QUARKS & NUCLEAR PHYSICS 2004

Structure of the Nucleon in the Valence Quark Region

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Temple University

- Structure of the nucleon; Inclusive spin responses
  - Valence region and quark orbital angular momentum
  - Moments of spin structure functions
    - Burkhardt-Cottingham sum rule
    - Color polarizabilities
- Structure of the nucleon; Semi-inclusive spin response
  - Transversity, Collins, Sivers, etc...

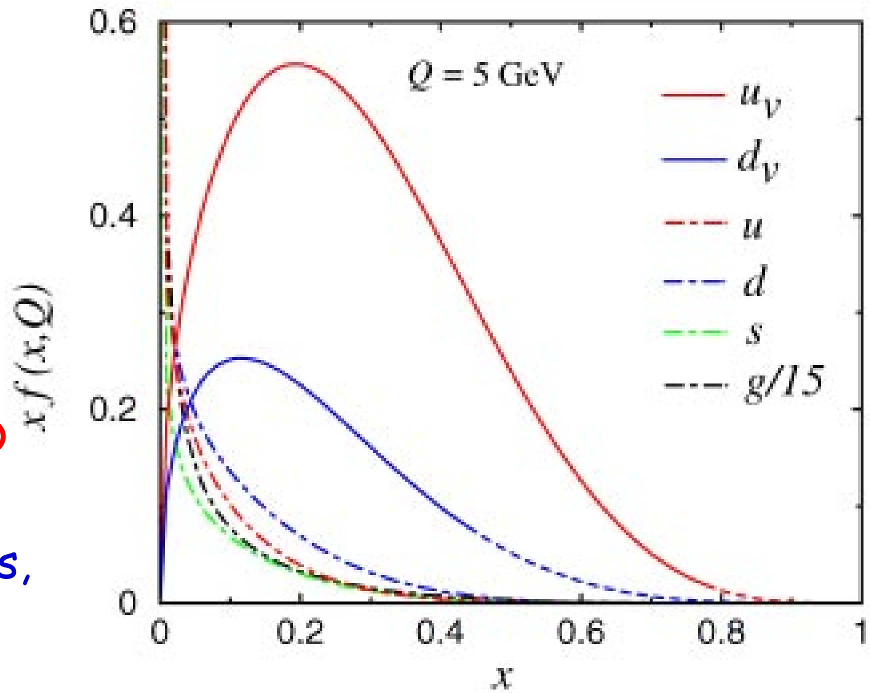
Introduction

Understand the nucleon structure in the valence quark region

- Complete knowledge of parton distribution functions (PDFs).
  - Unpolarized, helicity dependent and transversity distribution functions…

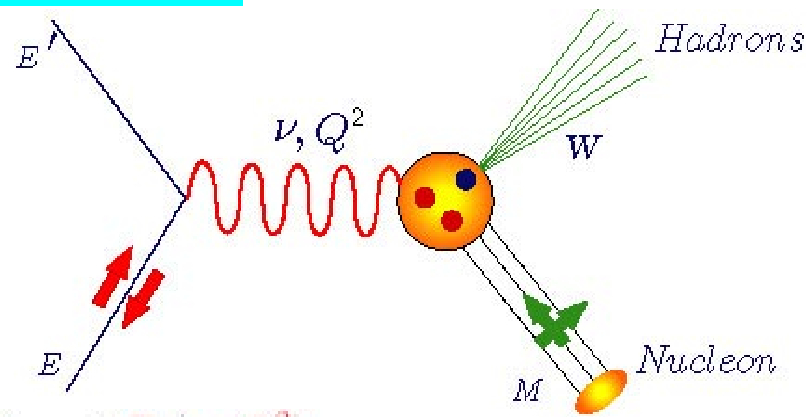
Why large x?

- large x exposes valence quarks - free of sea effects
- x->1 behavior – sensitive test of spin-flavor symmetry breaking
- important for higher moments of PDFs - compare with lattice QCD
- intimately related with resonances, quark-hadron duality



Inclusive DIS

- Unpolarized structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$
  - ➡ Proton & neutron measurements provide d/u distributions ratio



U $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow + \uparrow\Uparrow) = \frac{8\alpha^2\cos^2(\theta/2)}{Q^4}\left[\frac{F_2(x,Q^2)}{\nu} + \frac{2F_1(x,Q^2)}{M}\tan^2(\theta/2)\right]$$

- Polarized structure functions

  $g_1(x,Q^2)$ and $g_2(x,Q^2)$
  - ➡ Proton & neutron measurements combined with d/u provide the spin-flavor distributions Δu/u & Δd/d

Q^2 :Four-momentum transfer
x : Bjorken variable
ν : Energy transfer
M : Nucleon mass
W : Final state hadrons mass

L $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1(x,Q^2) - \frac{Q^2}{\nu}g_2(x,Q^2)\right]$$

T $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2Eg_2(x,Q^2)\right]$$

Virtual photon-nucleon asymmetries

$$A_1 = \frac{g_1(x,Q^2) - \gamma^2 g_2(x,Q^2)}{F_1(x,Q^2)}$$

$$A_2 = \frac{\gamma[g_1(x,Q^2) + g_2(x,Q^2)]}{F_1(x,Q^2)}$$

where $\gamma = \sqrt{Q^2}/\nu$

- Positivity constraints

$|A_1| \leq 1$ and $|A_2| \leq \sqrt{R(1+A_1)/2}$

In the quark-parton model:

$$F_1(x,\, Q^2) = \frac{1}{2}\sum_f e_f^2\, q_f(x,\, Q^2) \qquad g_1(x,\, Q^2) = \frac{1}{2}\sum_f e_f^2\, \Delta q_f(x,\, Q^2)$$

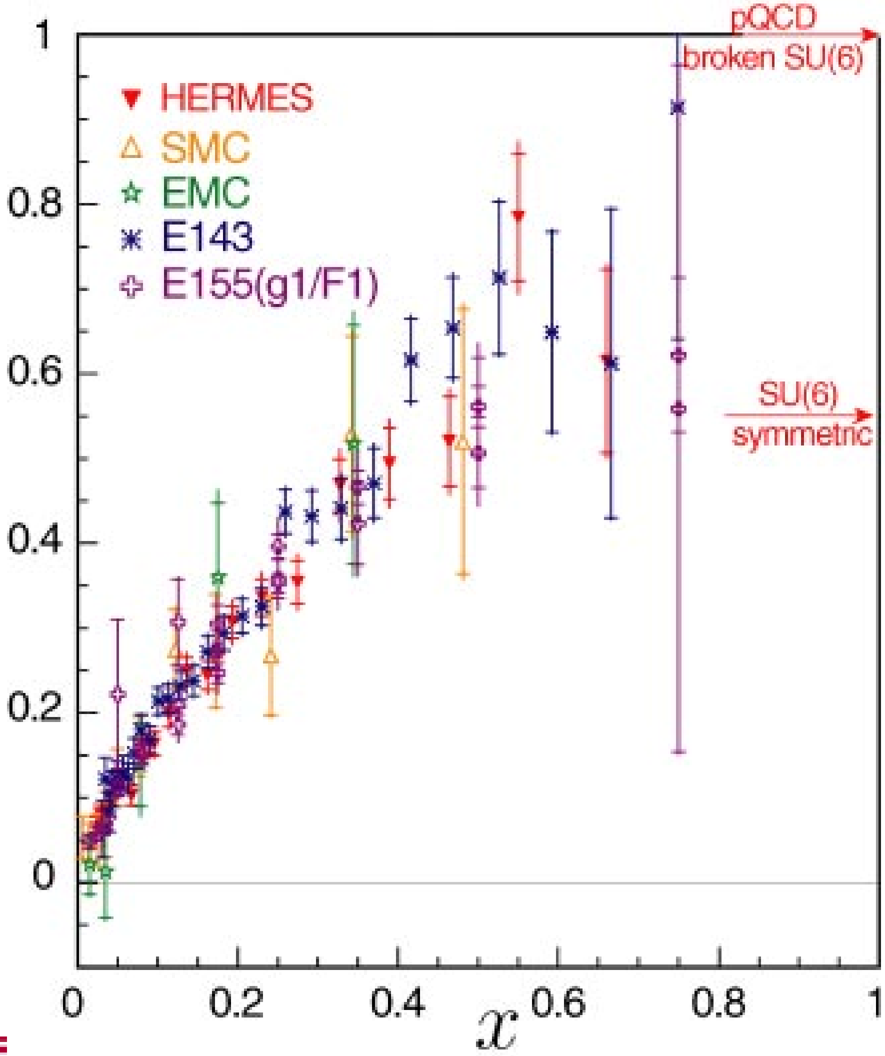
$$q_f(x) = q_f^{\uparrow}(x) + q_f^{\downarrow}(x) \qquad \Delta q_f(x) = q_f^{\uparrow}(x) - q_f^{\downarrow}(x)$$

$q_f(x)$ quark momentum distributions of flavor f

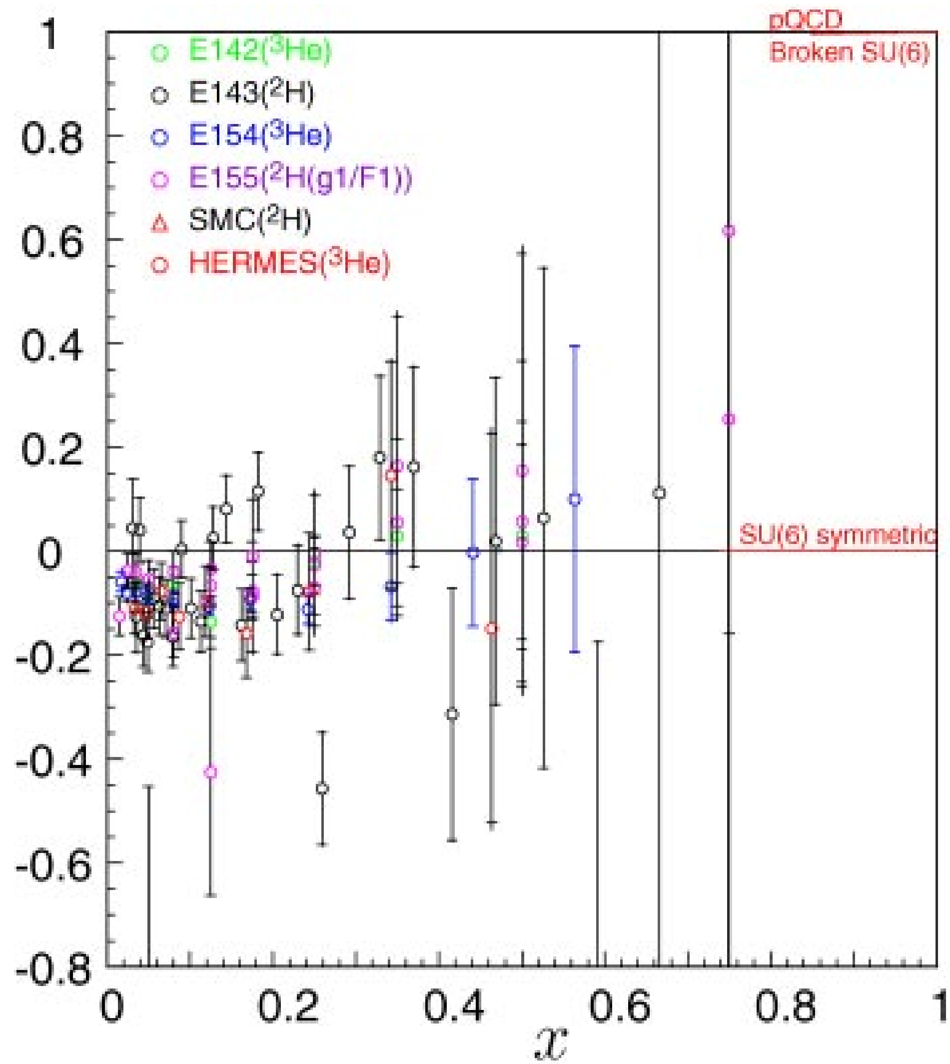
$\uparrow(\downarrow)$ parallel (antiparallel) to the nucleon spin

World data for A_1

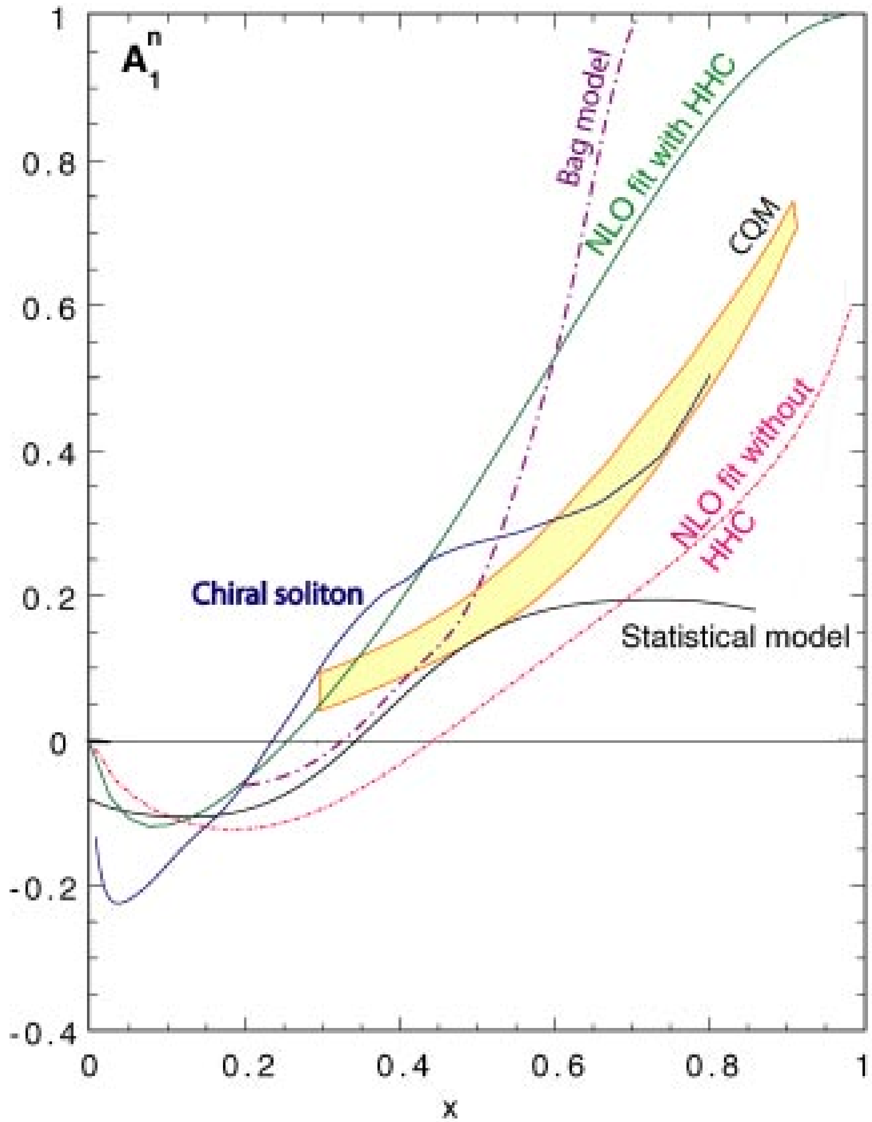
Proton



Neutron



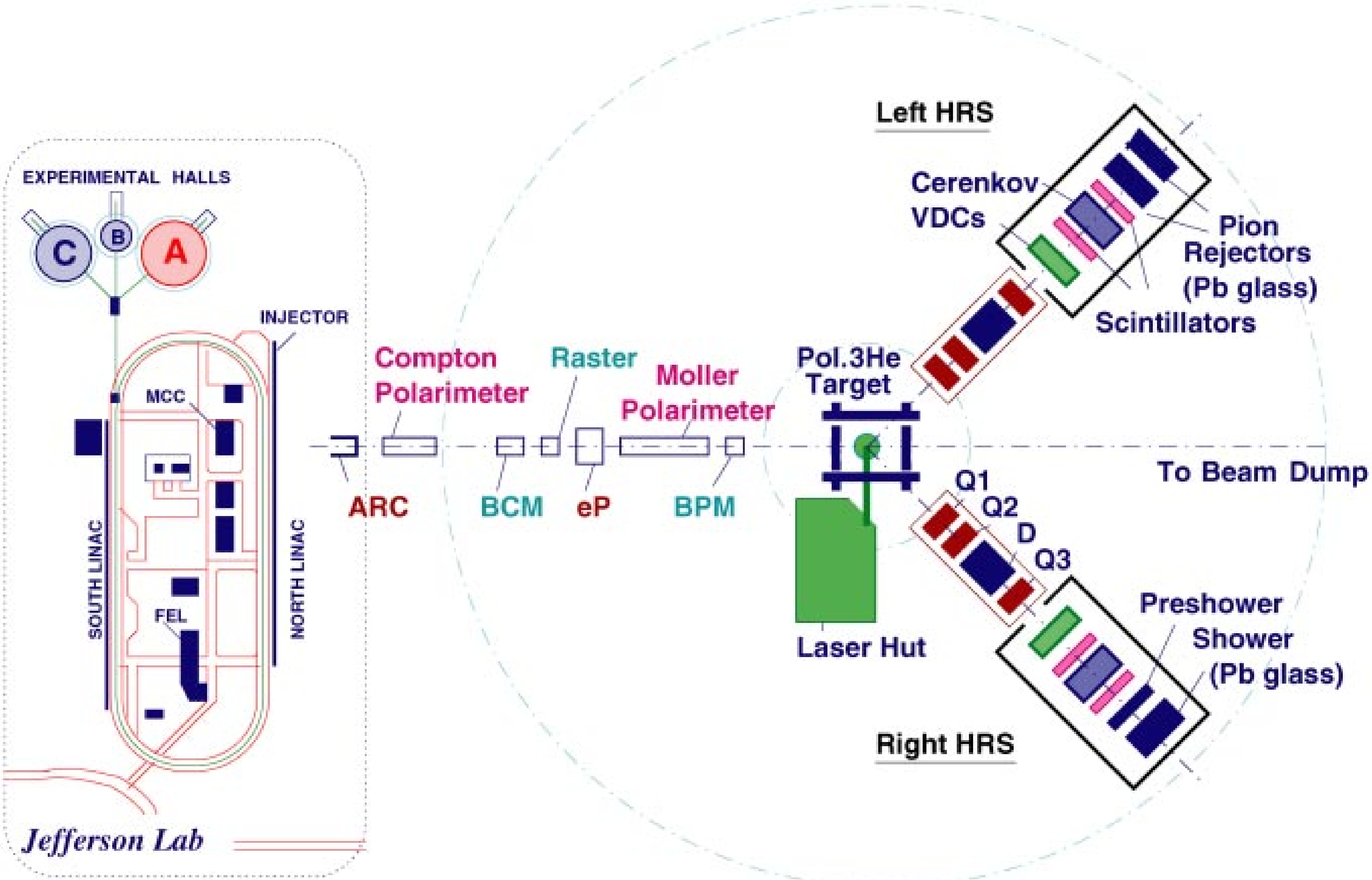
Polarized quarks as x--> 1



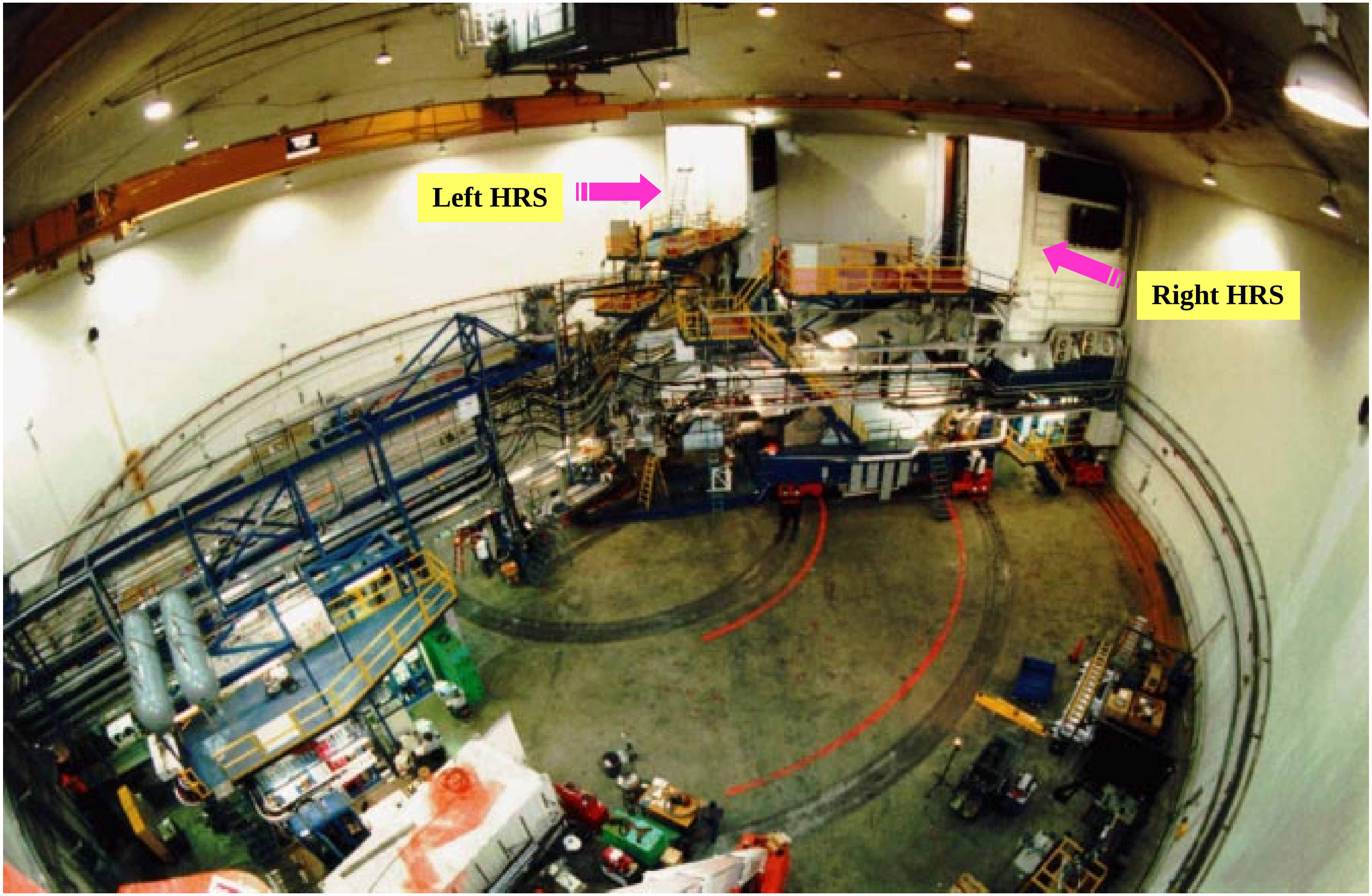
- SU(6) symmetry:
  - $A_1^p = 5/9$ $A_1^n = 0$ $d/u=1/2$
  - $\Delta u/u = 2/3$ $\Delta d/d = -1/3$
- Broken SU(6) via scalar diquark dominance
  - $A_1^p \rightarrow 1$ $A_1^n \rightarrow 1$ $d/u \rightarrow 0$
  - $\Delta u/u \rightarrow 1$ $\Delta d/d \rightarrow -1/3$
- Broken SU(6) via helicity conservation
  - $A_1^p \rightarrow 1$ $A_1^n \rightarrow 1$ $d/u \rightarrow 1/5$
  - $\Delta u/u \rightarrow 1$ $\Delta d/d \rightarrow 1$

Note that $\Delta q/q$ as x--> 1 is more sensitive to spin-flavor symmetry breaking effects than A_1

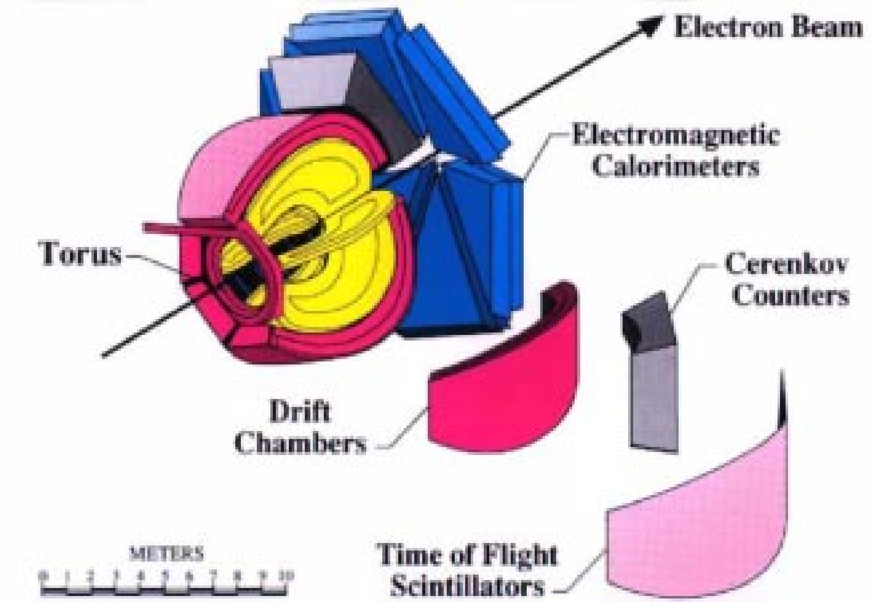
Hall A Experimental Setup



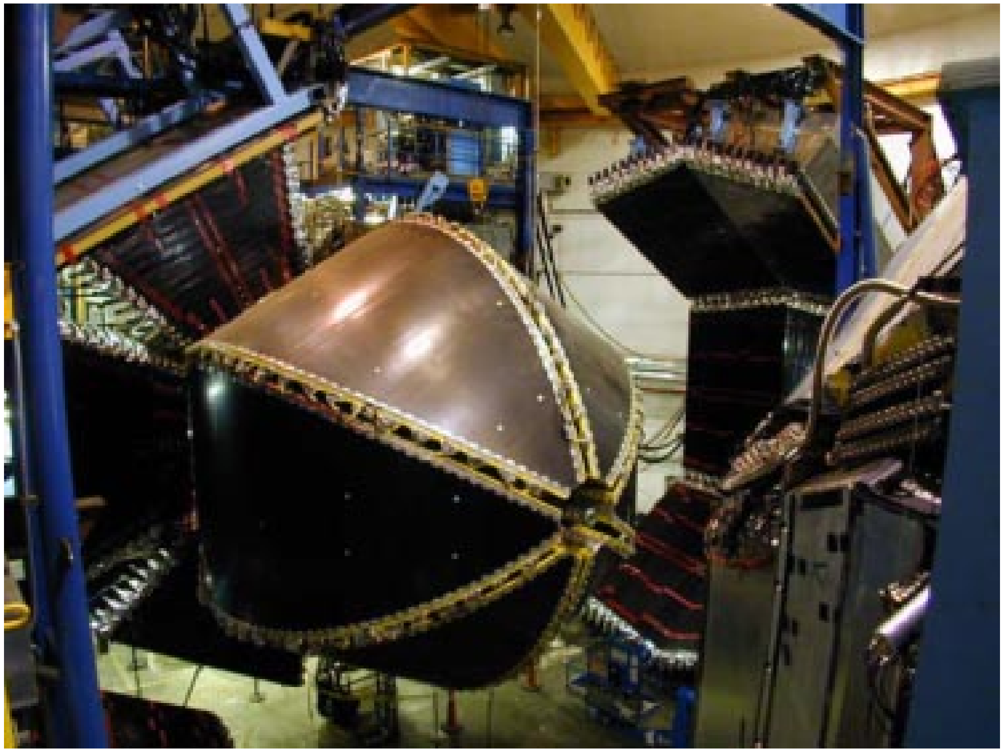
Hall A at Jefferson Lab



Hall B Experimental Setup

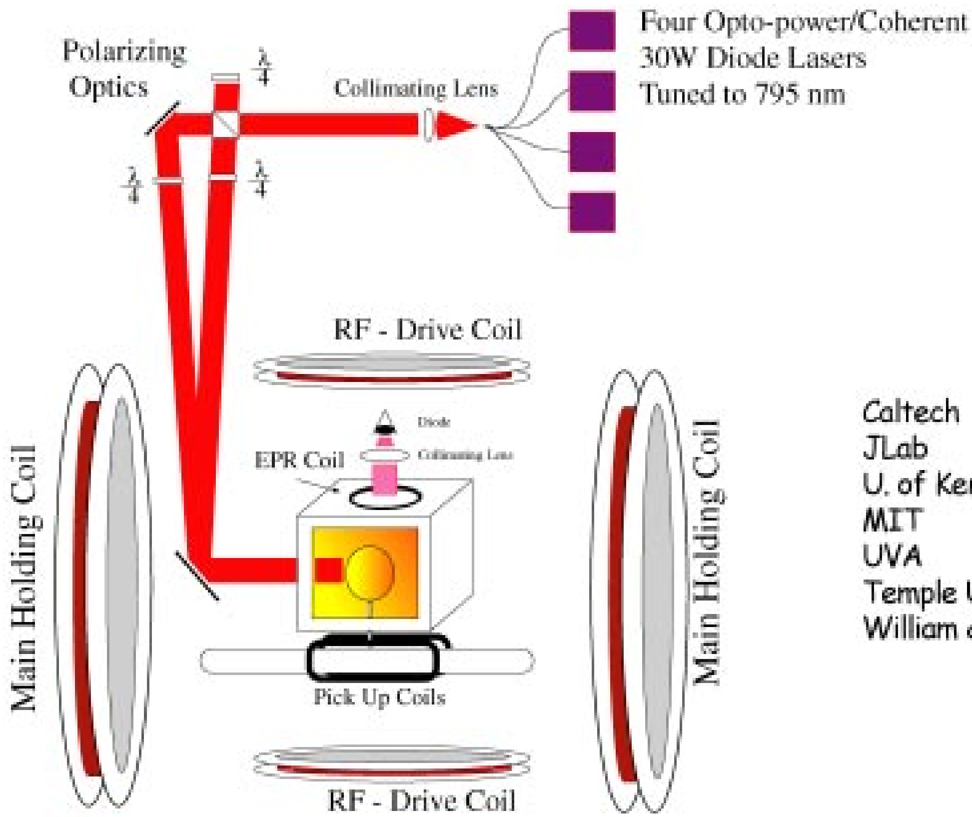


CEBAF
Large
Acceptance
Spectrometer



- Large kinematical coverage
- detection of charged and neutral particles
- Multiparticle final state

JLab Polarized ^{3}He target

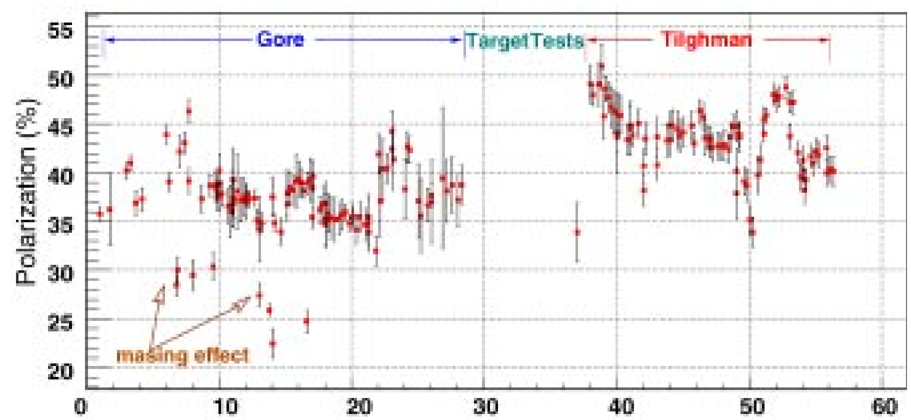


- NMR and EPR techniques for polarization monitoring.
- Elastic scattering for current induced depolarization.
- Target length 40 cm, window thickness 100 µm

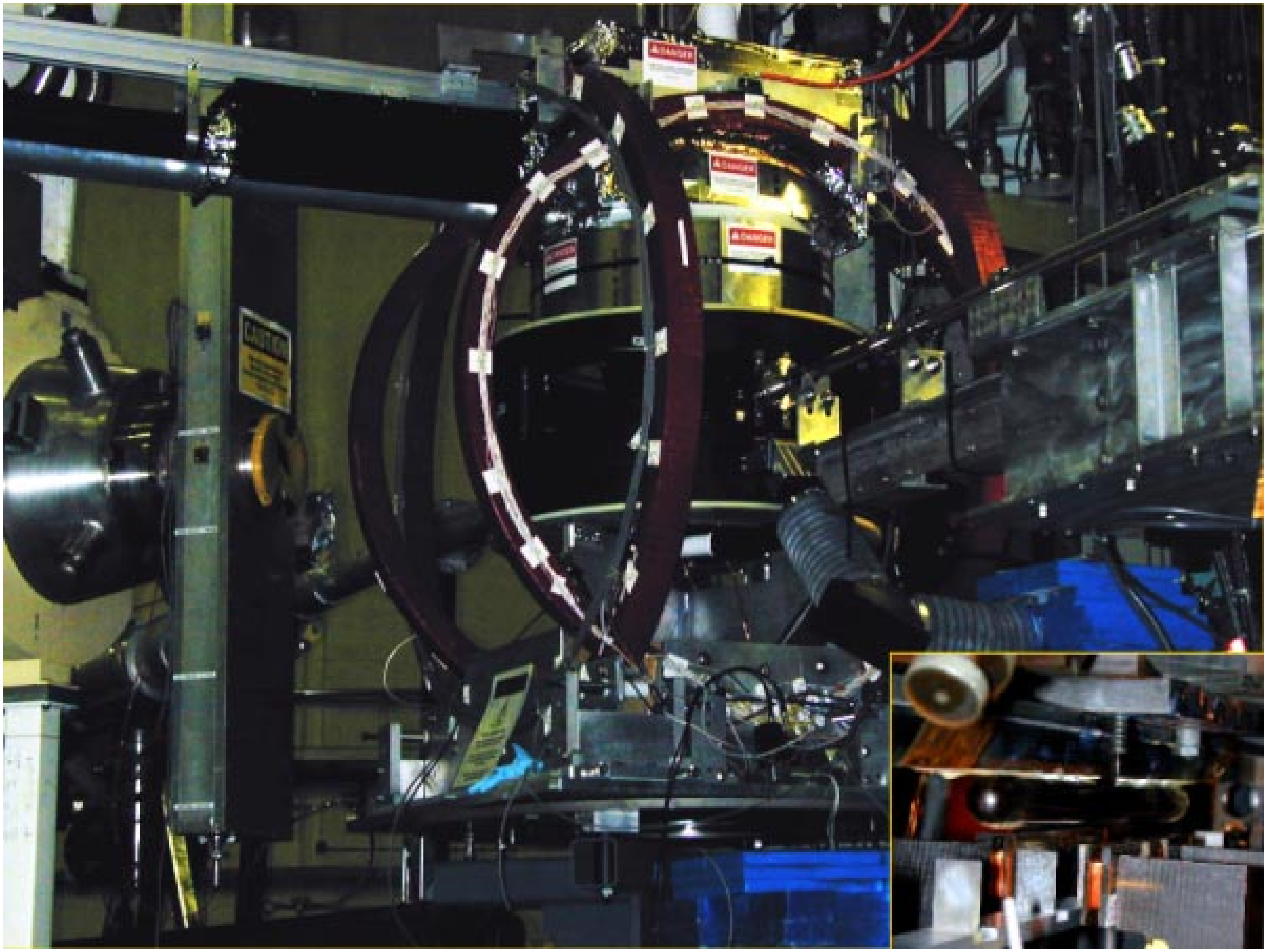
Caltech
JLab
U. of Kentucky
MIT
UVA
Temple U.
William & Mc

Performance of the target

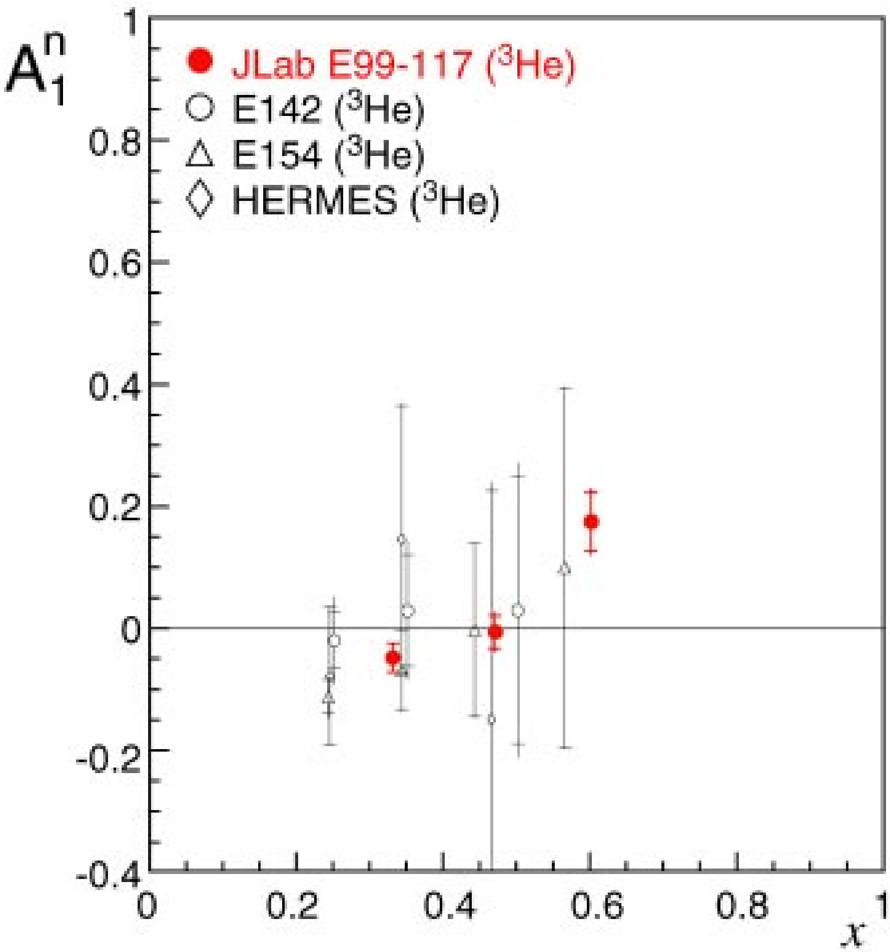
Cell Name	Field direction	0^0	180^0	270^0
Gore	June 06 – July 03	37%	35%	43%
Tilghman	July 13 – July 31	45%	43%	39%

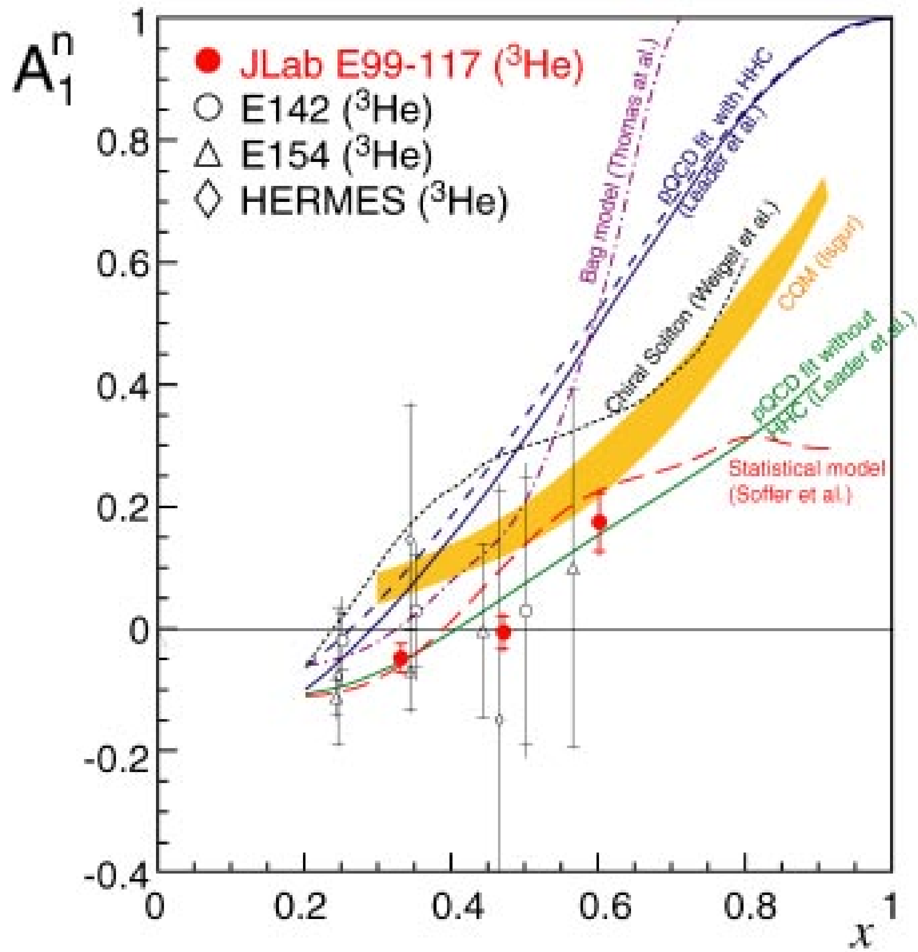


Polarized ^{3}He Target



JLab E99-117 A_1^n Results





Spokespeople: J.P. Chen, Z.-E.M. & P. Souder

Thesis student: X. Zheng

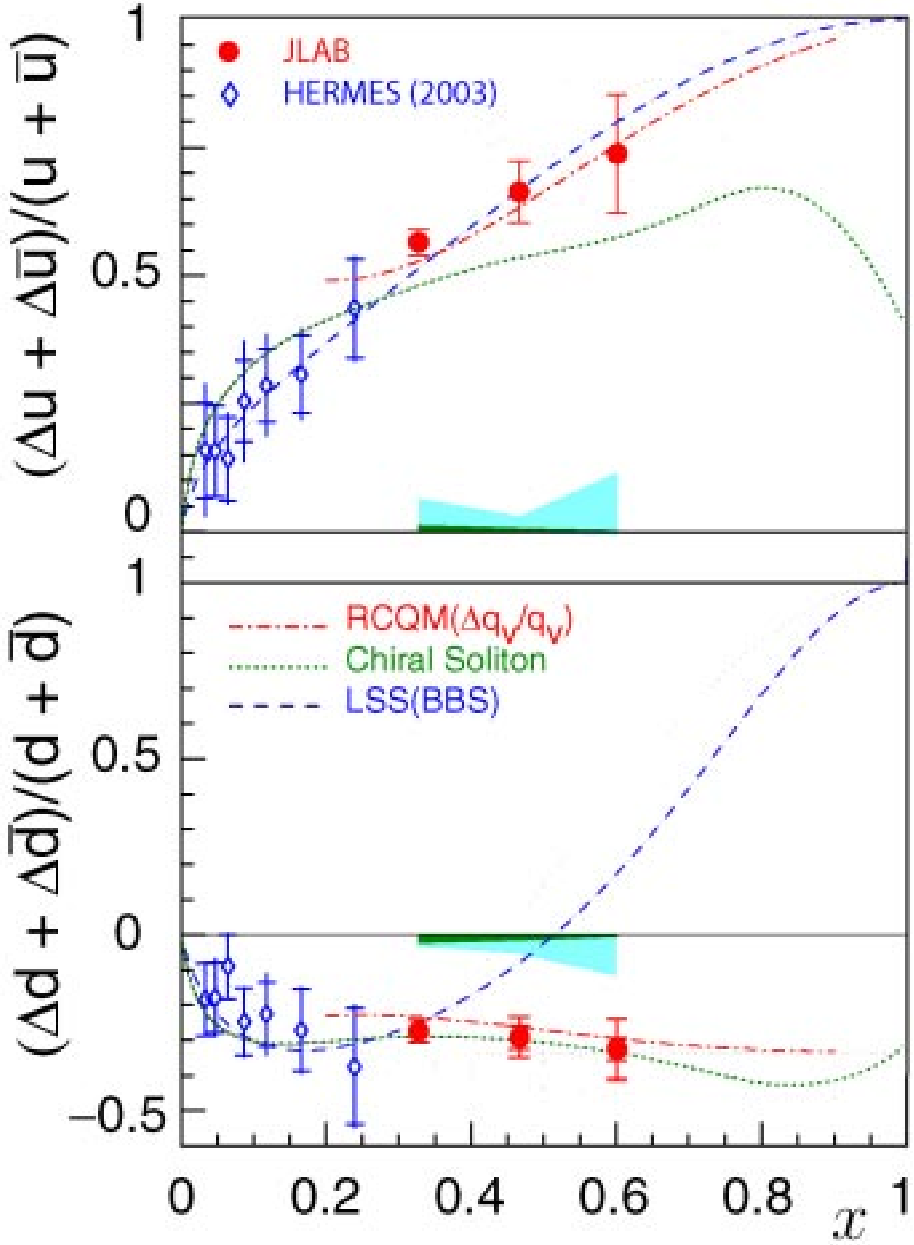
Phys. Rev. Lett. 92, 012004 (2004)

Helicity-Flavor Decomposition

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

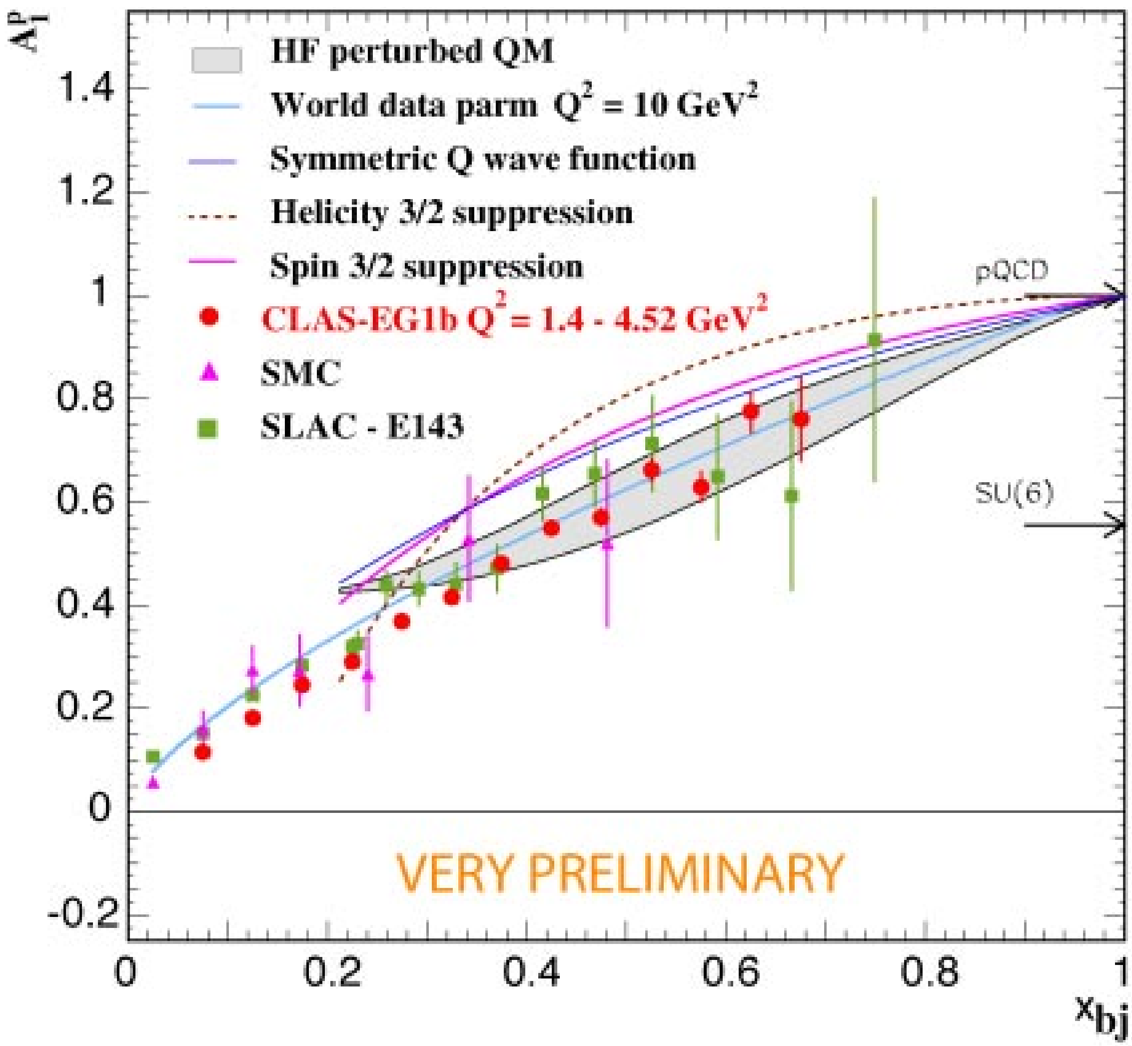
$$\frac{\Delta d+\Delta\bar{d}}{d}=\frac{4}{15}\frac{g_1^n}{F_1^n}(4+\frac{1}{R^{du}})-\frac{1}{15}\frac{g_1^p}{F_1^p}(1+4\frac{1}{R^{du}})$$

$$R^{du}=\frac{d+\bar{d}}{u+\bar{u}}$$

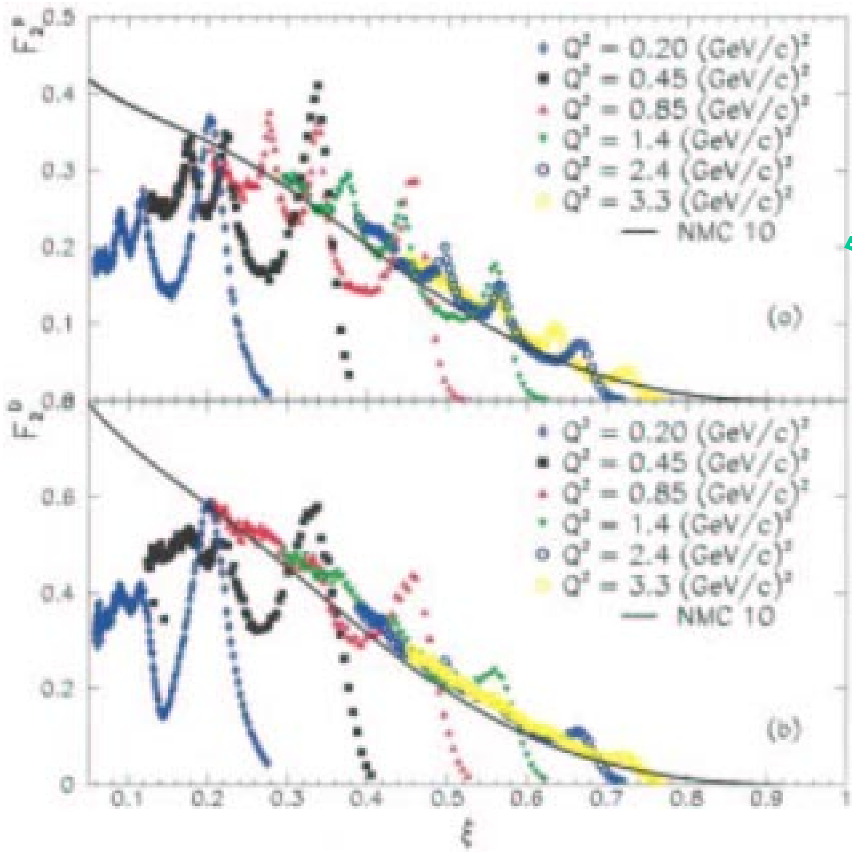


Hall B EG1b preliminary results

PROTON



Duality in the neutron spin structure

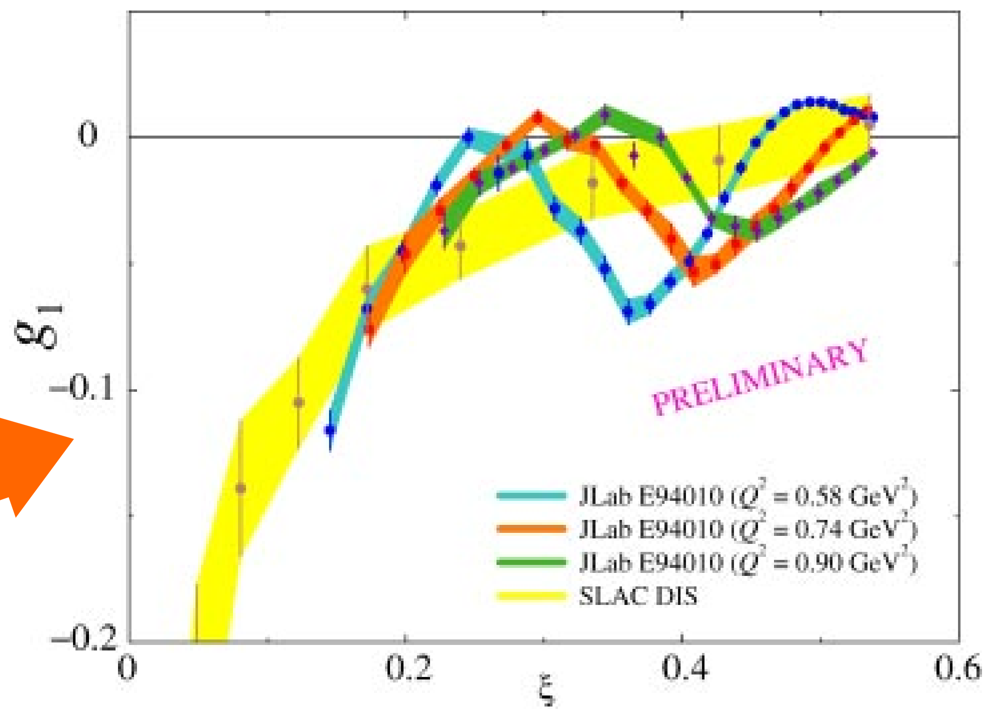


Helicity independent case

Proton and Deuteron

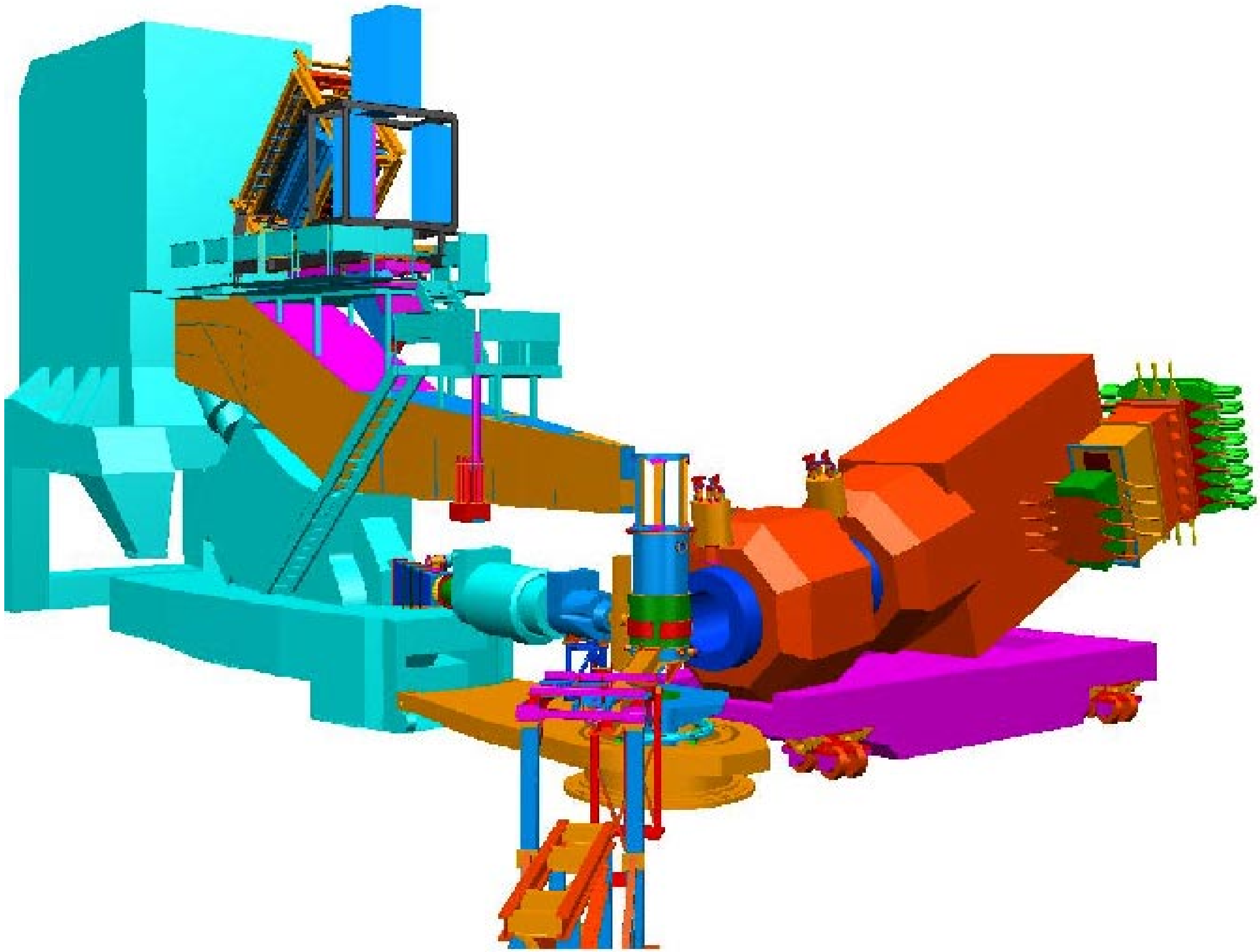
Niculescu et al. PRL 85 (2000) 1182

See W. Melnitchouk

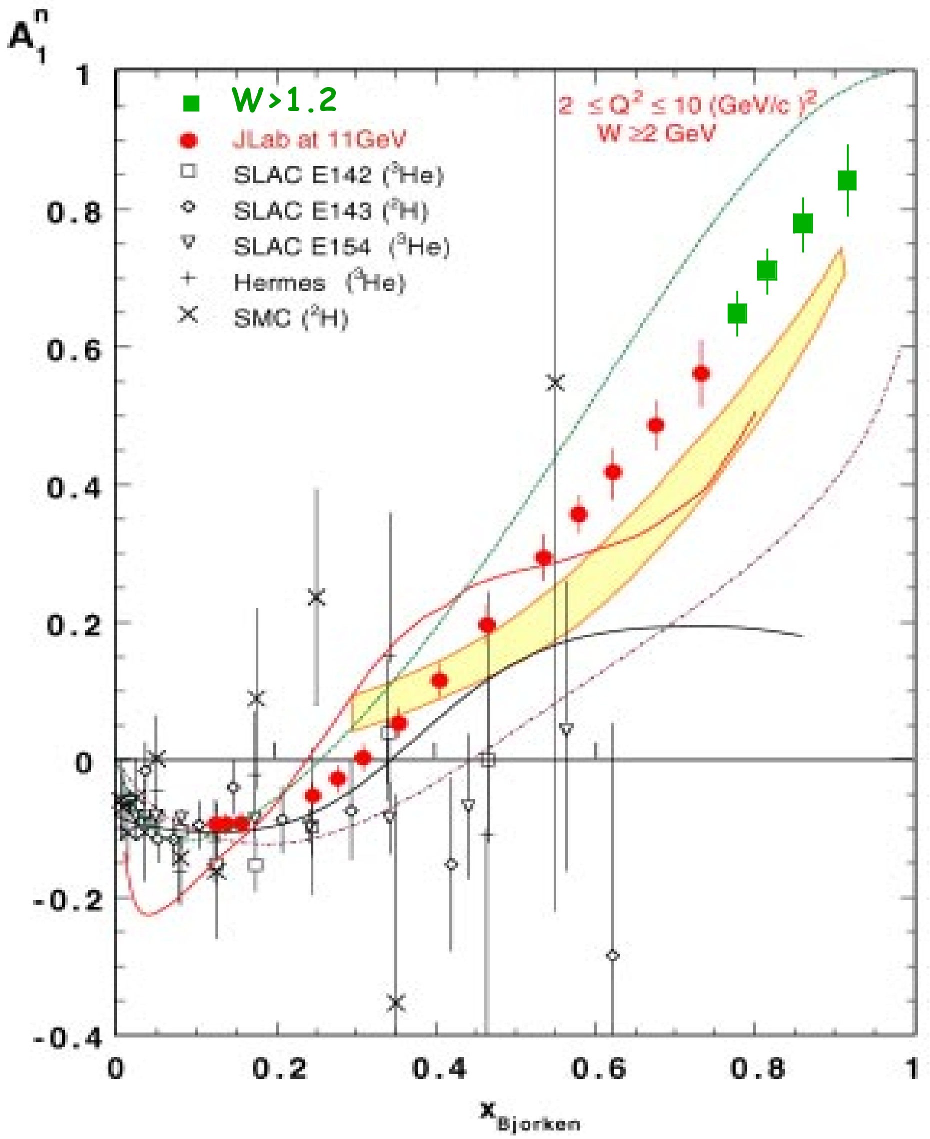


Hint of spin duality for the neutron!

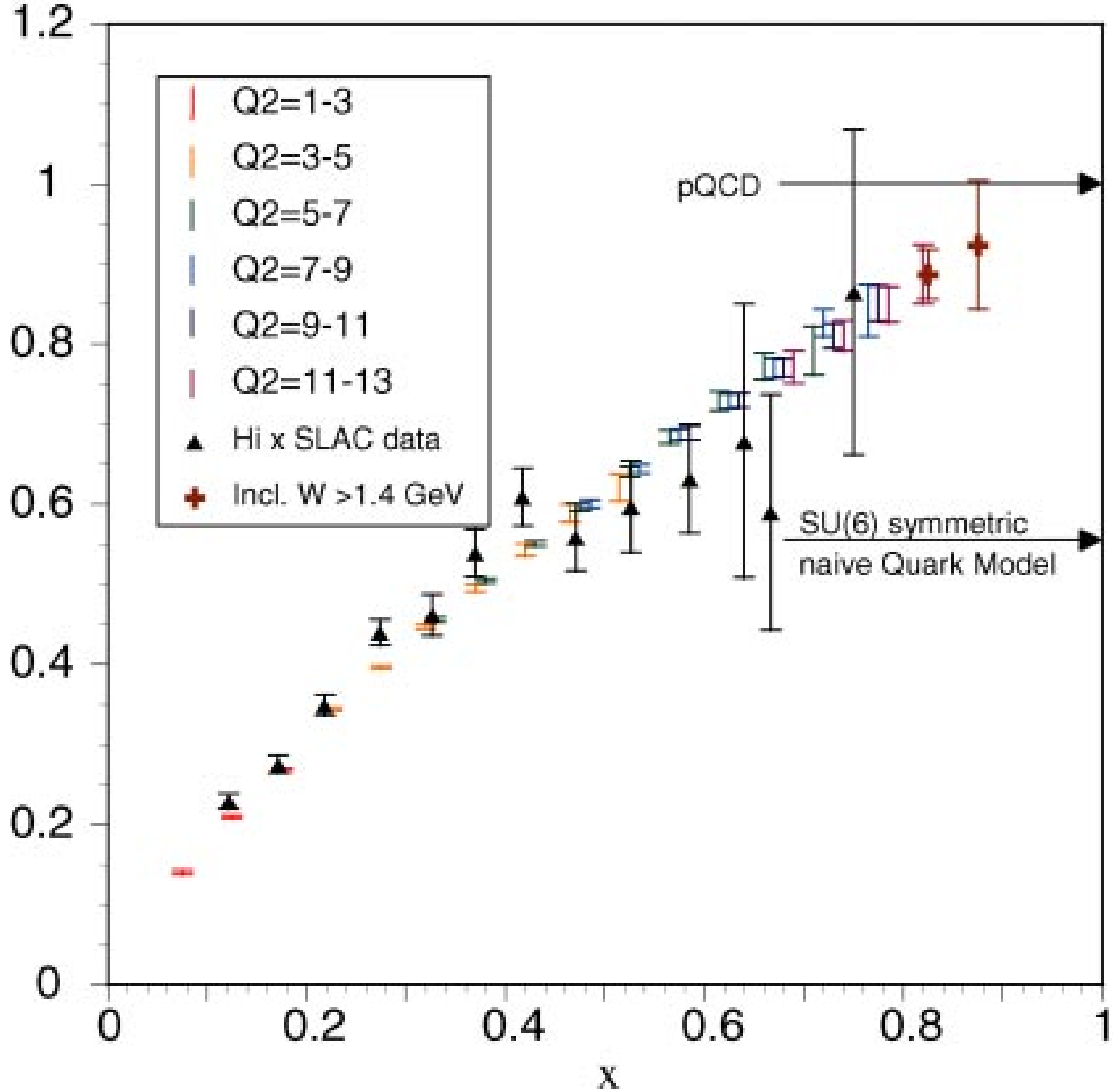
HRS+MAD spectrometers in Hall A



A_1^n at 11 GeV with MAD in Hall A

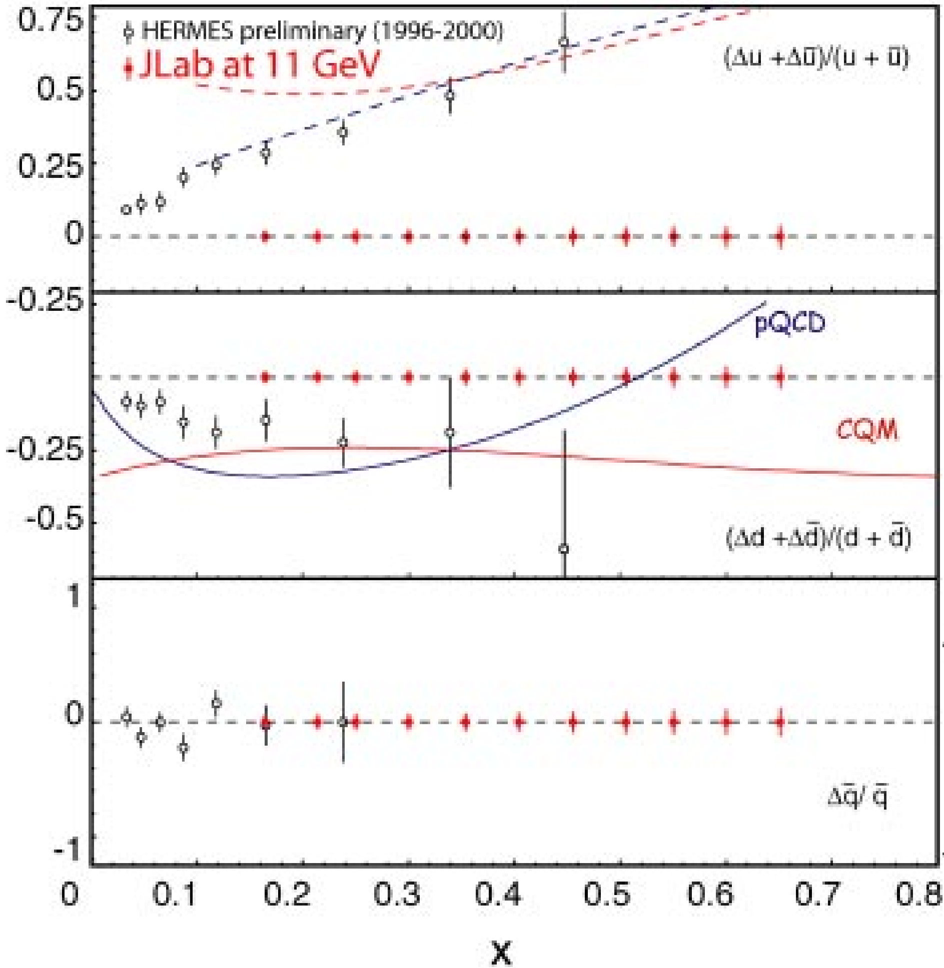


A_1^p at 11 GeV with CLAS++

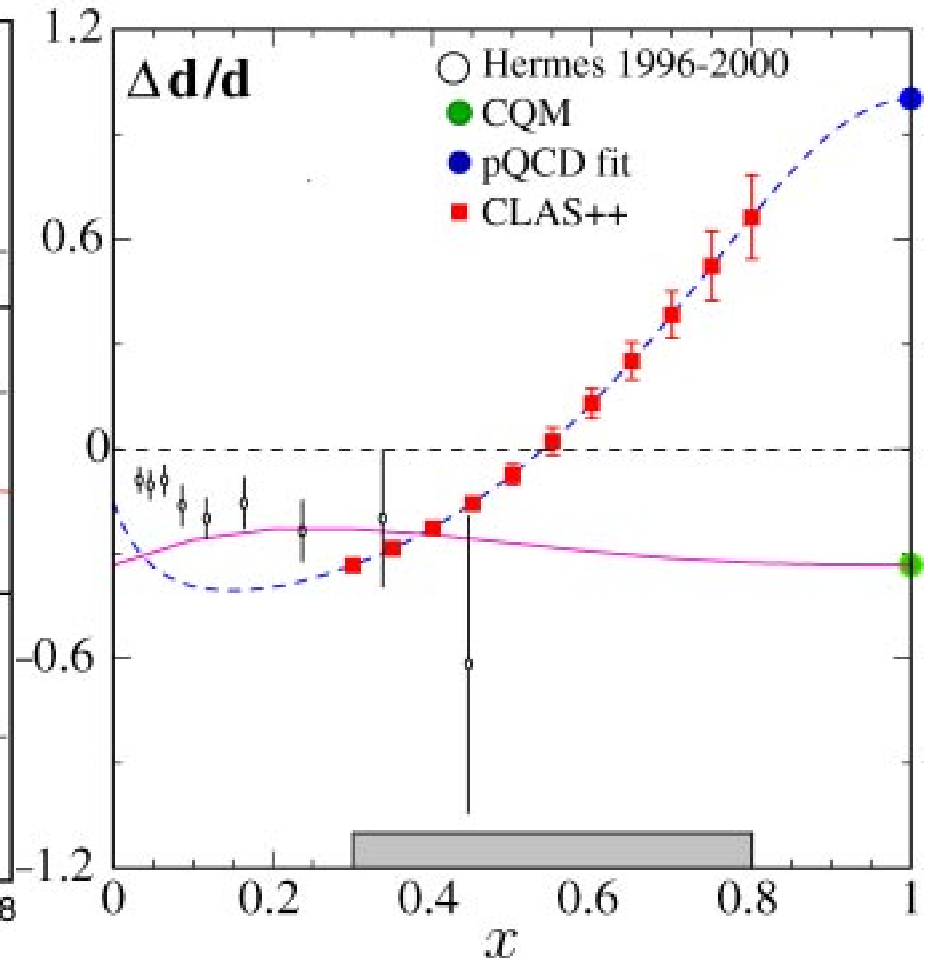


Helicity-Flavor Decomposition

Hall A with MAD



Hall B with CLAS++

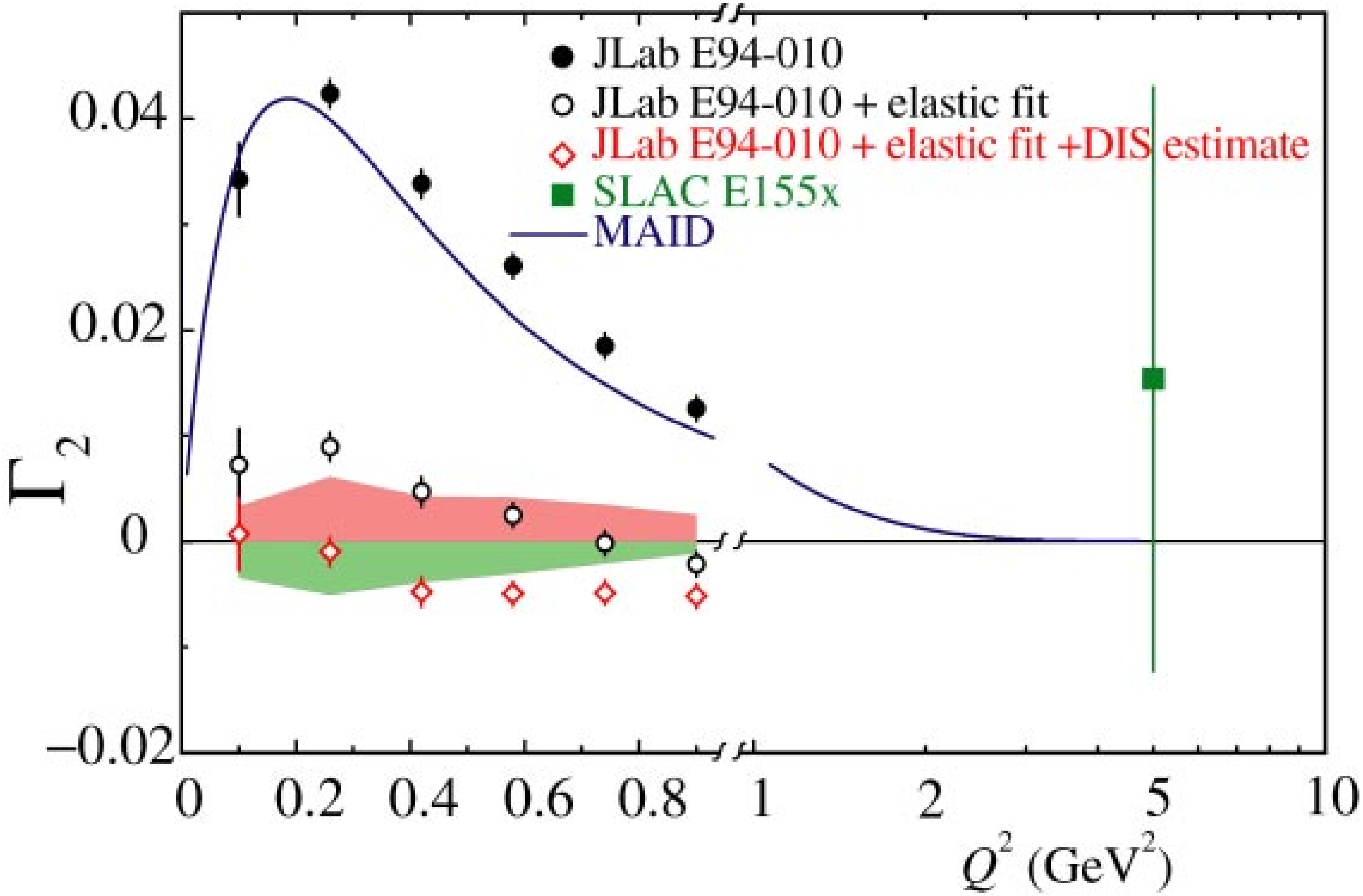


Burkhardt-Cottingham Sum Rule

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

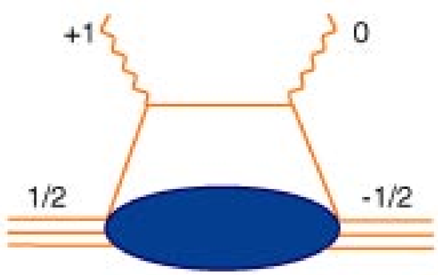
- Dispersion relation for a spin-flip Compton amplitude
  - Causality
  - Analyticity
  - Absence of a J=0 pole with non polynomial residue
- Doesn't follow from Operator Product Expansion and is valid at all Q^2 if valid at one Q^2
- Many scenarios of g_2's low x behavior which would invalidate the sum rule are discussed in the literature.

Γ_2 Results of Jlab E94-010

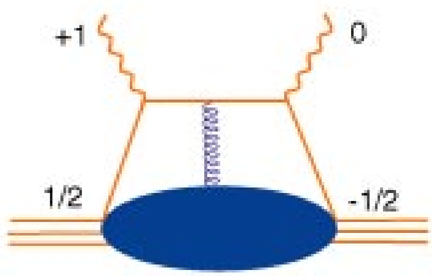


M. Amarian et al. Phys. Rev. Lett. 92, 022301 (2004)

Quark-Gluon Correlations and g_2



Carry one unit of orbital angular momentum



Couple to a gluon

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

- a twist-2 term (Wandzura & Wilczek, 1977):

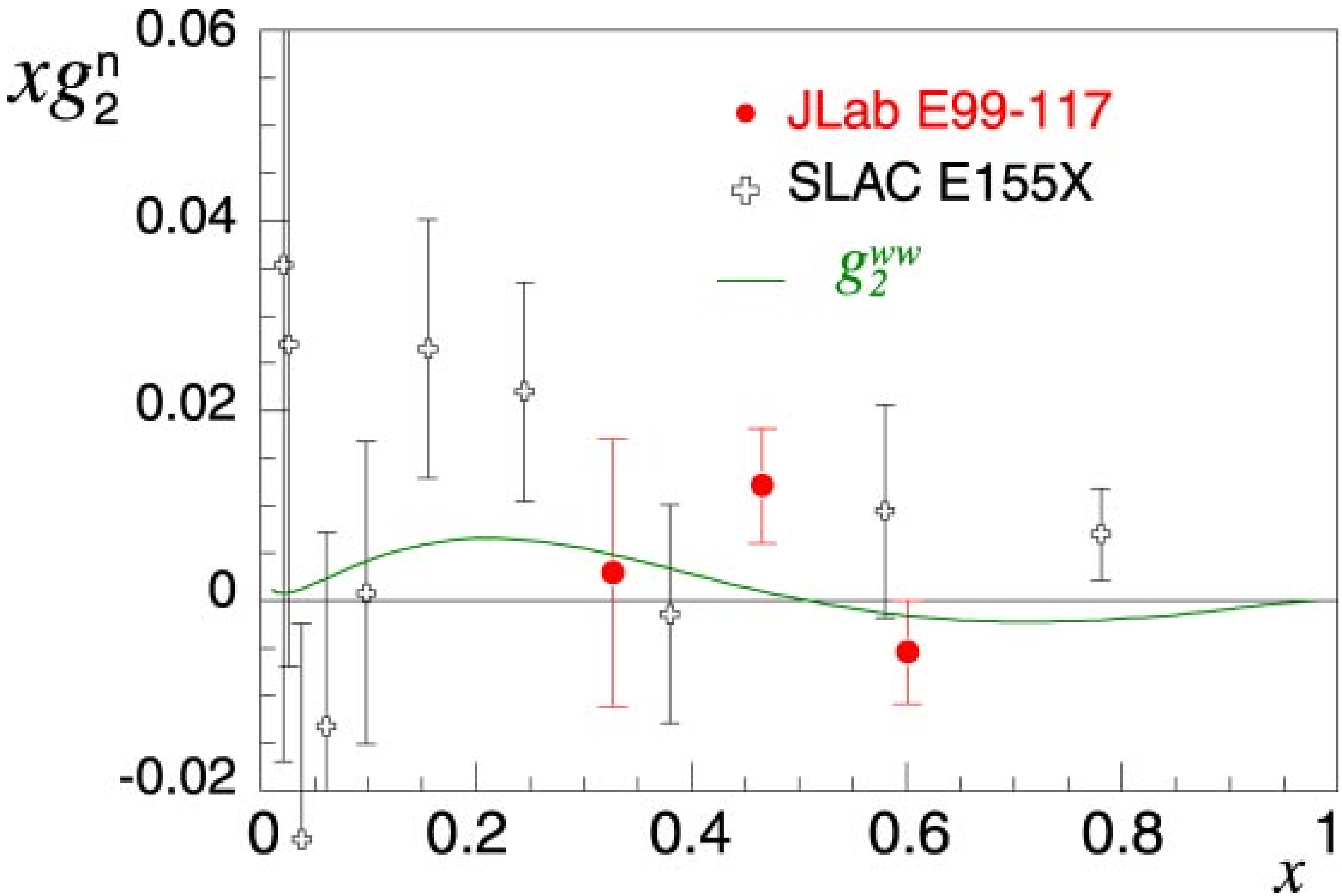
$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_0^1 g_1(y,Q^2)\frac{dy}{y}$$

- a twist-3 term with a suppressed twist-2 piece (Cortes, Pire & Ralston, 92):

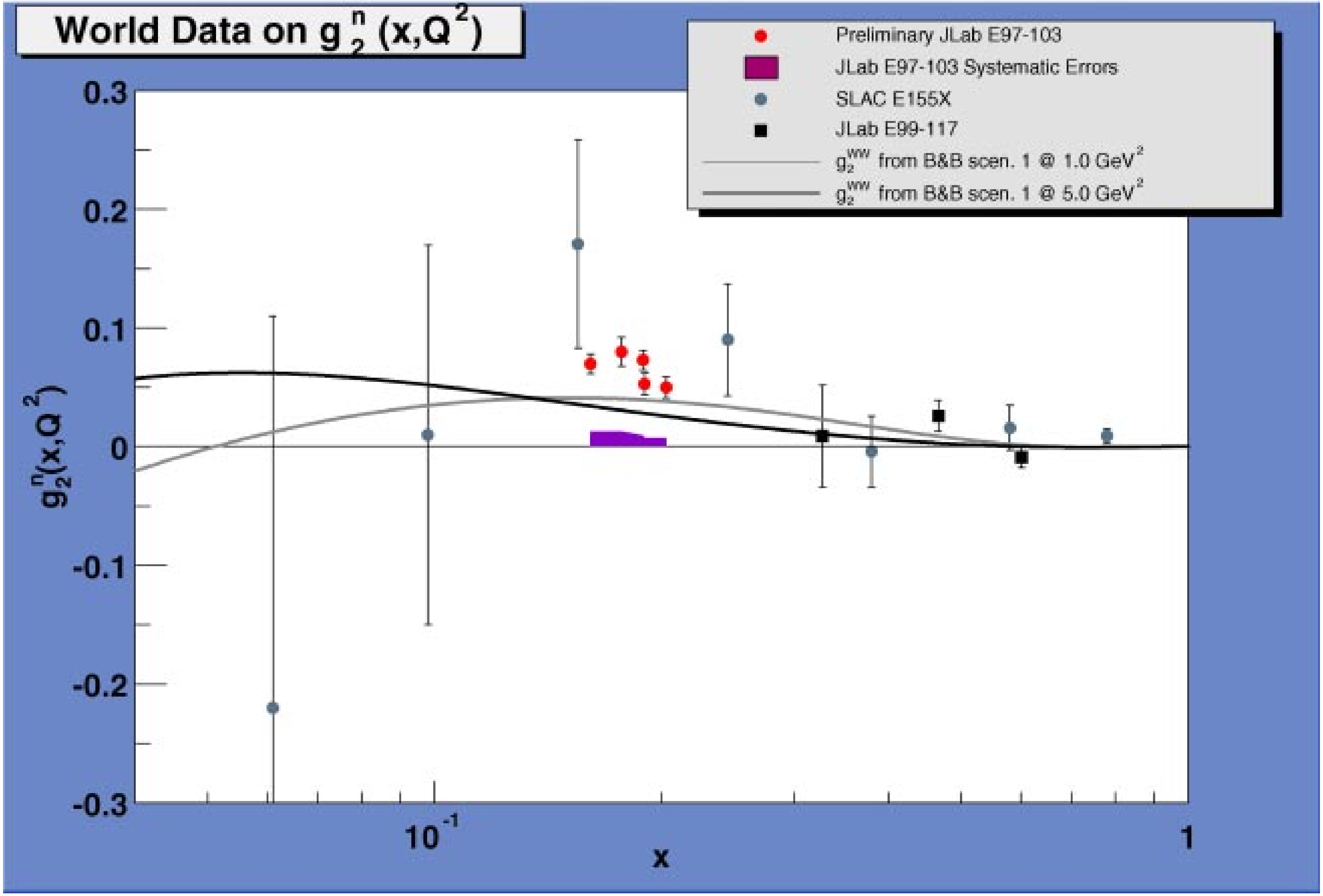
$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M}h_T(y,Q^2) + \xi(y,Q^2)\right)\frac{dy}{y}$$

transversity

quark-gluon correlation



0.06
0.04
0.02
0
-0.02
xg_2^n
JLab E99-117
SLAC E155X
g_2^{ww}
0
0.2
0.4
0.6
0.8
1
x


World Data on $g_2^n(x,Q^2)$
Preliminary JLab E97-103
JLab E97-103 Systematic Errors
SLAC E155X
JLab E99-117
g_2^{WW} from B&B scen. 1 @ 1.0 GeV^2
g_2^{WW} from B&B scen. 1 @ 5.0 GeV^2
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
$g_2^n(x,Q^2)$
10^{-1}
1
x

Moments of Structure Functions

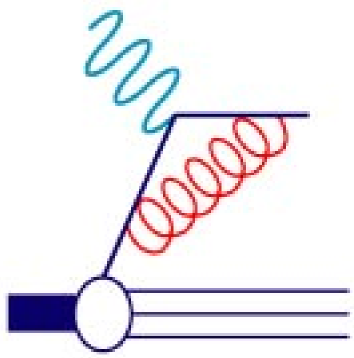
$$\Gamma_1(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \mu_2 + \frac{\mu_4}{Q^2} + \frac{\mu_6}{Q^4} + \cdots$$

leading twist (→ μ_2) higher twist

$$\mu_2^{p,n}(Q^2) = \left(\pm\frac{1}{12}g_A + \frac{1}{36}a_8\right) + \frac{1}{9}\Delta\Sigma \quad \text{+ pQCD corrections}$$

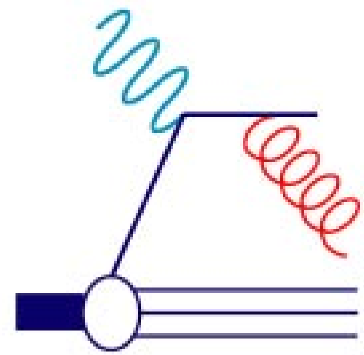
$g_A = 1.257$ and $a_8 = 0.579$ are the triplet and octet axial charge, respectively

$\Delta\Sigma$ = singlet axial charge



$$g_A = \Delta u - \Delta d$$
$$a_8 = \Delta u + \Delta d - 2\Delta s$$
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

pQCD radiative corrections



Study of Higher Twists (continued)

$$\mu_4(Q^2) = \frac{M^2}{9}\left[a_2(Q^2) + 4d_2(Q^2) + 4f_2(Q^2)\right]$$

Twist - 2 (TMC) Twist - 3 Twist -4

where a_2 d_2 and f_2 are higher moments of g_1 and g_2

e.g. $$d_2(Q^2) = \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx = \int_0^1 x^2\,\overline{g_2}(x,Q^2)dx$$

$$a_2(Q^2) = \int_0^1 x^2 g_1(x,Q^2)\,dx$$

- To extract f_2, d_2 needs to be determined first.
- Both d_2 and f_2 are required to determine the color polarizabilities

Color "polarizabilities"

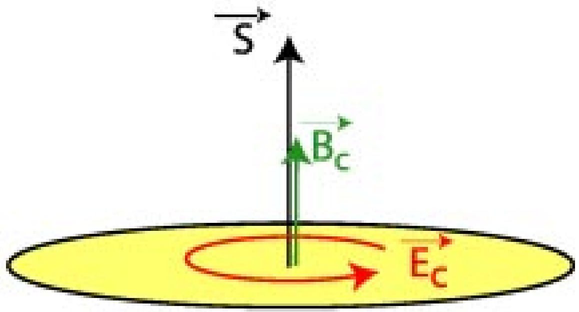
How does the gluon field respond when a nucleon is polarized ?

Define color magnetic and electric polarizabilities (in nucleon rest frame):

$$\chi_{B,E} 2M^2\vec{S} = \langle PS|\vec{O}_{B,E}|PS\rangle$$

where $\vec{O}_B = \psi^\dagger g\vec{\boldsymbol{B}}\psi$

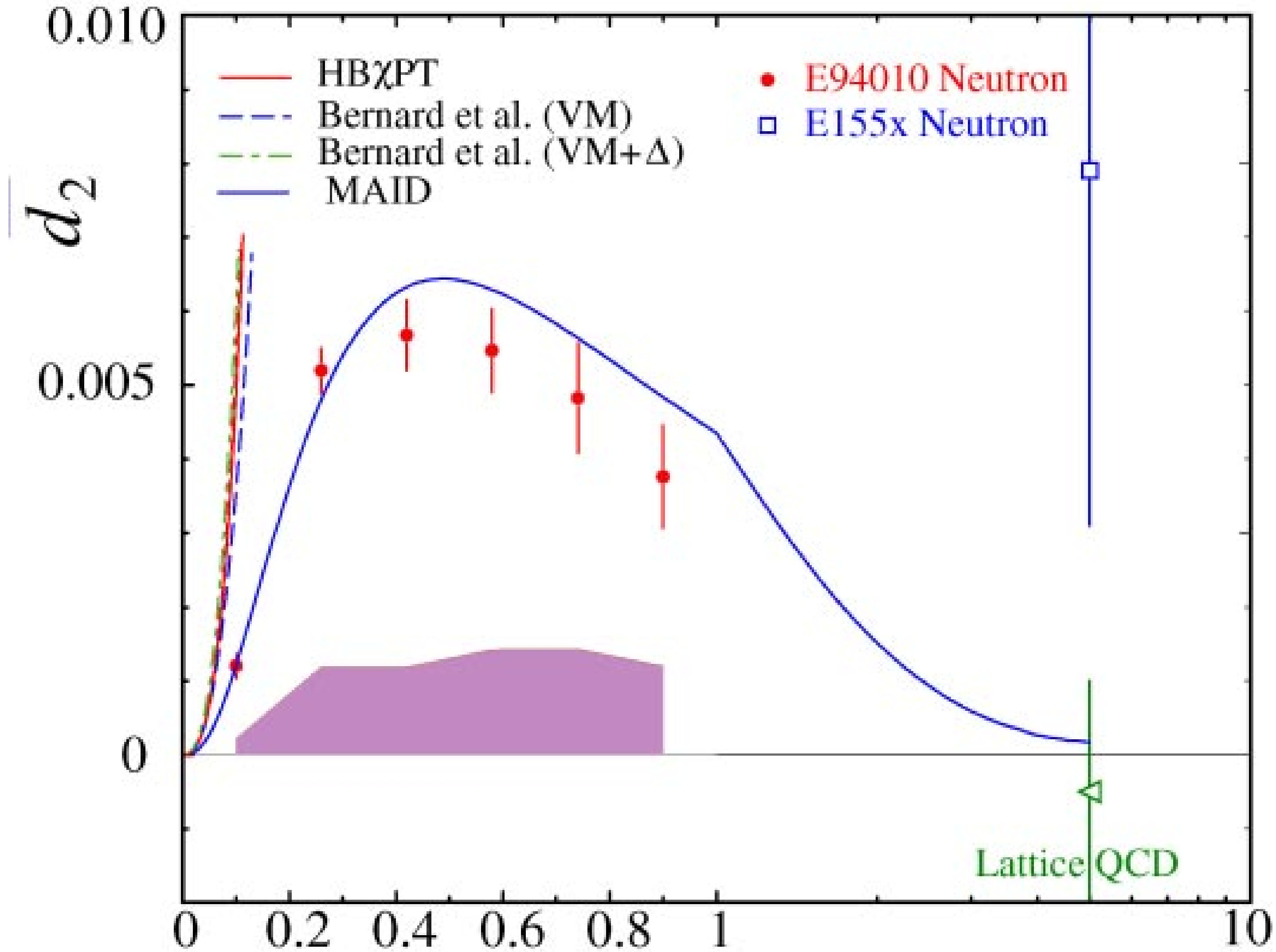
$$\vec{O}_E = \psi^\dagger\vec{\alpha}\times g\vec{\boldsymbol{E}}\psi$$



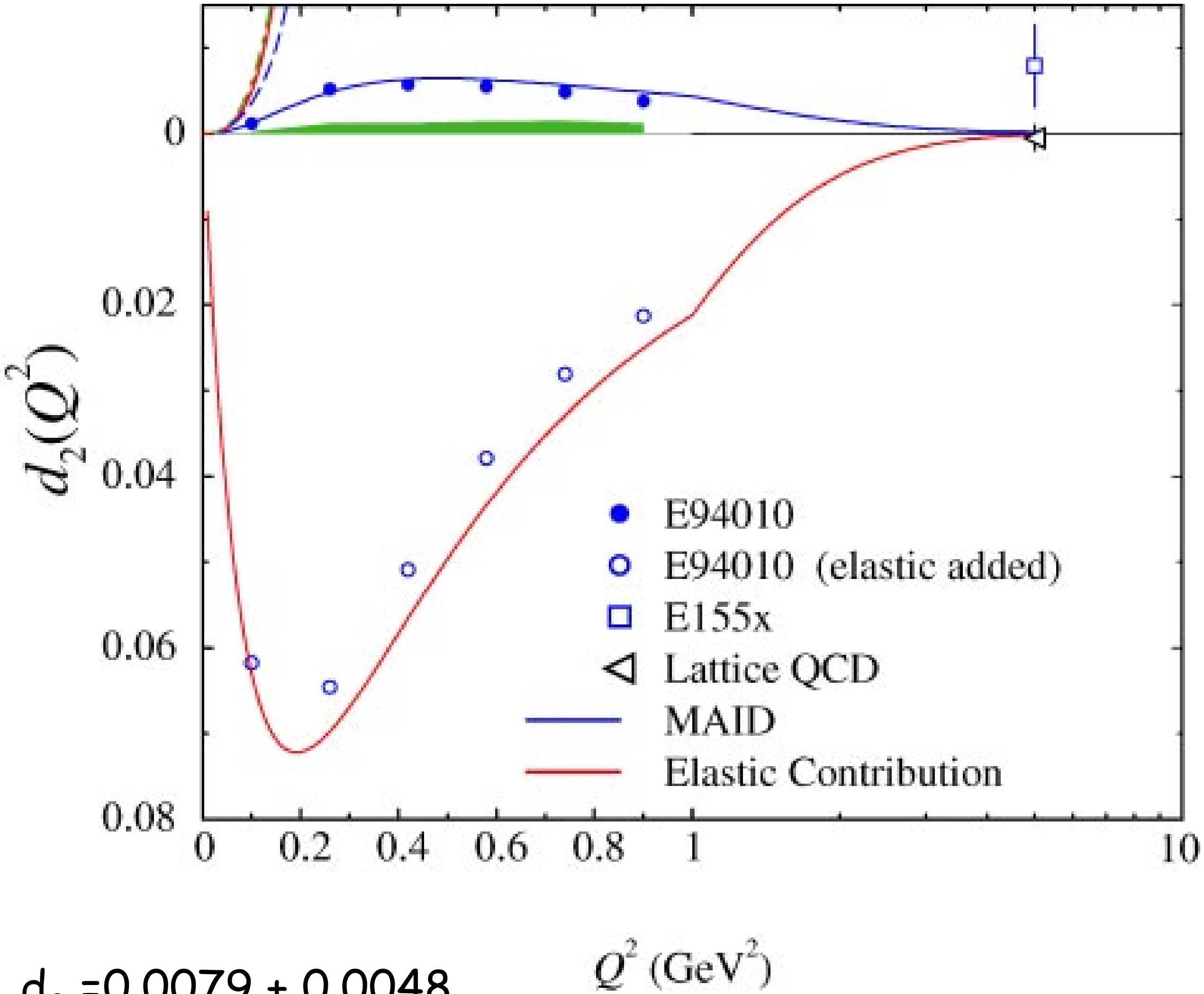
$$\chi_E^n = (4d_2^n + 2f_2^n)/3$$
$$\chi_B^n = (4d_2^n - f_2^n)/3$$

χ_E and χ_B represent the response of the color $\vec{B}$ & $\vec{E}$ fields to the nucleon polarization

d_2 results of Jlab E94-010



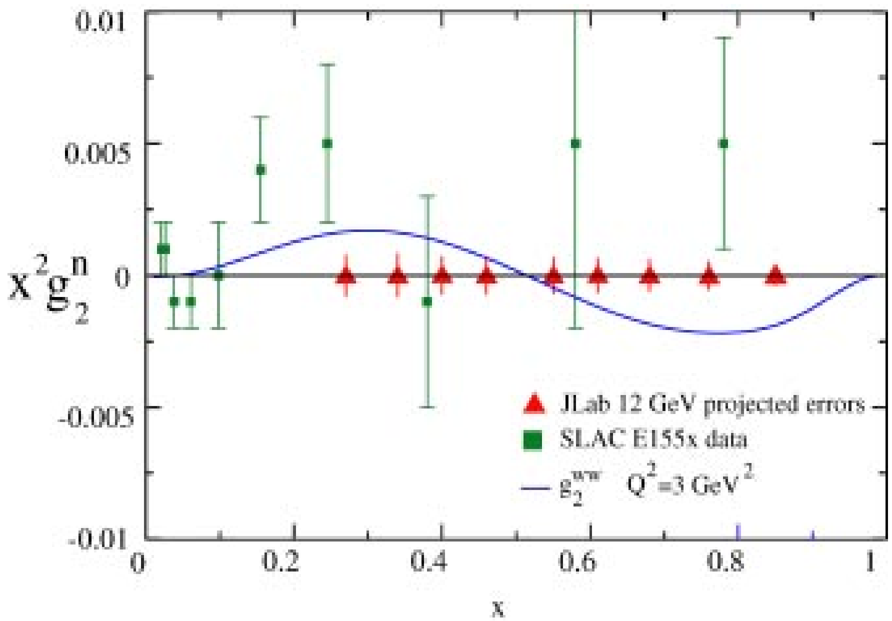
Adding the elastic contribution

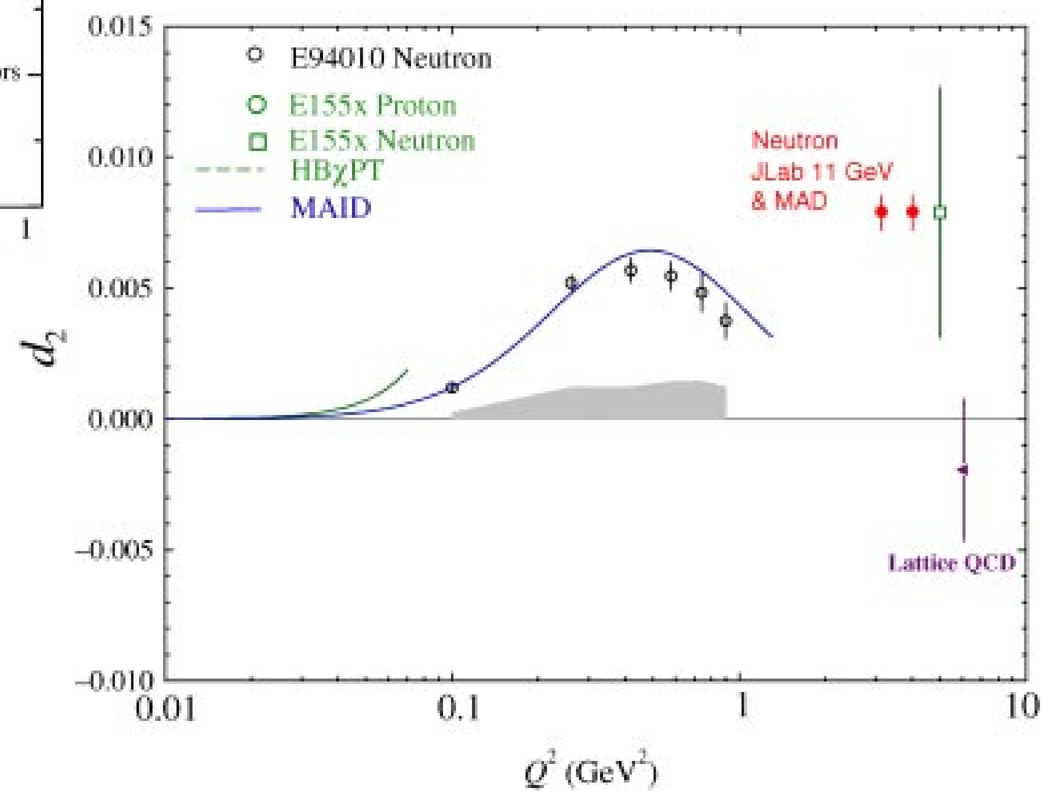


E155x: d_2 =0.0079 ± 0.0048

Updated value using E99-117: d_2=0.0062 ± 0.0028

g_2 and d_2 with 11 GeV at JLab

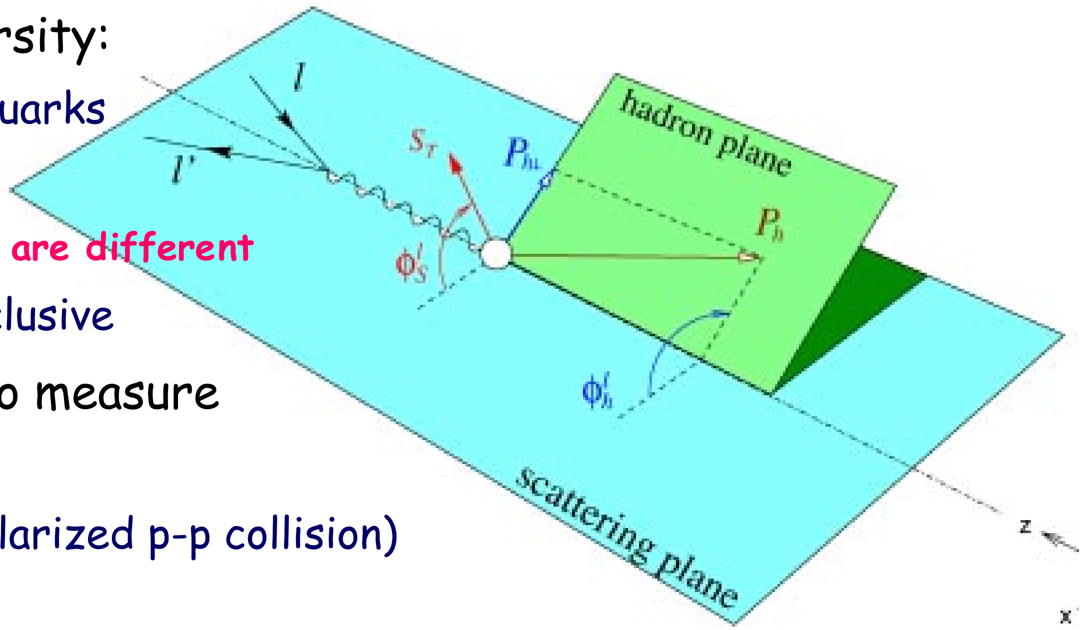




Semi-Inclusive/Transversity

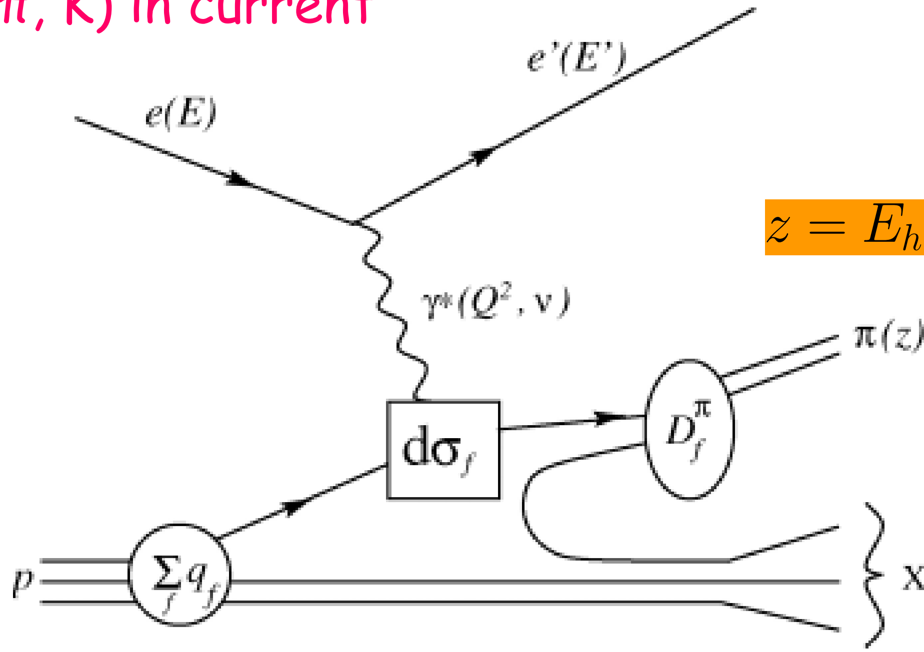
See N. Makins

- Three twist-2 quark distributions:
  - Density distribution: $q(x,Q^2)= q^{\uparrow}(x) + q^{\downarrow}(x)$
  - Helicity distribution: $\Delta q(x,Q^2)= q^{\uparrow}(x) - q^{\downarrow}(x)$
  - Transversity distribution: $\delta q(x,Q^2)= q^{\perp}(x) + q_{\perp}(x)$
- Some characteristics of transversity:
  - $\delta q(x) = \Delta q(x)$ for non relativistic quarks
  - δq and gluons do not mix
    - **--> Q2 evolution for δq and Δq are different**
  - Chiral-odd--> not accessible in inclusive
- It takes two chiral-odd objects to measure transversity
  - Drell-Yan (doubly transversely polarized p-p collision)
  - Semi-inclusive DIS
    - Chiral-odd distribution function (**transversity**)
    - Chiral-Odd fragmentation function (**Collins function**)



Semi-inclusive DIS

- Spin-flavor decomposition of valence and sea quarks by tagging hadron (e.g. π, K) in current fragmentation region



$z = E_h/\nu$

$$d\sigma = \sum_f e_f^2 \; q_f(x) \; D_f^h(z)$$

(z) quark-D> hadron

fragmentation function

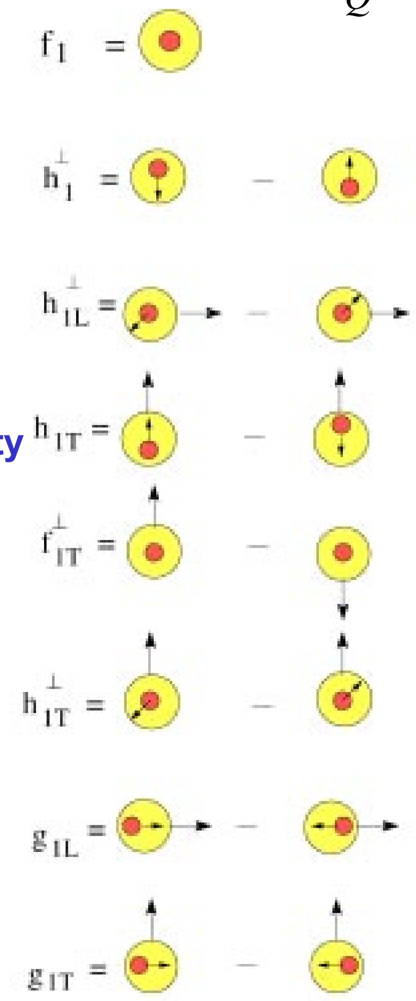
- unpolarized or polarized beam and target
- mass of unobserved X system, W_X > 2 GeV

All Eight Quark Distributions Are Probed in Semi-Inclusive DIS

$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4} \times$$

Transversity

Sivers



$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z, P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

Unpolarized

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z, P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

Polarized target

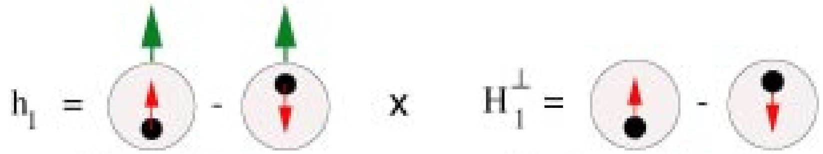
$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z, P_{h\perp}^2)$$

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z, P_{h\perp}^2)\}$$

Polarized beam and target

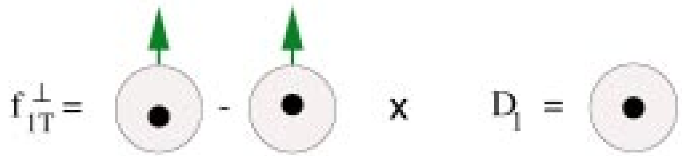
S_L and S_T: Target Polarizations; λ_e: Beam Polarization

- Transversity "Collins effect": Finding in a polarized target nucleon a transverse-polarized quark, which fragments with a transverse momentum correlated with that quark polarization



chiral-odd, T-even chiral-odd, T-odd

- "Sivers effect": Finding in a transverse-polarized target nucleon a quark with correlated primordial transverse momentum



chiral-even, T-odd chiral-even, T-even

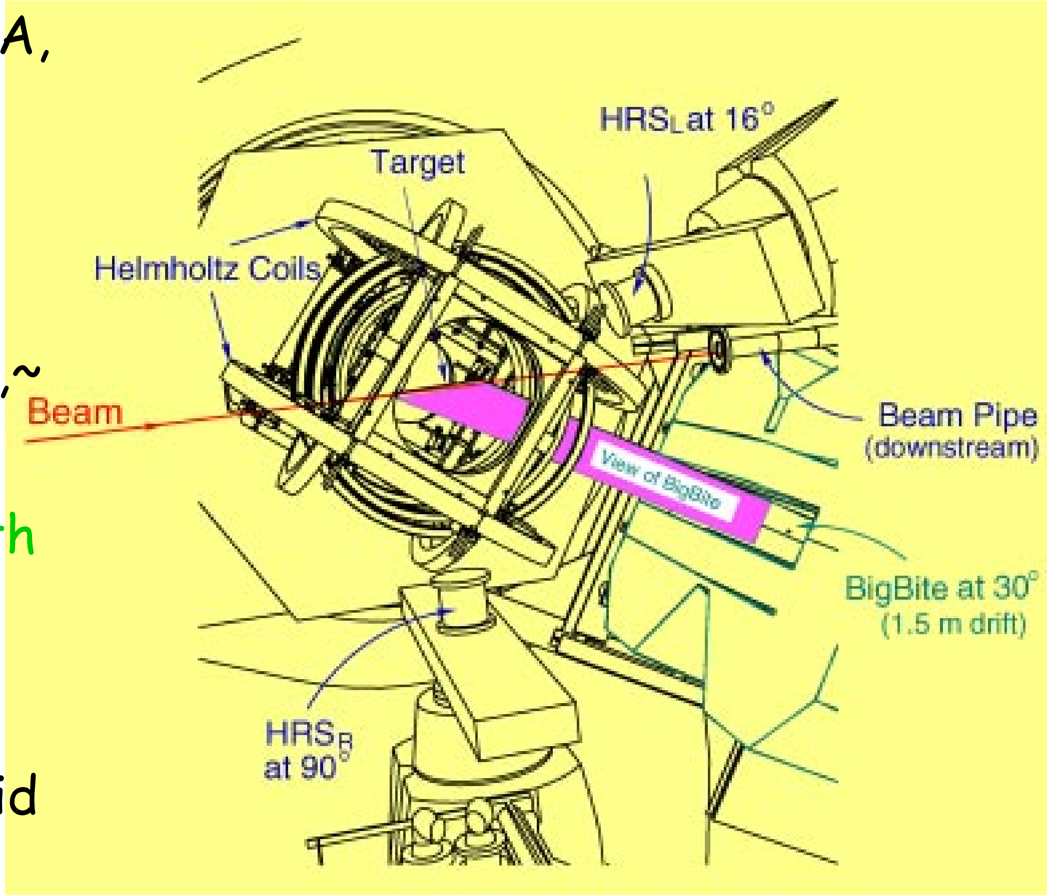
- (Boer & Mulders) Finding in an unpolarized target nucleon a quark with correlated transverse polarization and primordial transverse momentum

chiral-odd, T-odd x chiral-odd, T-odd

Jlab Hall A E03-004 / $^3He^{\uparrow}$ (e,e'π^-)X

Spokespeople: J.-P Chen, X. Jiang & J.-C. Peng

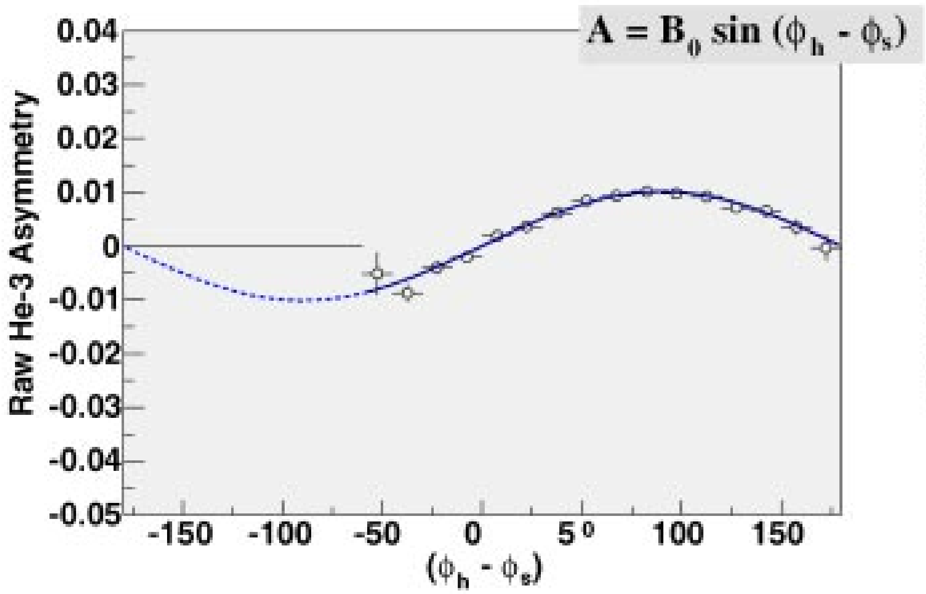
- Beam
  - Polarized (P~80%) e-, 15 μA, helicity flip at 60Hz
- Target
  - Optically pumped Rb+spin exchange ^{3}He, 50 mg/cm2,~ 40% polarization
  - Transversely polarized with tunable direction
- Electron detection
  - Bigbite spectrometer, Solid angle 60 msr, θ=30°
- Charged pion detection
  - HRS spectrometer, θ=16°



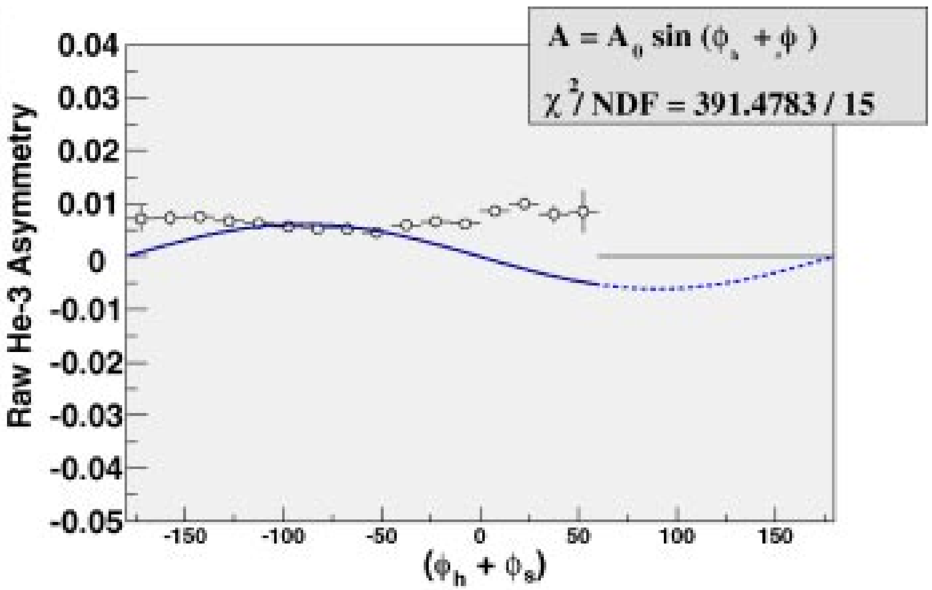
Disentangling Collins and Sivers Effects

Monte Carlo assuming 1.0% asymmetry due to Sivers effect

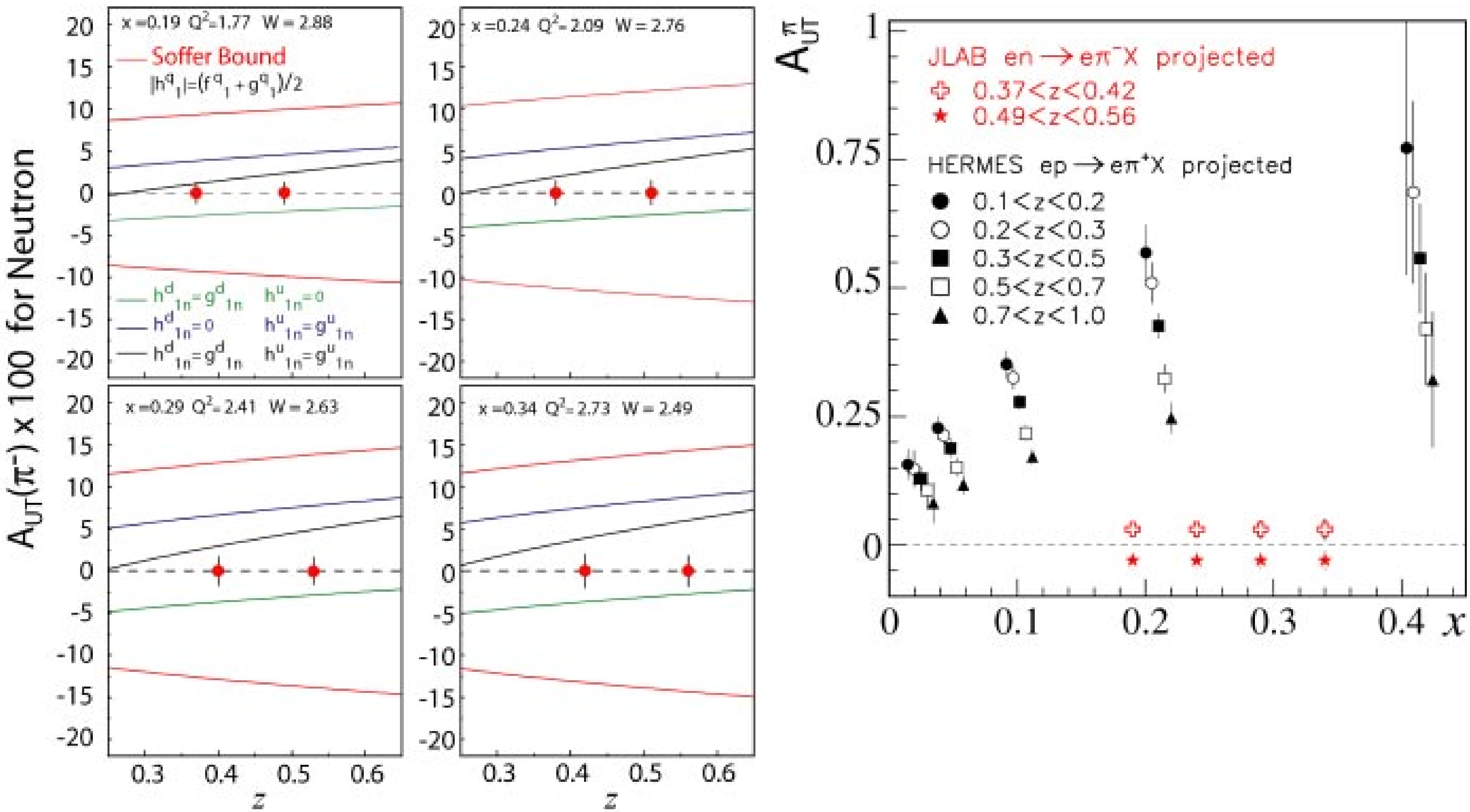
Asymmetry versus Sivers angle



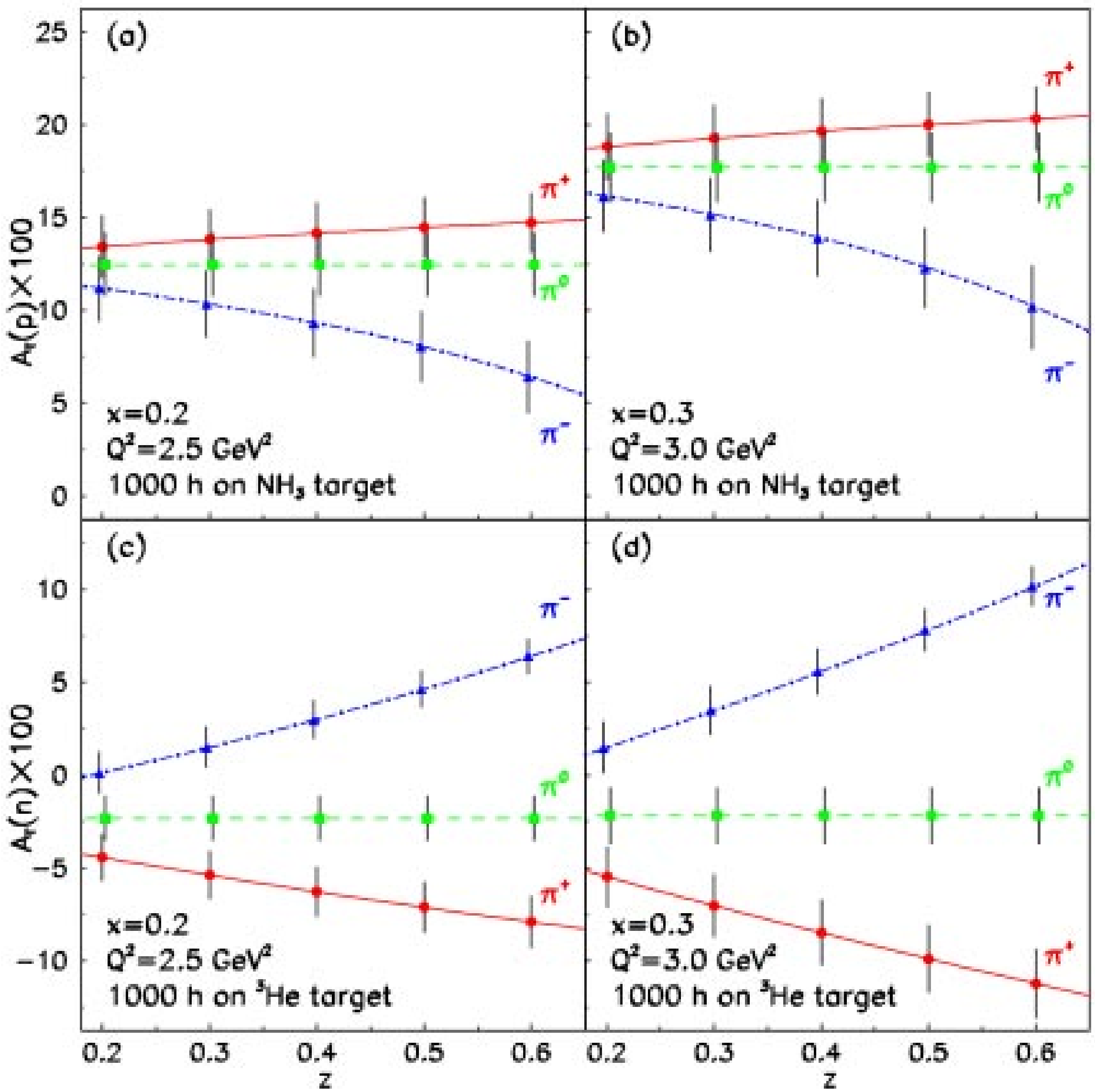
Asymmetry versus Collins Angle



Expected result from JLab at 6 GeV



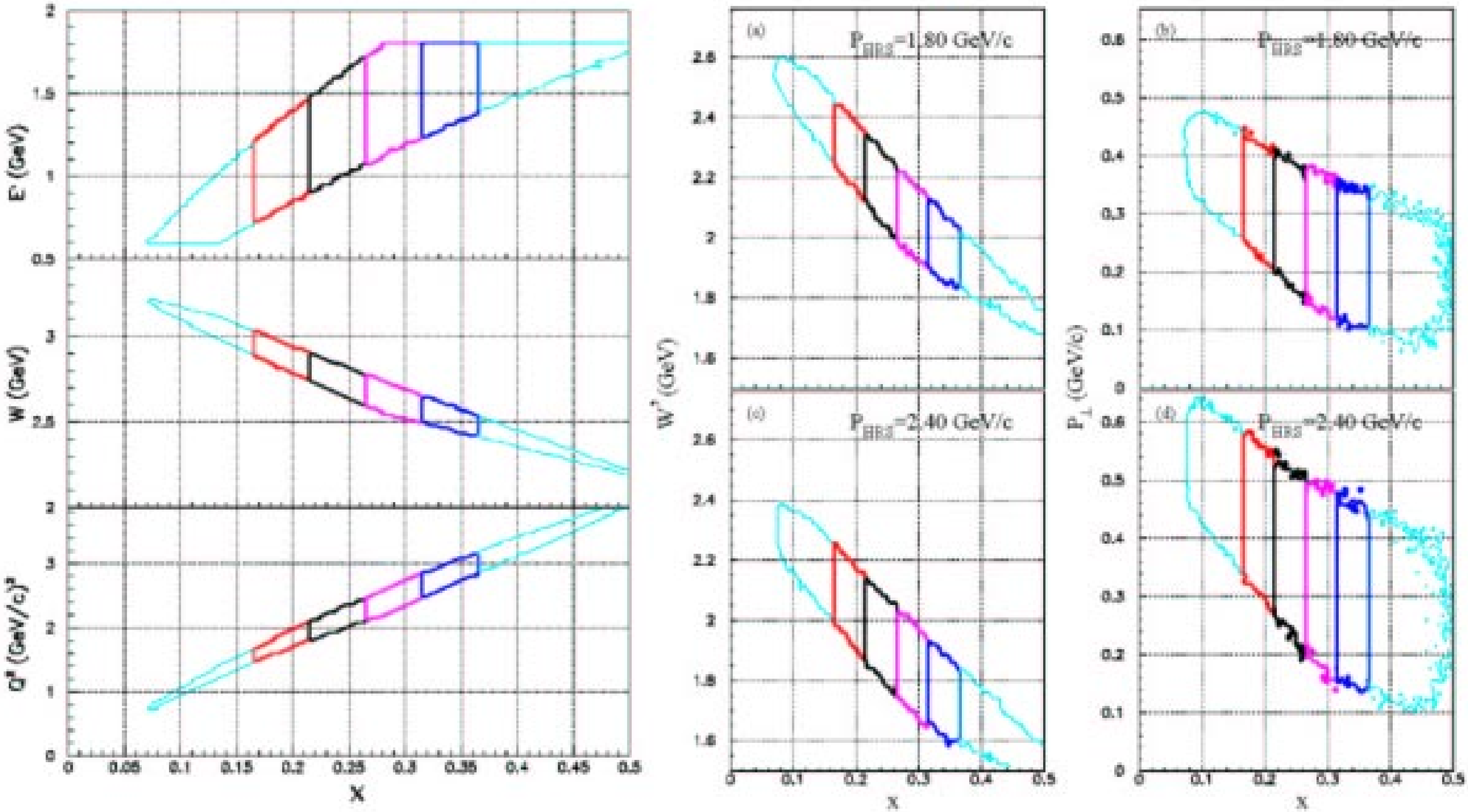
Jlab 12 GeV projections



Summary

- Neutron A_1 crosses zero around x ~ 0.4 and becomes positive at large x.
- $\Delta d/d$ is negative up to x= 0.6 consistent with RCQM models but not with hadron helicity conservation assumption.
- The Burkhardt-Cottingham sum rule seems verified within errors for $Q^2 < 1$ GeV^2 .
- Neutron d_2 is small but finite in the resonance region. Precision measurements of g_2 in the range $1 < Q^2 < 4$ GeV^2 are required for an accurate extraction of color polarizabilities.
- 11 GeV at JLab will allow to extend the investigation of the nucleon spin structure in the large x region through inclusive and semi-inclusive reactions, this includes transversity and other transverse momentum distributions.

Kinematic Acceptance



Hall-A : x: 0.19 - 0.34, Q^2: 1.8 - 2.7 GeV^2, W: 2.5 - 2.9 GeV, z: 0.37 - 0.56

HERMES: $\langle Q^2 \rangle = 2.5\ GeV^2$