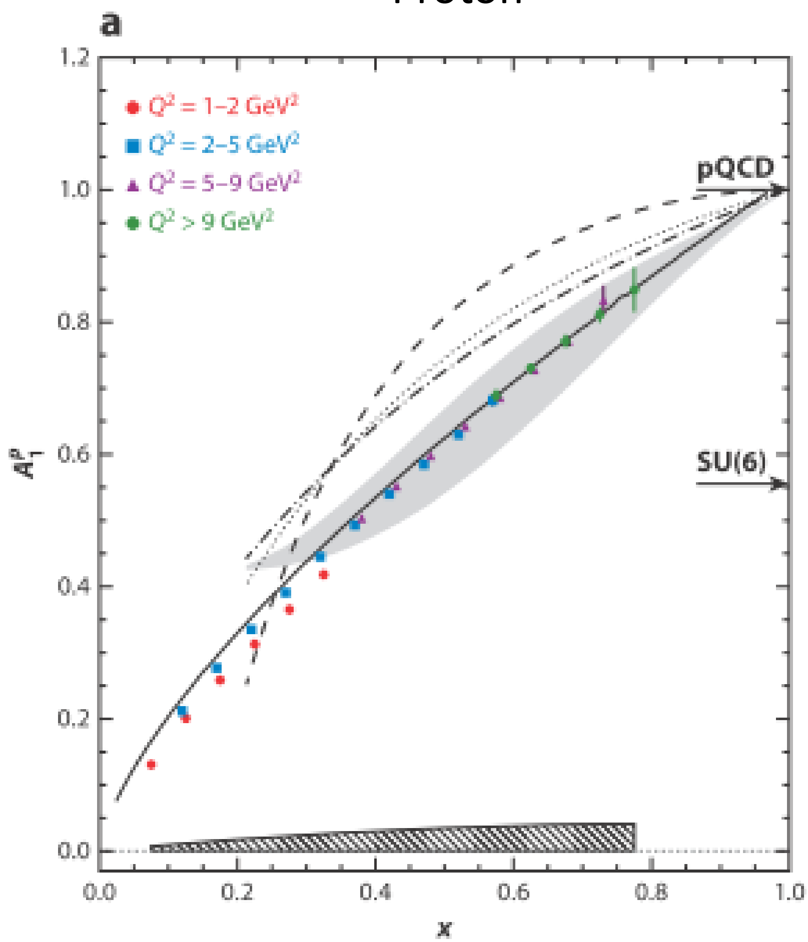
Large x dependence of proton A_1

Upcoming measurement of parallel asymmetry with polarized proton and deuteron with CLAS12. PR12-06-109 Contact: S. Kuhn

Deuteron



Proton



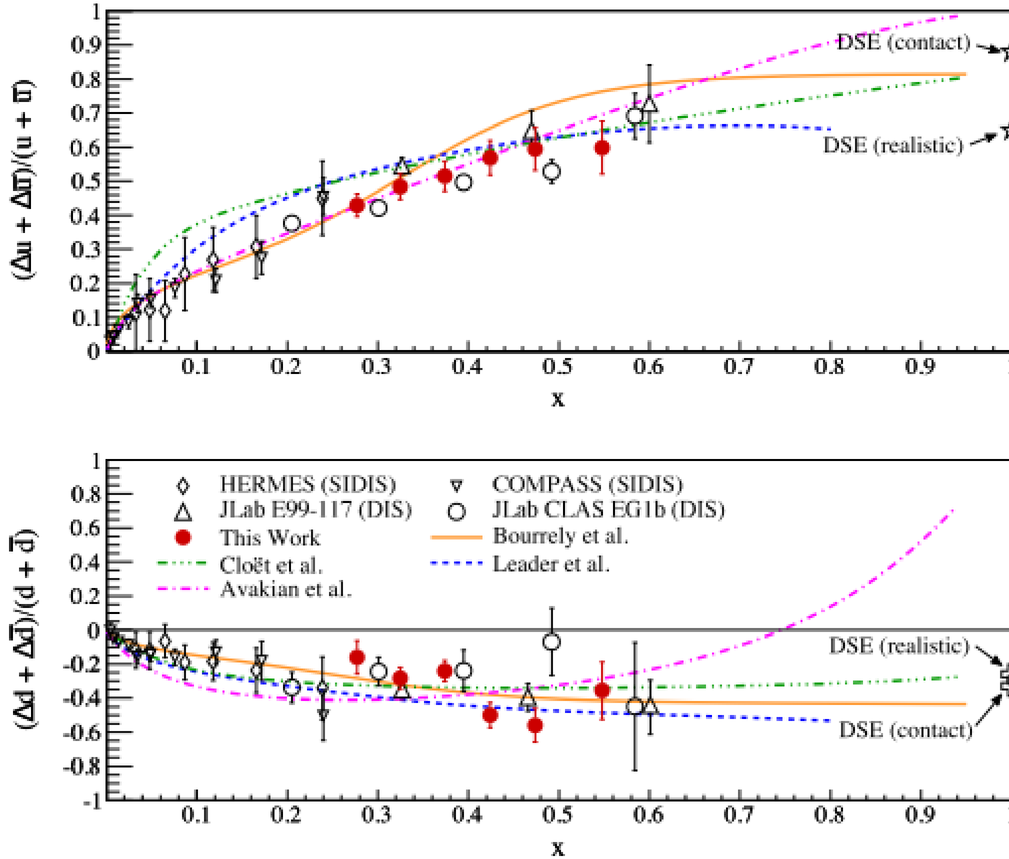
Polarized to Unpolarized Quark ratios

Combined measurements of previous proton and recent Hall A neutron g_1/F_1

$$\frac{\Delta u + \Delta \bar{u}}{u + \bar{u}} = \frac{4}{15}\frac{g_1^p}{F_1^p}\left(4 + R^{du}\right) - \frac{1}{15}\frac{g_1^n}{F_1^n}\left(1 + 4R^{du}\right)$$

$$\frac{\Delta d + \Delta \bar{d}}{d + \bar{d}} = \frac{4}{15}\frac{g_1^n}{F_1^n}\left(4 + \frac{1}{R^{du}}\right) - \frac{1}{15}\frac{g_1^p}{F_1^p}\left(1 + 4\frac{1}{R^{du}}\right)$$

$$R^{du} \equiv (d + \bar{d})/(u + \bar{u})$$

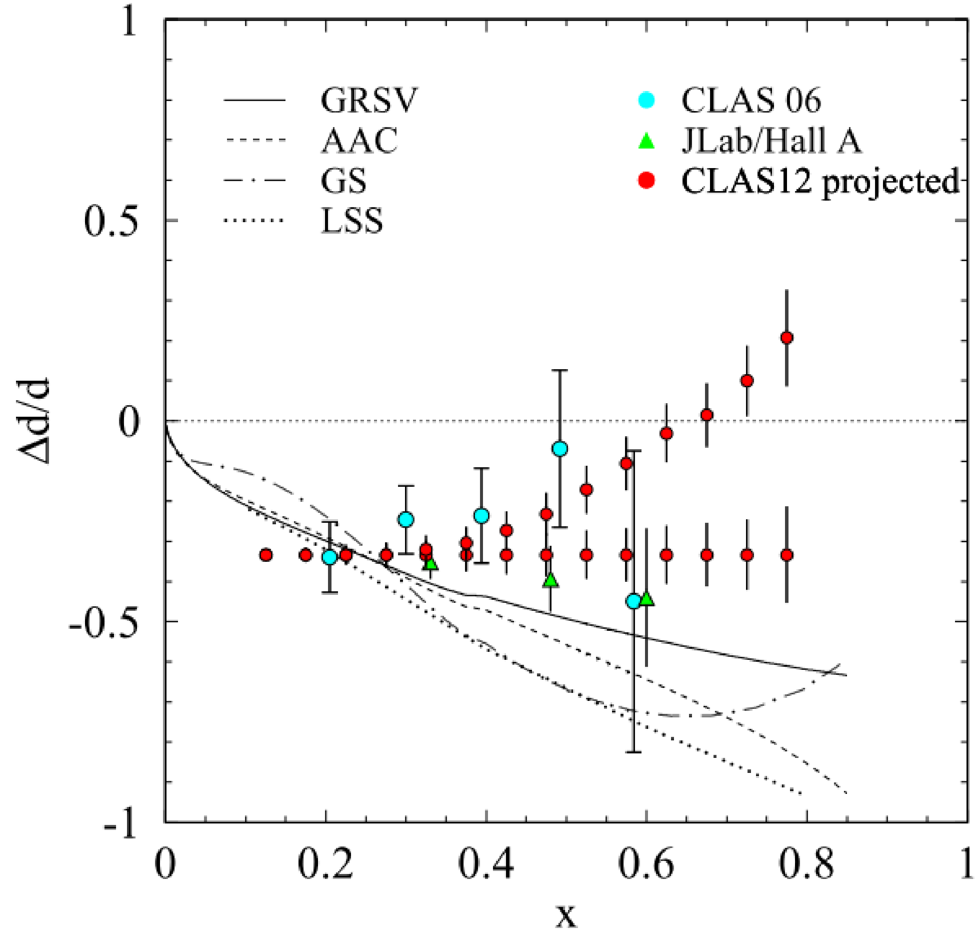


D. Flay et al. Phys. Rev. D 94, 052003 (2016)

Extract the down quark valence helicity distribution

The future Hall B measurement of proton and deuteron asymmetries can be combined.

$$\frac{\Delta d + \Delta \bar{d}}{d + \bar{d}} = \frac{4}{15}\frac{g_1^n}{F_1^n}\left(4 + \frac{1}{R^{du}}\right) - \frac{1}{15}\frac{g_1^p}{F_1^p}\left(1 + 4\frac{1}{R^{du}}\right)$$



Two sets of projected error bars

- Constant
- Slow rise to 1 and x=1

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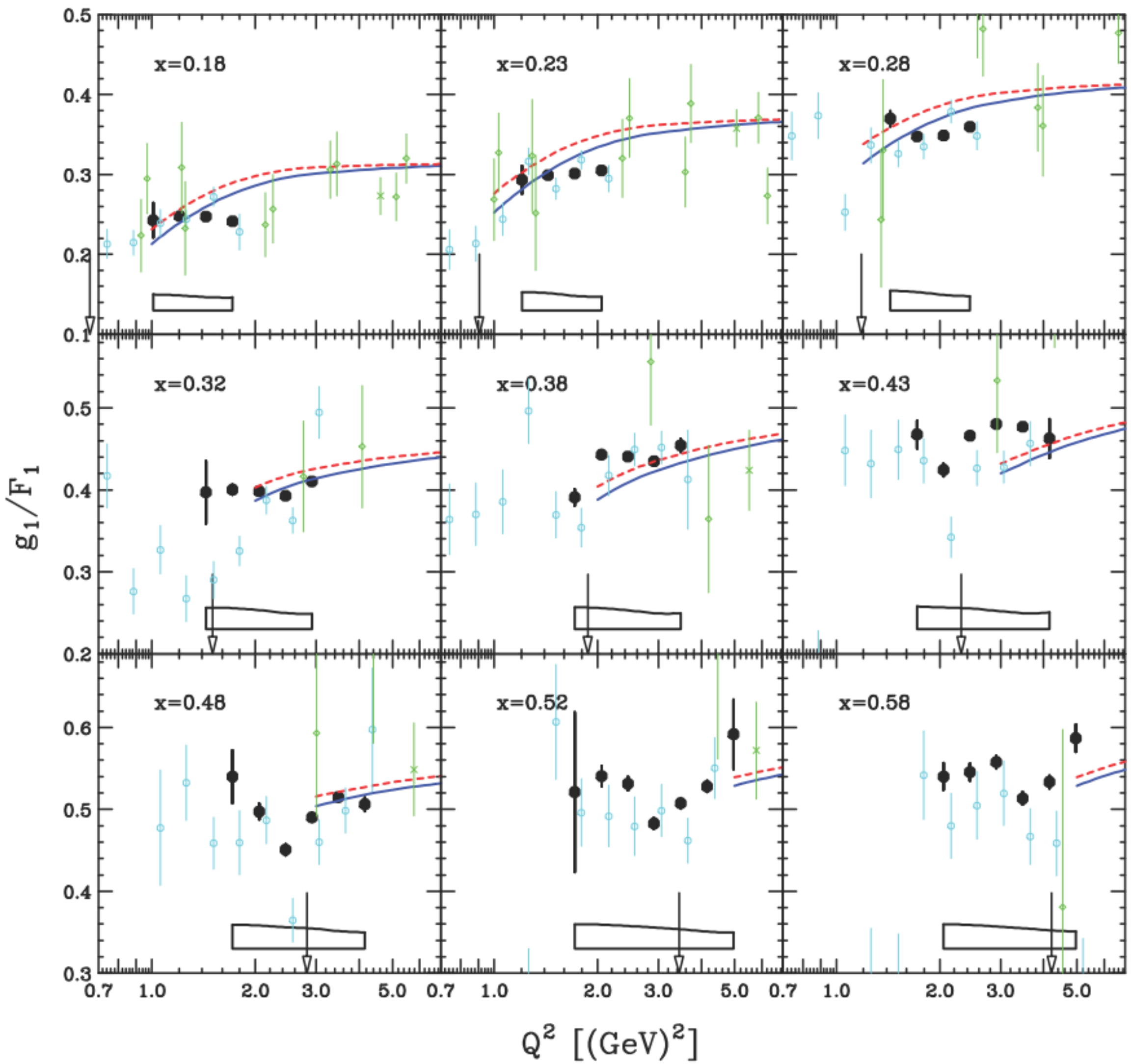
Q^2 dependence of proton g_1/F_1

- New Hall B data on polarized proton and deuteron to extract g_1/F_1 with improved statistical precision compared to earlier Hall B experiments.
- Need precision to distinguish between power-law higher twist and logarithmic gluon radiation in the polarized parton distribution.
- To give a feel, the plots have pQCD calculations from LSS with $\Delta G > 0$ (blue) and $\Delta G < 0$ (red)

PHYSICAL REVIEW C 90, 025212 (2014

Proton



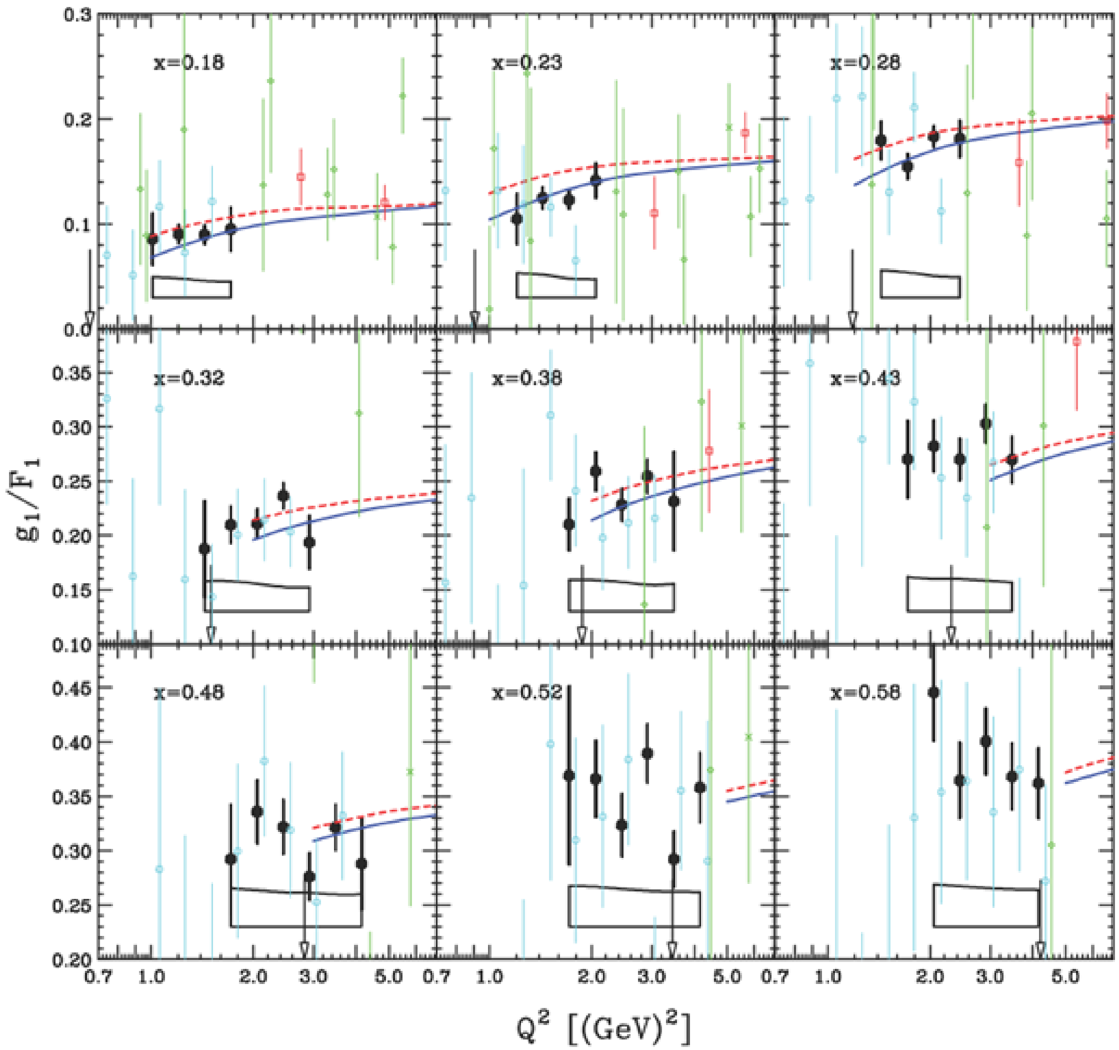
Jefferson Lab

Q^2 dependence of deuteron g_1/F_1

- New Hall B data on polarized proton and deuteron to extract g_1/F_1 with improved statistical precision compared to earlier Hall B experiments.
- Need precision to distinguish between power-law higher twist and logarithmic gluon radiation in the polarized parton distribution.
- To give a feel, the plots have pQCD calculations from LSS with $\Delta G > 0$ (blue) and $\Delta G < 0$ (red)

PHYSICAL REVIEW C 90, 025212 (2014)

Deuteron



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Test of effective theories of QCD at low Q^2

Measurements of moments of structure functions provide tests of effective theories of QCD

Generalized GDH sum rule

$$I_{TT}(Q^2) = \frac{M^2}{4\pi^2\alpha}\int_{\nu_0}^{\infty}\frac{\kappa_f}{\nu}\frac{\sigma_{1/2}(\nu,Q^2)-\sigma_{3/2}(\nu,Q^2)}{\nu}d\nu$$
$$= \frac{2M^2}{Q^2}\int_0^{x_0}\left[g_1(x,Q^2)-\frac{4M^2}{Q^2}x^2g_2(x,Q^2)\right]dx$$

Ji and Osborne generalized sum rule

$$\Gamma_1(Q^2) \equiv \int_0^{x_0} g_1(x,Q^2)dx = \frac{Q^2 S_1}{8},$$

S_1 is the forward virtual Compton amplitude

Burkhardt-Cottingham sum rule

$$\Gamma_2(Q^2) \equiv \int_0^1 g_2(x,Q^2)dx = 0$$

Neutron structure function moments at low Q^2

- In Hall A, E97-110 measured neutron g_1 and g_2 using polarized ^{3}He and detecting electrons in the HRS.
- New results in V. Sulkosky et al. arXiv:1908.05709
- Benchmark test of chiral effective field theory

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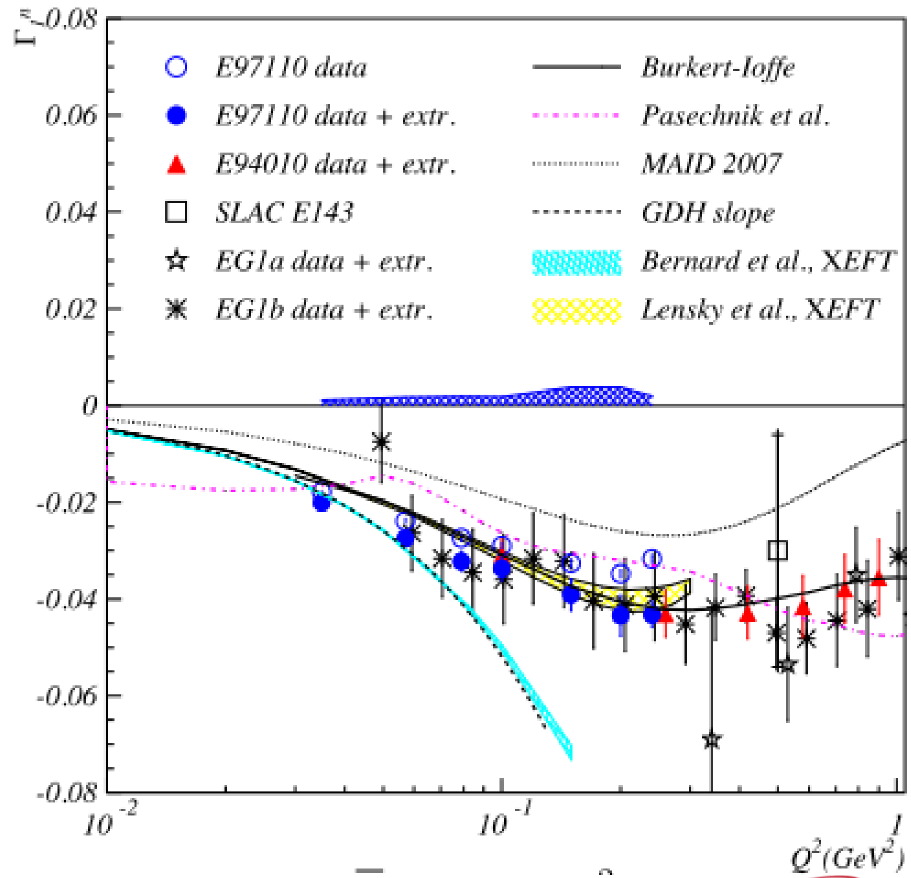

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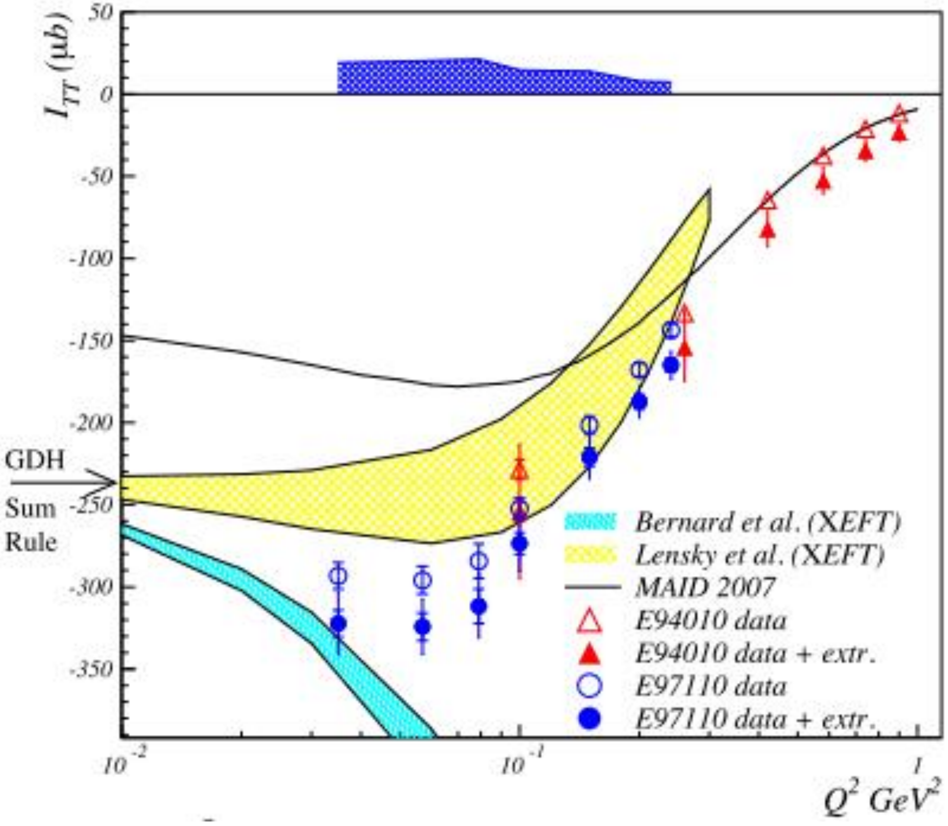
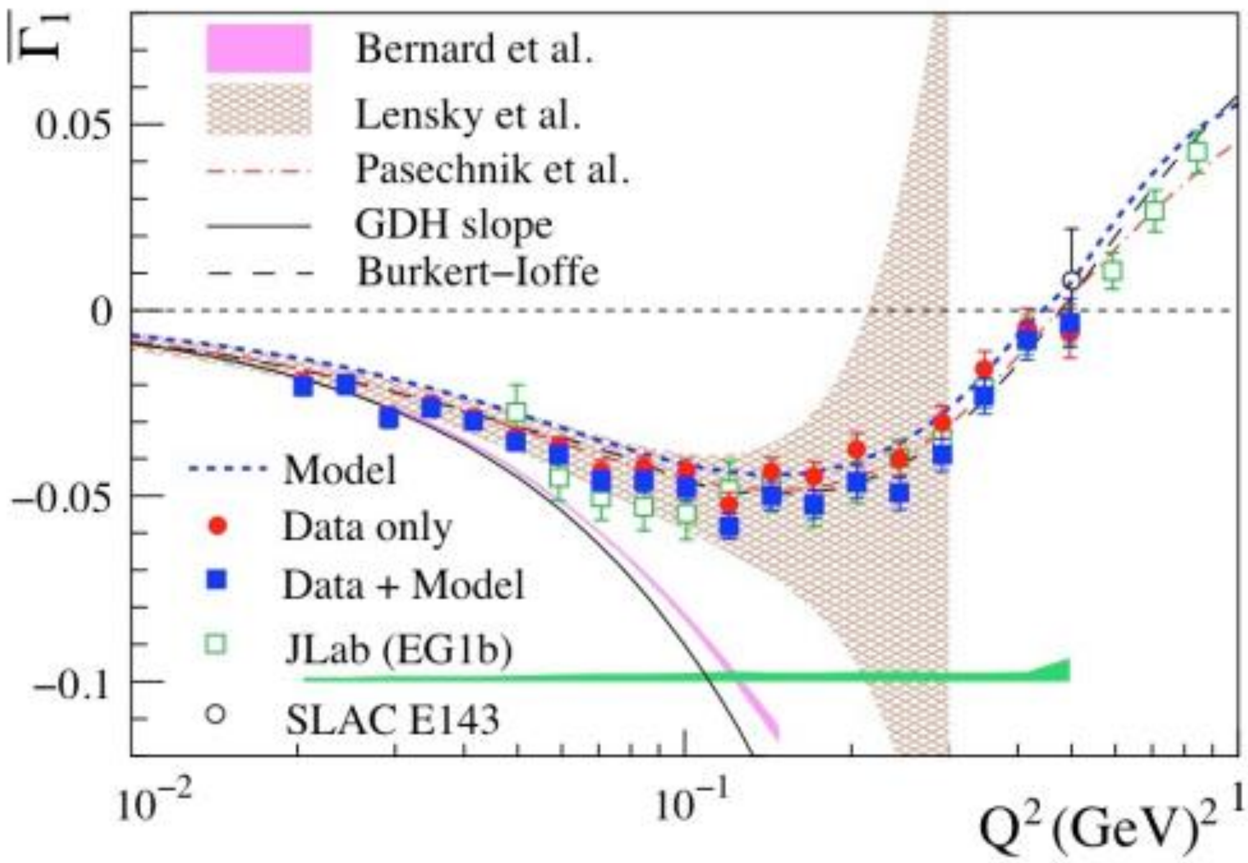


Deuteron structure function moments at low Q^2

- In Hall B, CLAS measured proton and deuteron g_1 at low Q^2
- Phys. Rev. Lett. 120, 062501 (2018)

Deuteron data



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Summary

- Presented proton and neutron d_2 as a function of Q^2
  - Q^2 dependence is puzzling
  - Need new lattice QCD calculations over range of Q^2
- Upcoming measurements with 11 GeV accelerator
  - CLAS12 measure proton and deuteron g_1/F_1
    - Measure proton A_1 as x approaches 1.
    - Q^2 dependence in bins of x.
  - In Fall 2019, start two experiments Hall C
    - Measure polarized 3He g_1 and g_2
    - Extract neutron A_1 as x approaches 1.
    - Extract neutron d_2 at Q^2 = 3,4,5 and 6 GeV^2
- Benchmark tests of chiral effective theory at low Q2
  - No theory can explain all the data.
  - Expect results from Hall A from proton g_1 and g_2 soon.