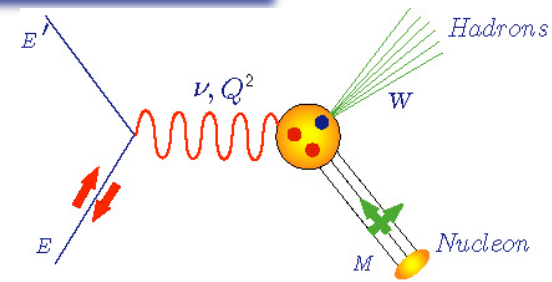
Progress in High-p_T Physics at RHIC
RIKEN BNL Research Center Workshop
March 17-19, 2010 at Brookhaven National Laboratory

Nucleon Spin Structure Studies at JLab

Zein-Eddine Meziani
Temple University

- Longitudinal nucleon spin structure at large x
- Quark-gluon correlations and the color Lorentz force

Spin Structure Functions



- Unpolarized structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$

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 $g_2(x,Q^2)$

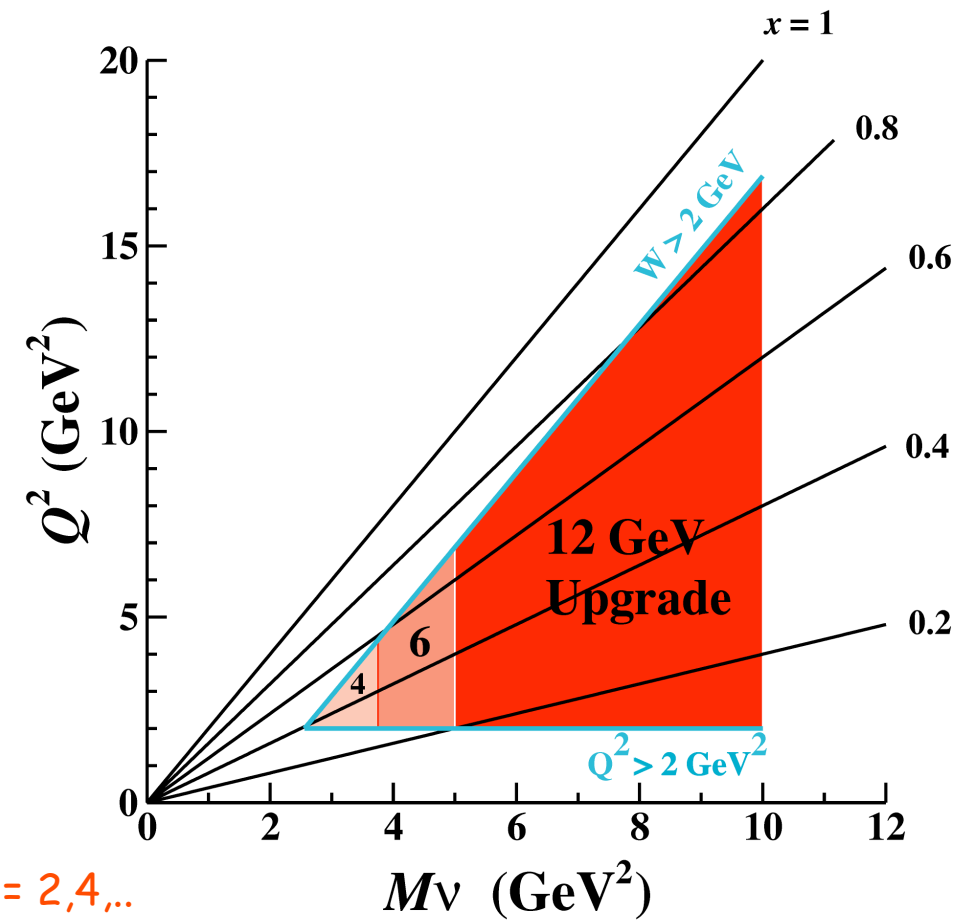
Q^2 :Four-momentum transfer
x : Bjorken variable
ν : Energy transfer
M : Nucleon mass
W : Final state hadrons mass

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 $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2Eg_2(x,Q^2)\right]$$

Nucleon structure in the valence region

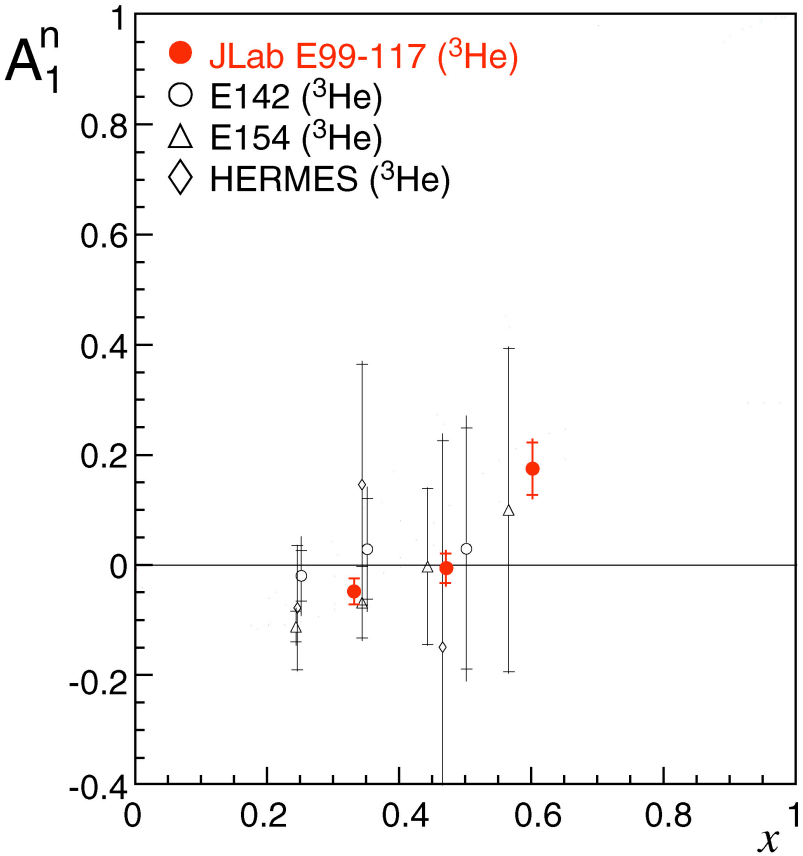
- Access to very large x (x > 0.4)
  - Clean region
    - No strange sea effects
    - No explicit hard gluons to be included
- Quark models can be a powerful tool to investigate the structure of the nucleon
- Comparison with lattice QCD is possible for higher moments of structure functions.

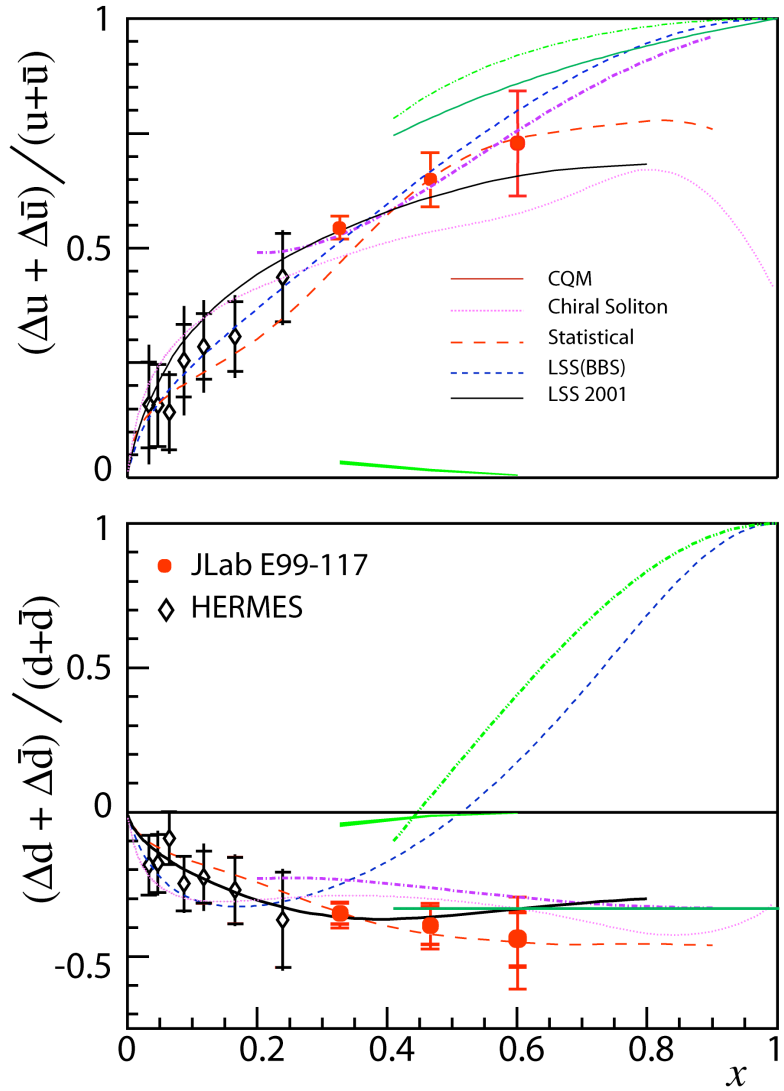


$$M_n(Q^2) = \int_0^1 dx\, x^{n-2}\, F_2(x, Q^2) \qquad n = 2,4,..$$

$$M_n(Q^2) = \int_0^1 dx\, x^{n-1}\, g_1(x, Q^2), \qquad n = 1, 3, 5...$$

A_1^n and Helicity-Flavor Decomposition



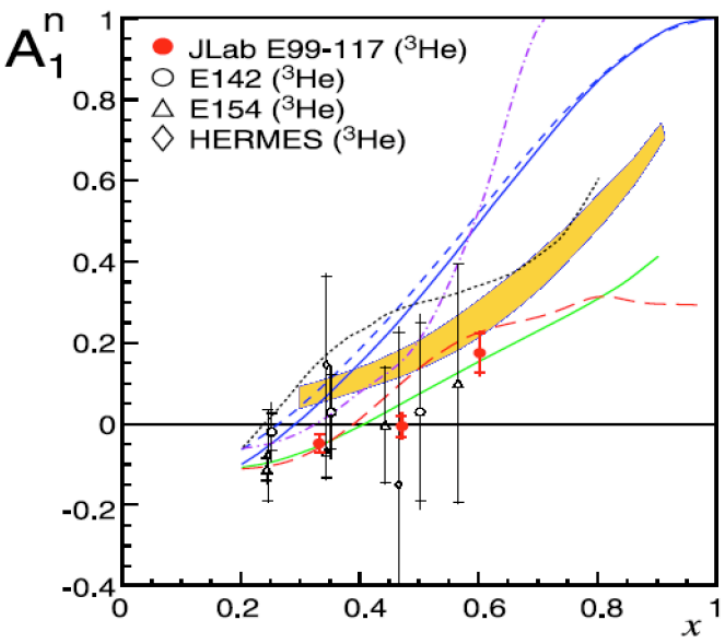


HiX 2004 Workshop, Marseille, France

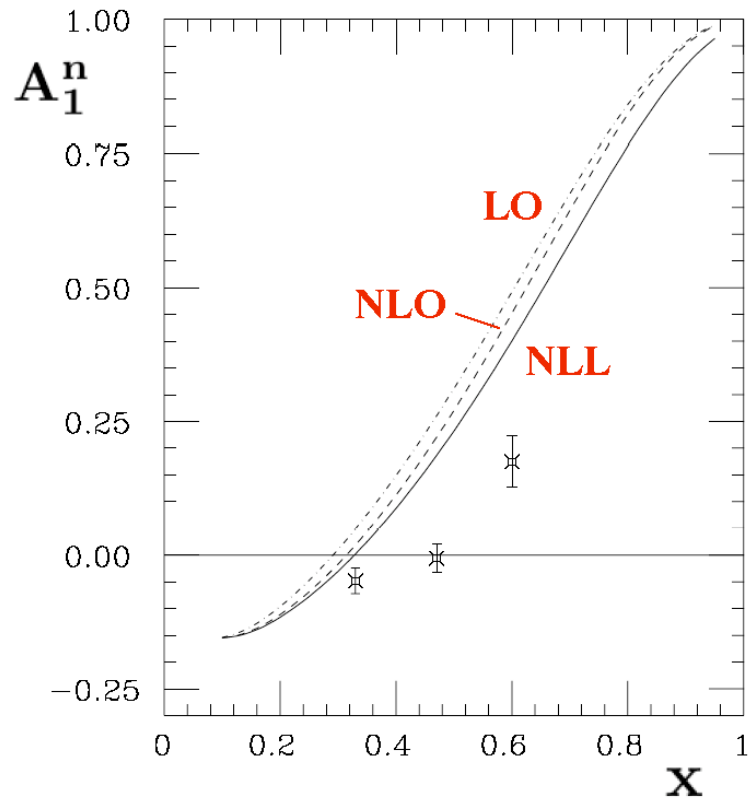
W. Vogelsang

Another toy example : spin asymmetry A_1^n

Resummation effects cancel exactly in Mellin space, and "almost" in x-space :

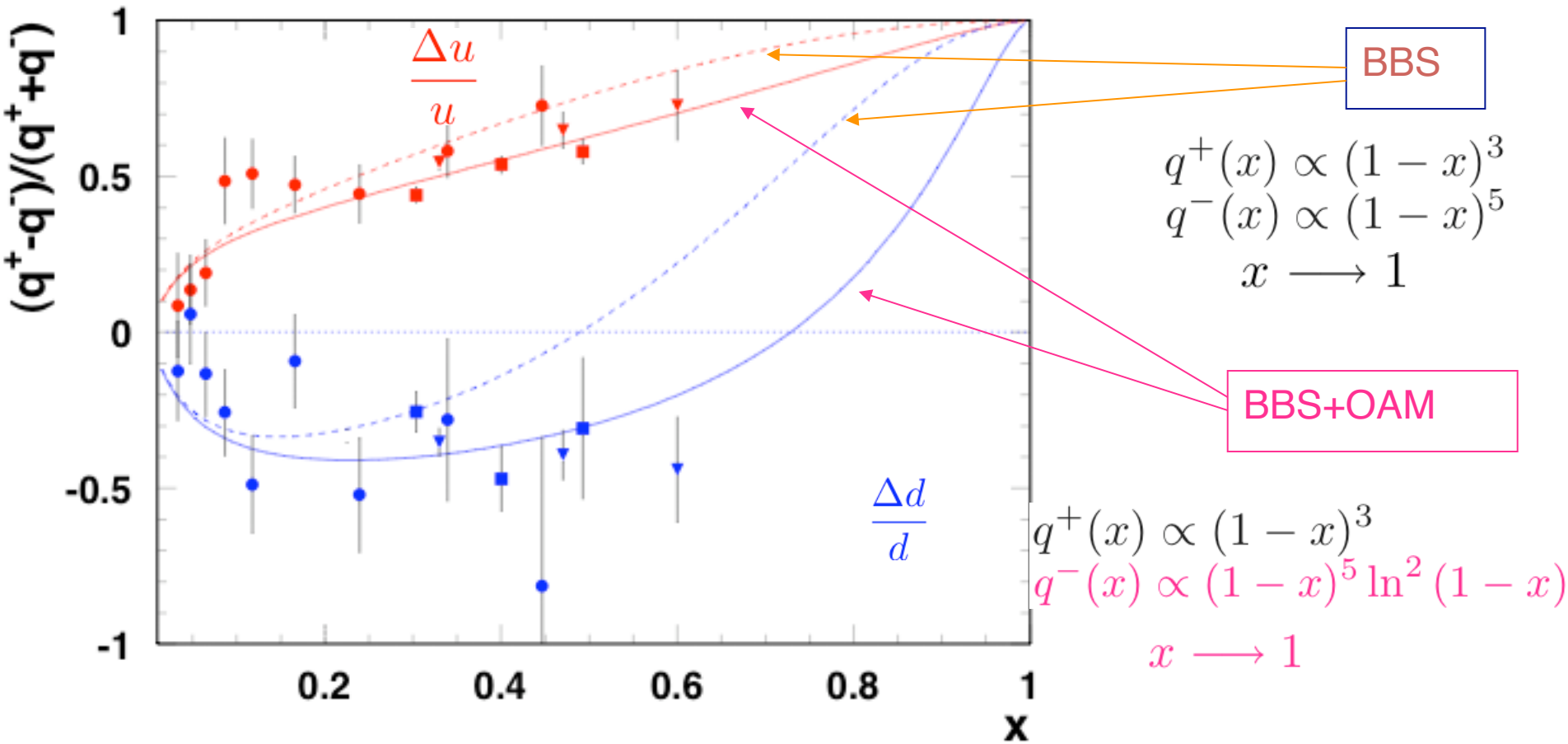


JLab Hall A (E99-117)



Effect of quark orbital angular momentum

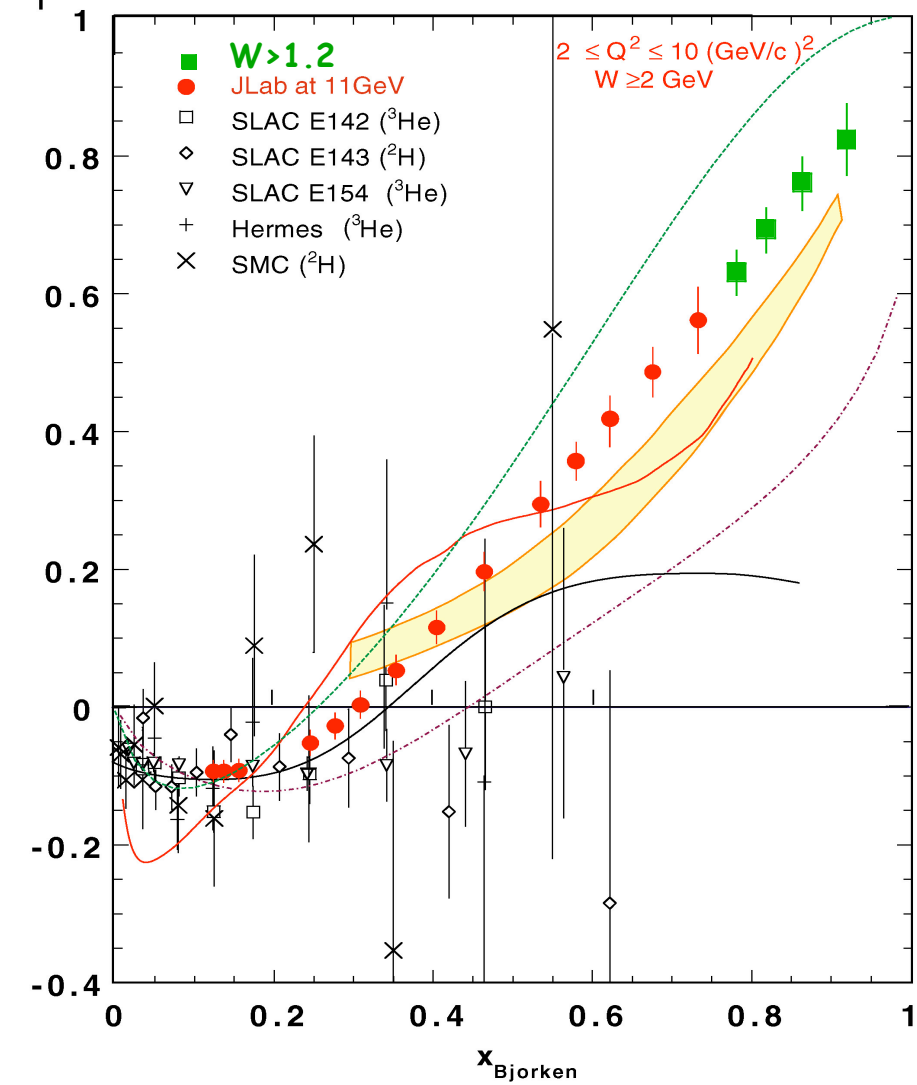
Inclusive DIS Hall A and B and Semi-Inclusive DIS Hermes



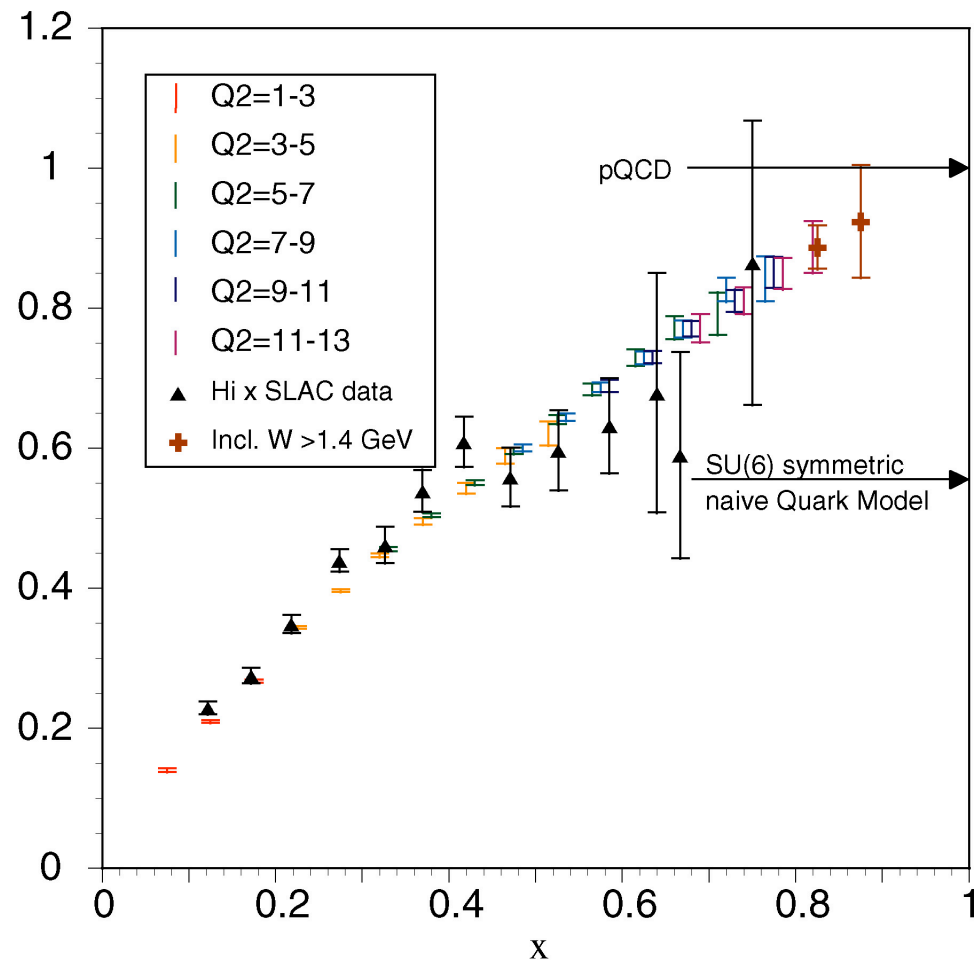
Avakian, Brodsky, Deur and Yuan

Inclusive measurements of asymmetries

A_1^n at 11 GeV

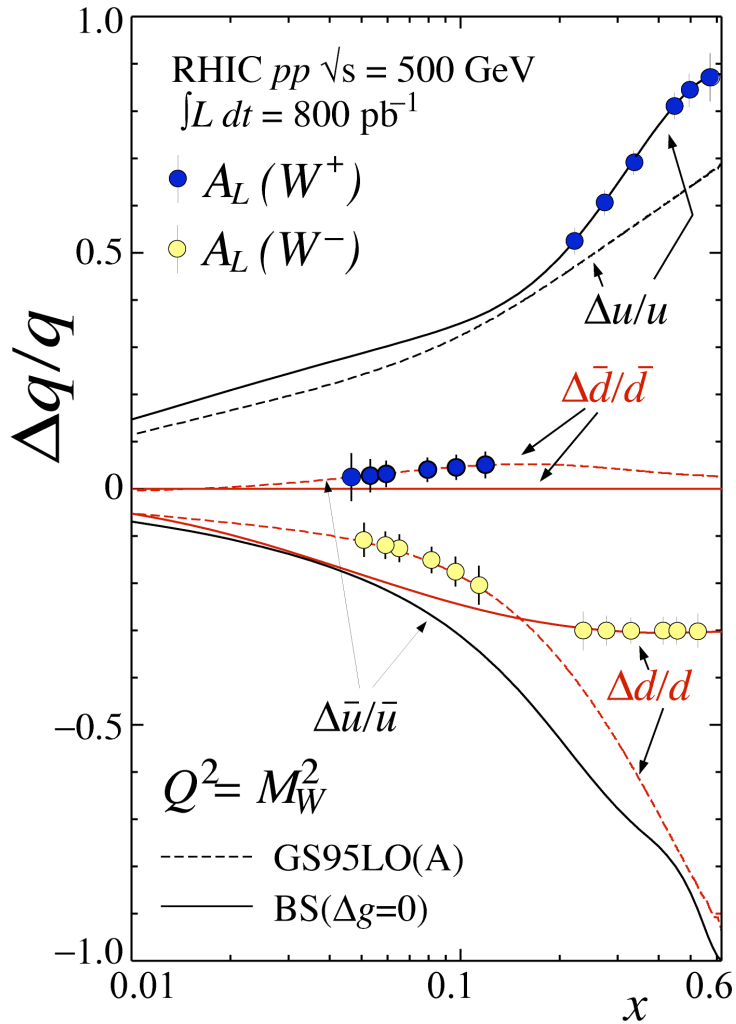


A_1^p at 11 GeV

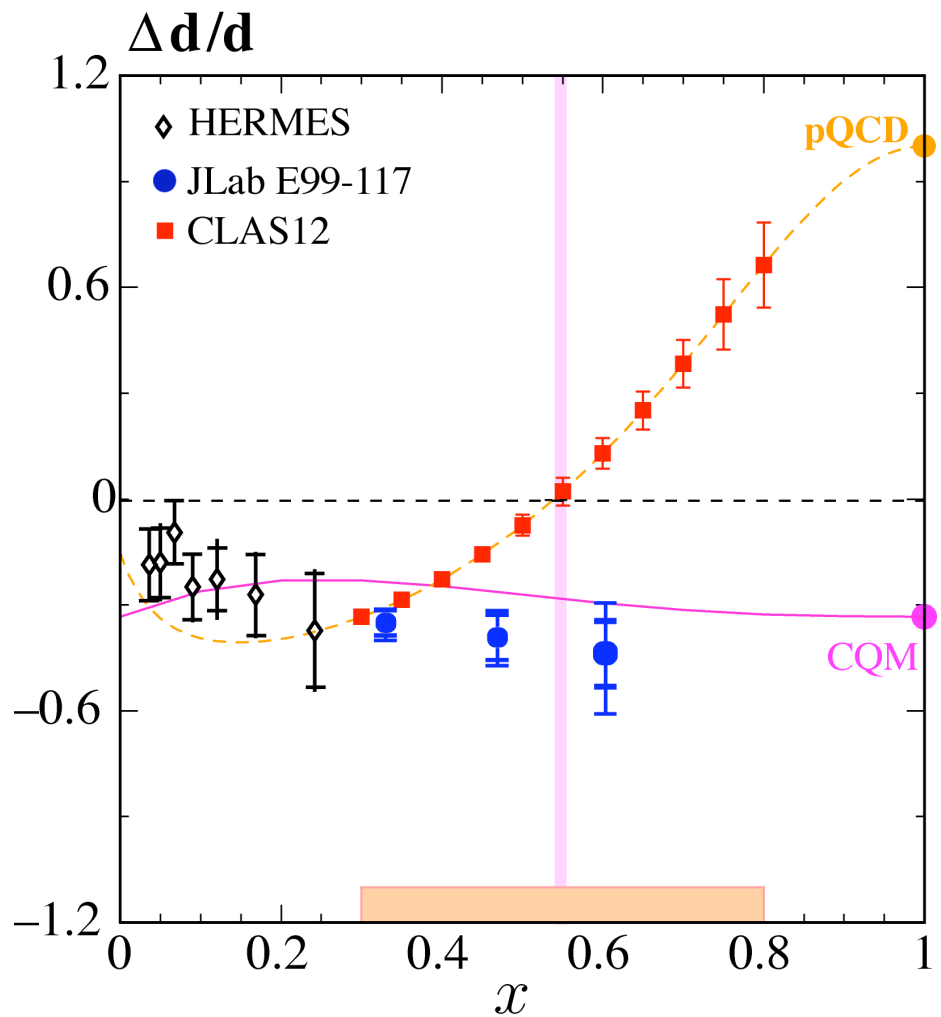


Flavor decomposition

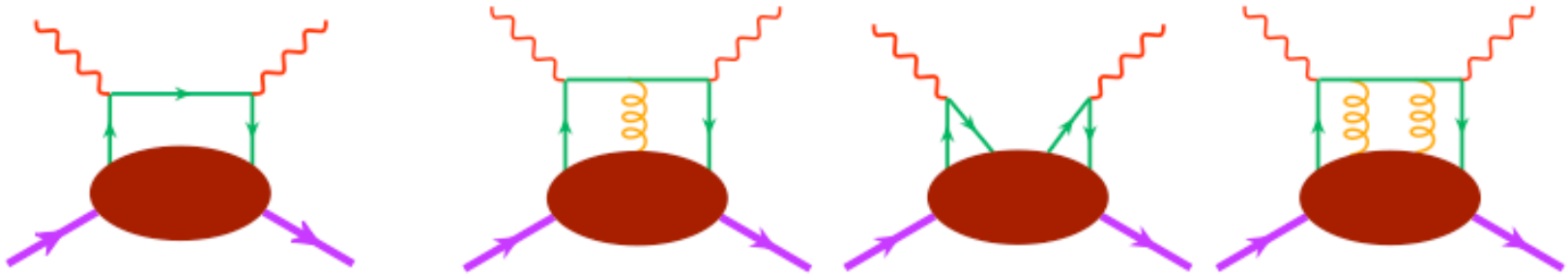
At RHIC with W production



At JLab 12 GeV with SIDIS



Moments of Structure Functions



$\tau = 2$

single quark scattering

$\tau > 2$

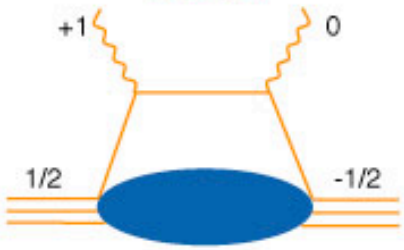
qq and qg correlations

$$\Gamma_1(Q^2) \equiv \int_0^1 \mathrm{d}x\, g_1(x, Q^2)$$

$$= \Gamma_1^{\text{twist}-2}(Q^2) + \frac{M_N^2}{9\,Q^2}\left[a_2(Q^2) + 4\,d_2(Q^2) + 4\,f_2(Q^2)\right] + \mathcal{O}\left(\frac{M_N^4}{Q^4}\right)$$

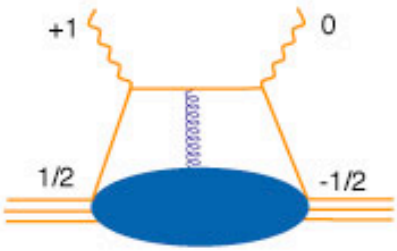
Quark-Gluon Correlations and g_2

twist-2



Carry one unit of orbital angular momentum

twist-3



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):

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

- 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

Moments of Structure Functions (continued)

➡ $a_2(Q^2) \equiv 2\int_0^1 \mathrm{d}x\, x^2\, g_1^{\mathrm{twist}-2}(x,Q^2)$ ⟶ target mass correction term

➡ $d_2(Q^2)$ ⟶ dynamical twist-3 matrix element

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

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

$$d_2 S^{[\mu}P^{\{\nu]}P^{\lambda\}} = \frac{1}{8}\sum_q < P,S|\bar{\psi}_a g\tilde{G}^{\{\mu\nu}\gamma^{\lambda\}}\psi_a|P,S >$$

➡ $f_2(Q^2)$ ⟶ dynamical twist-4 matrix element

$$f_2 M^2 S^\mu = \frac{1}{2}\sum_q e_q^2 < N|\bar{\psi}_q g\widetilde{F}^{\mu\nu}\gamma_\nu\psi_q|N >$$

"Color Polarizabilities"

X.Ji 95, E. Stein et al. 95

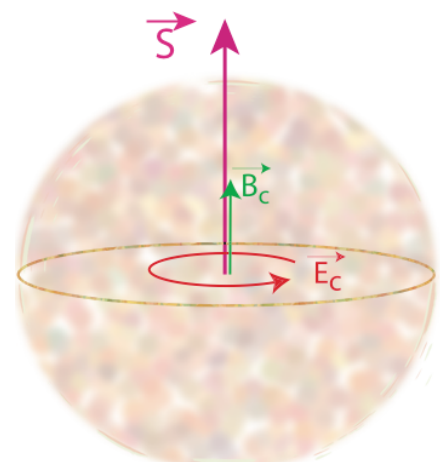
How does the gluon field respond when a nucleon is polarized ?

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

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



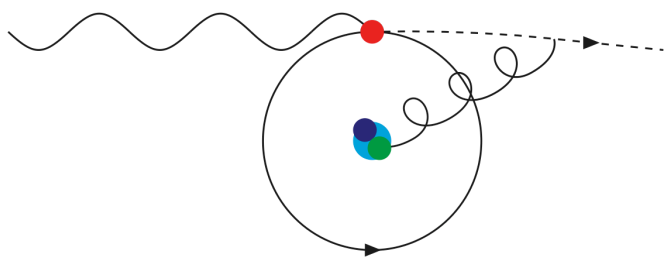
$$d_2 = (\chi_E + 2\chi_B)/8$$

$$f_2 = (\chi_E - \chi_B)/2$$

d_2 and f_2 represent the response of the color $\vec{B}$ & $\vec{E}$ fields to the nucleon polarization

Average Color Lorentz Force (M. Burkardt)

$$\int dx x^2 \bar{g}_2(x) = \frac{1}{3} d_2 = \frac{1}{6MP^{+2}S^x} \langle P, S | \bar{q}(0) g G^{+y}(0) \gamma^+ q(0) | P, S \rangle$$



↪ d_2 a measure for the **color Lorentz force** acting on the struck quark in SIDIS in the instant **after being hit by the virtual photon**

$$\langle F^y(0) \rangle = -M^2 d_2 \qquad \text{(rest frame; } S^x = 1\text{)}$$

- Interpretation of d_2 with the transverse FSI force in DIS also consistent with $\langle k_\perp^y \rangle \equiv \int_0^1 dx \int \mathrm{d}^2 k_\perp \, k_\perp^2 f_{1T}^\perp(x, k_\perp^2)$ in SIDIS (Qiu, Sterman)

$$\langle k_\perp^y \rangle = -\frac{1}{2p^+} \left\langle P, S \left| \bar{q}(0) \int_0^\infty dx^- g G^{+y}(x^-) \gamma^+ q(0) \right| P, S \right\rangle$$

semi-classical interpretation: average $k_\perp$ in SIDIS obtained by correlating the quark density with the transverse impulse acquired from (color) Lorentz force acting on struck quark along its trajectory to (light-cone) infinity

Hall A d_2^n and Hall C SANE experiments

Neutron

Spokespeople:
B. Sawatzky, S. Choi, X. Jiang and Z.-E.M

Students:
David Flay, Diana Parno, Matthew Posik

and the Hall A collaboration

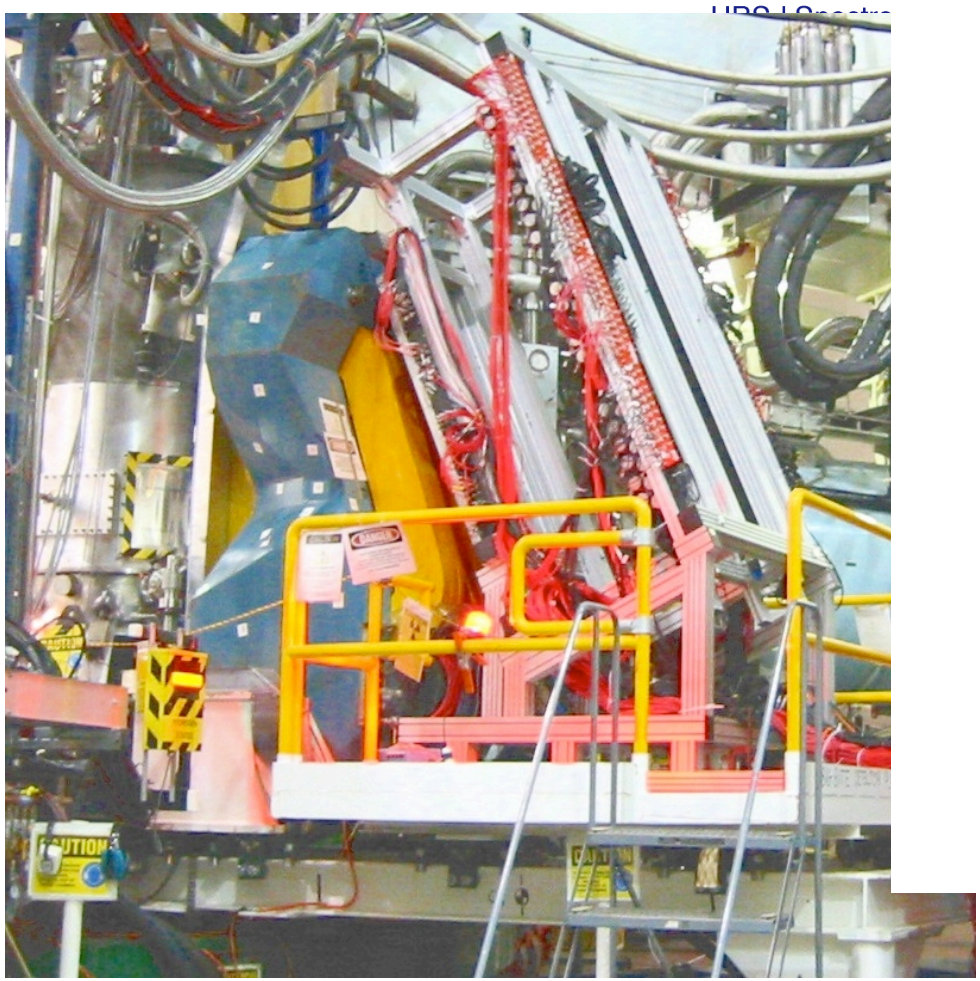
Proton

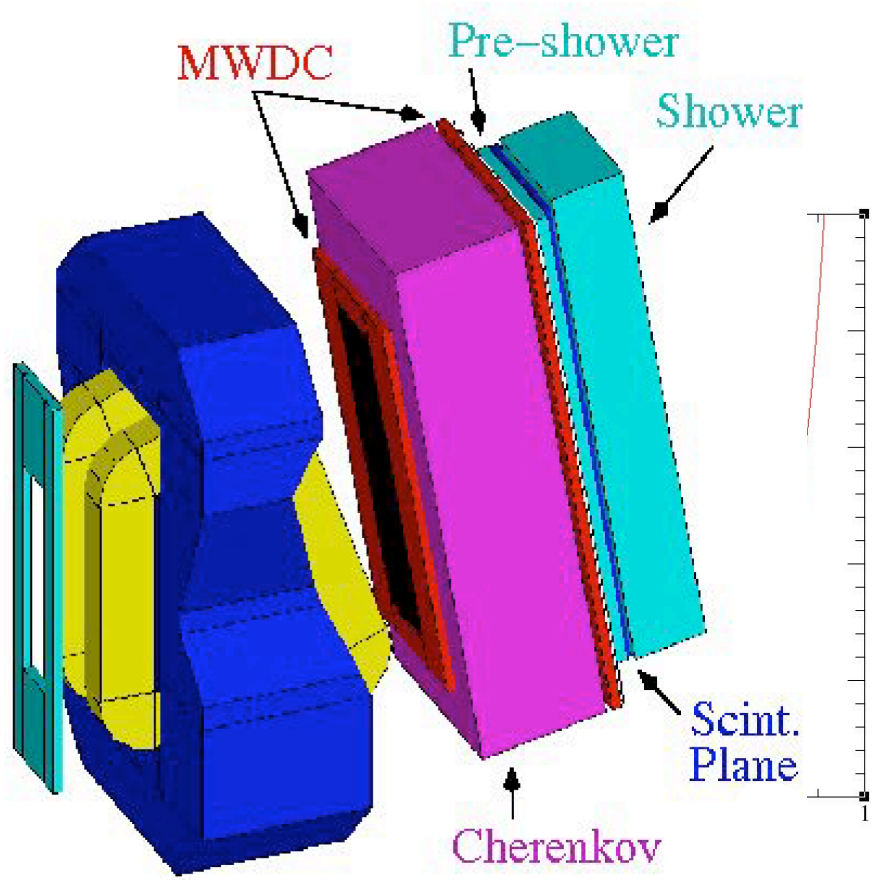
Spokespeople:
O. Rondon, S. Choi, M. Jones,, Z.-E. M

Students:
Whitney Armstrong, Hoo Kang, Aneesha Liyanage, James Maxwell, Jonathan Mulholland

and the Hall C collaboration

Experiment E06-114 (d_2^n) in Hall A



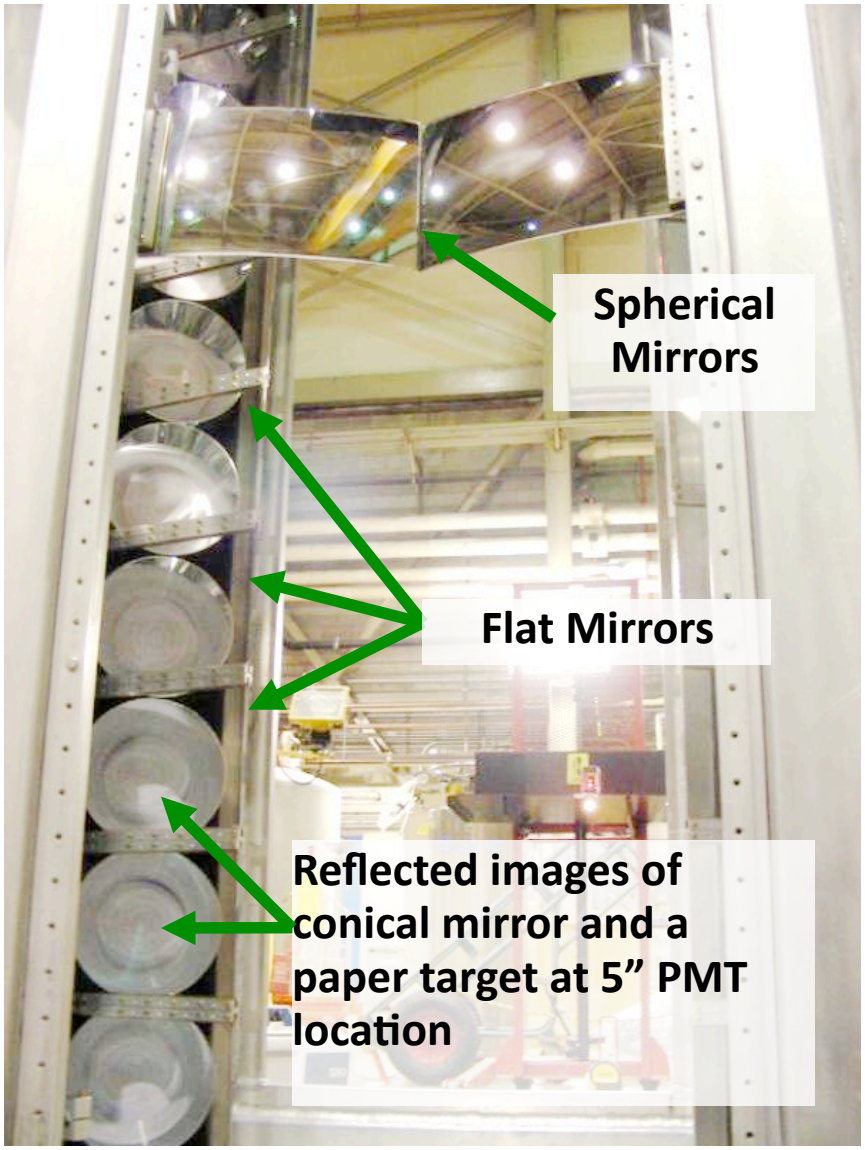


Two beam energies 4.6 and 5.7 GeV
(4 pass, 5 pass)

Experiment ran Jan.-Mar. 09

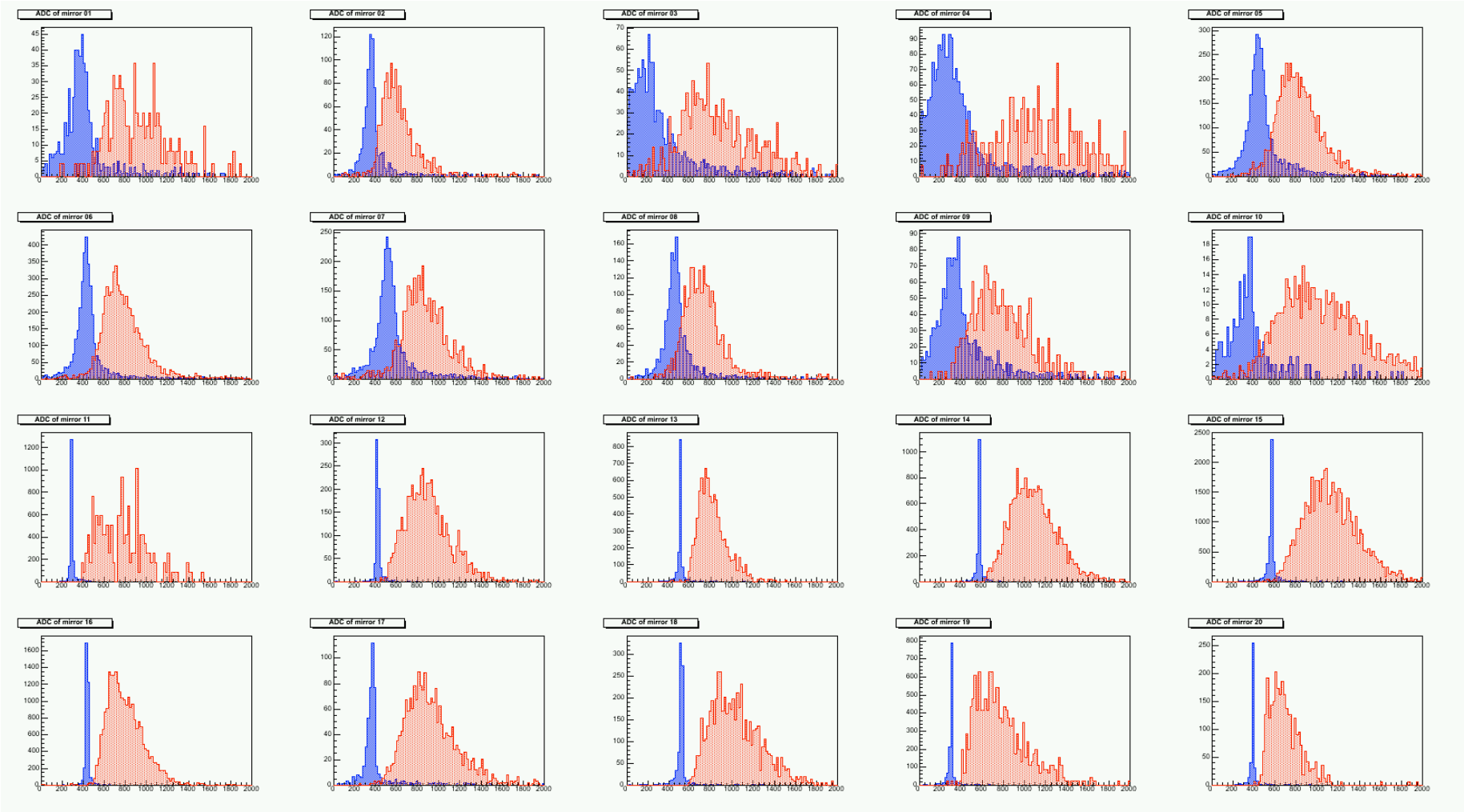
BigBite fixed at single scattering angle (θ=45°)
(data divided into 10 bins during analysis)

BB Cherenkov During Assembly (viewed from rear)

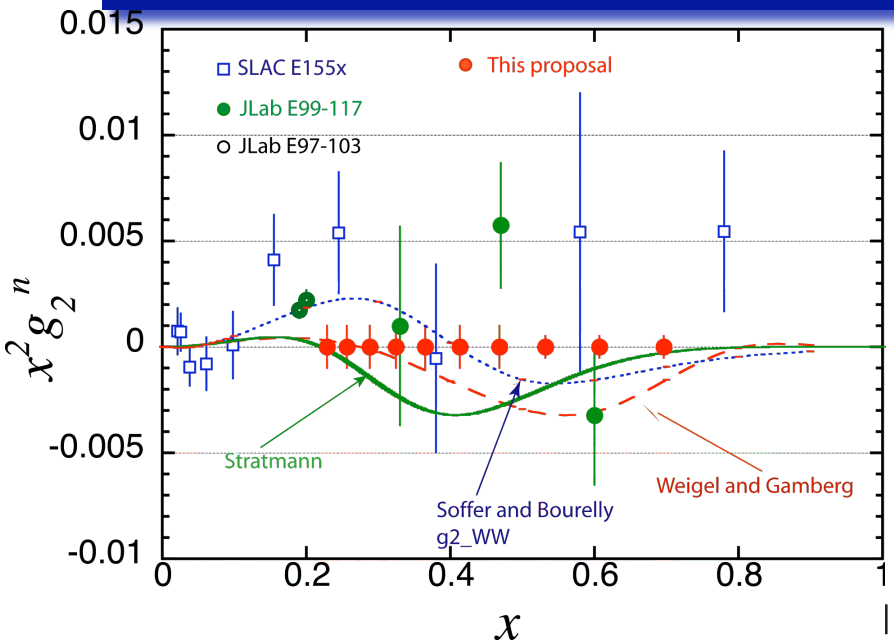


Big Bite Cherenkov Performance

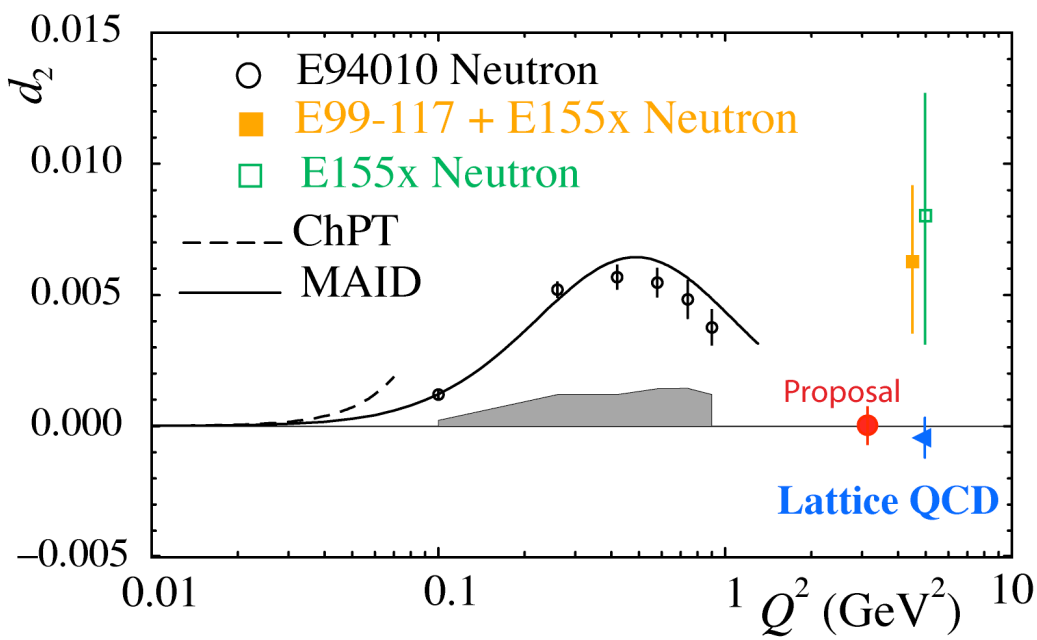
- Cherenkov ADC for electron events
  - signal: position cut, good timing
  - background: track cut on 'wrong' (distant) mirror



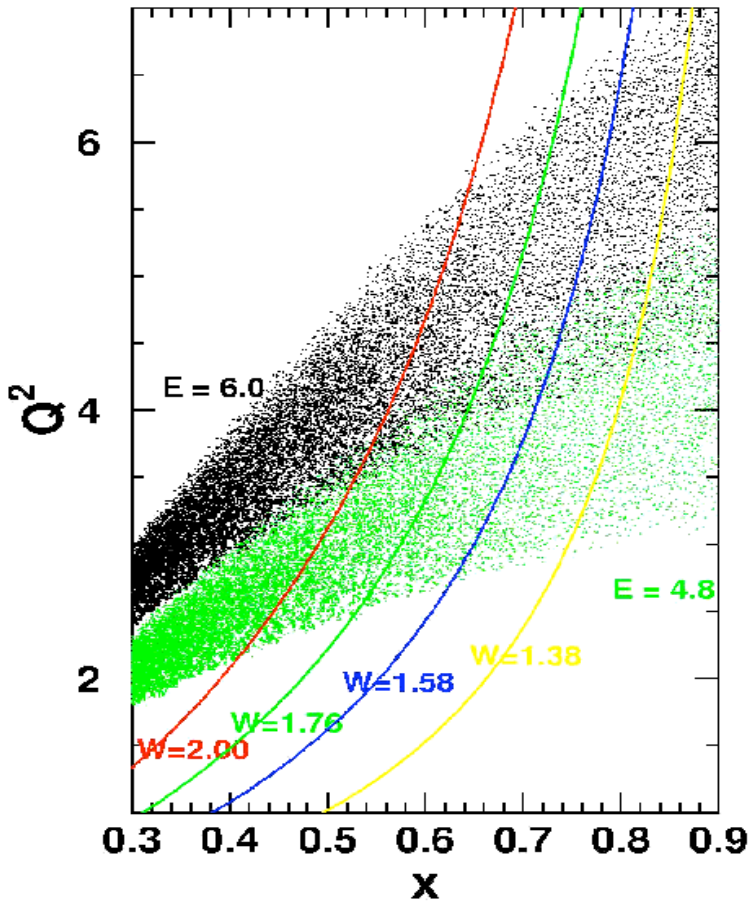
Expected precision in Experiment E06-114

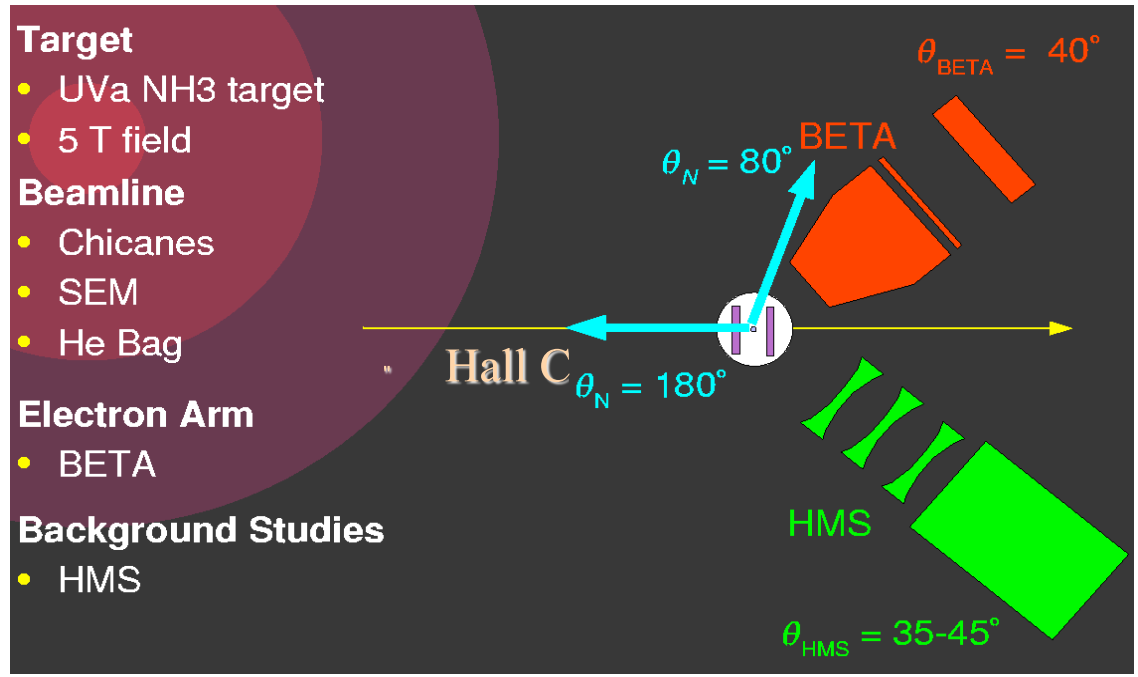


- At large Q^2, d_2 coincides with the reduced twist-3 matrix element of gluon and quark operators
- At low Q^2, d_2 is related to the spin polarizabilities



SANE experiment in Hall C





- Two beam energies:
  - **6.0 GeV (black)**
  - **4.8 GeV (green)**

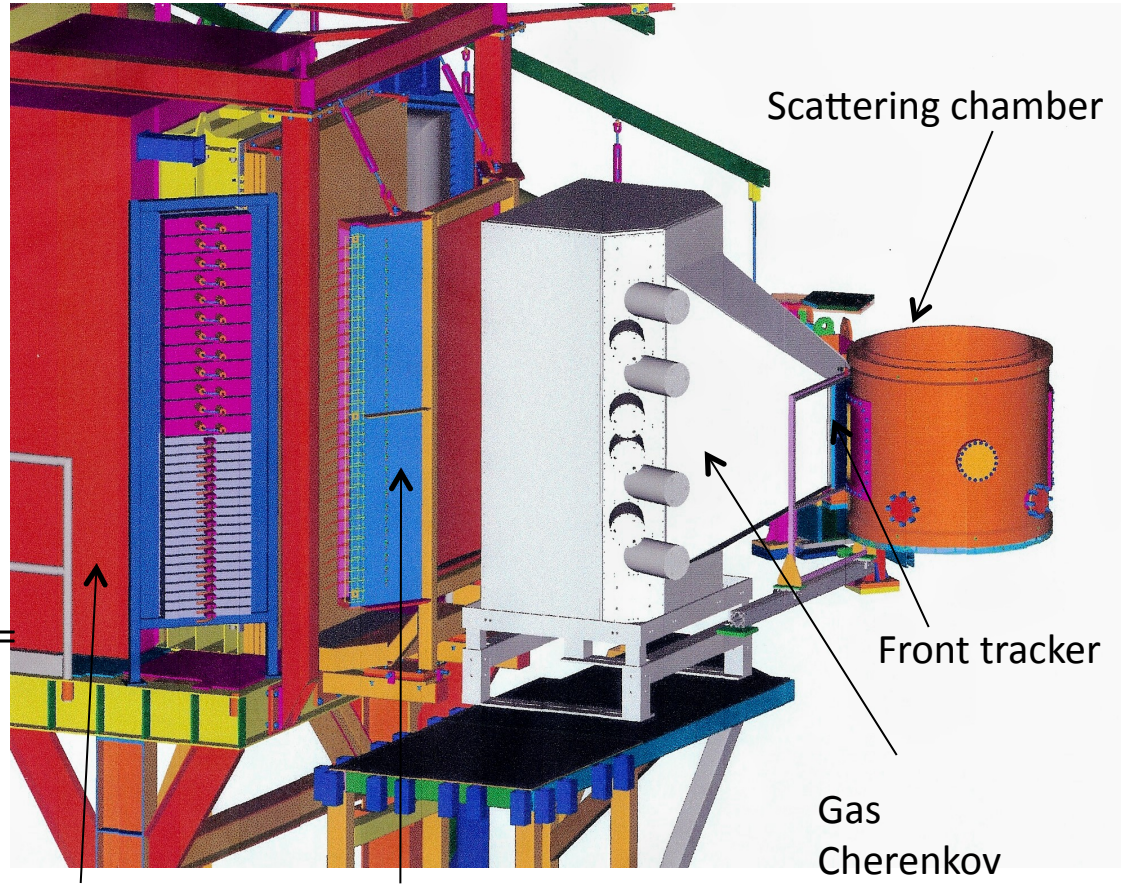
CEBAF polarized beam

- 85 nA
- 75% beam polarization

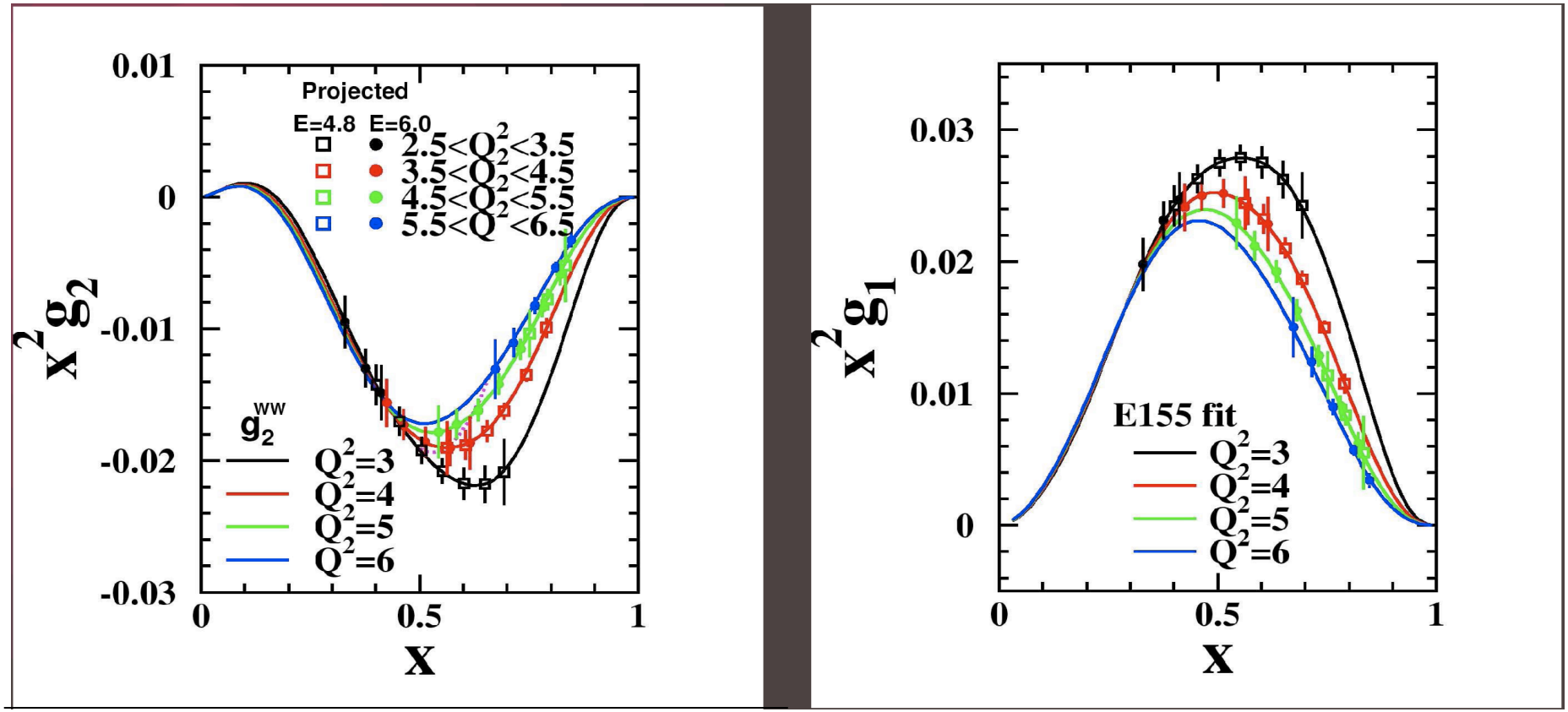
Experiment Ran January-March 09

BETA detector

- Three subsystems:
  - Lead glass calorimeter BigCal: Energy Measurement
  - Gas Cherenkov: e- identification
  - Lucite hodoscope: tracking
  - Front tracker: tracking
- Target field sweeps low *E* background
- Characteristics
  - Effective solid angle (with cuts) = 0.194 sr
  - Energy resolution 5%/$\sqrt{E(GeV)}$
  - *angular resolution = 2°*
  - *1000:1 pion rejection*

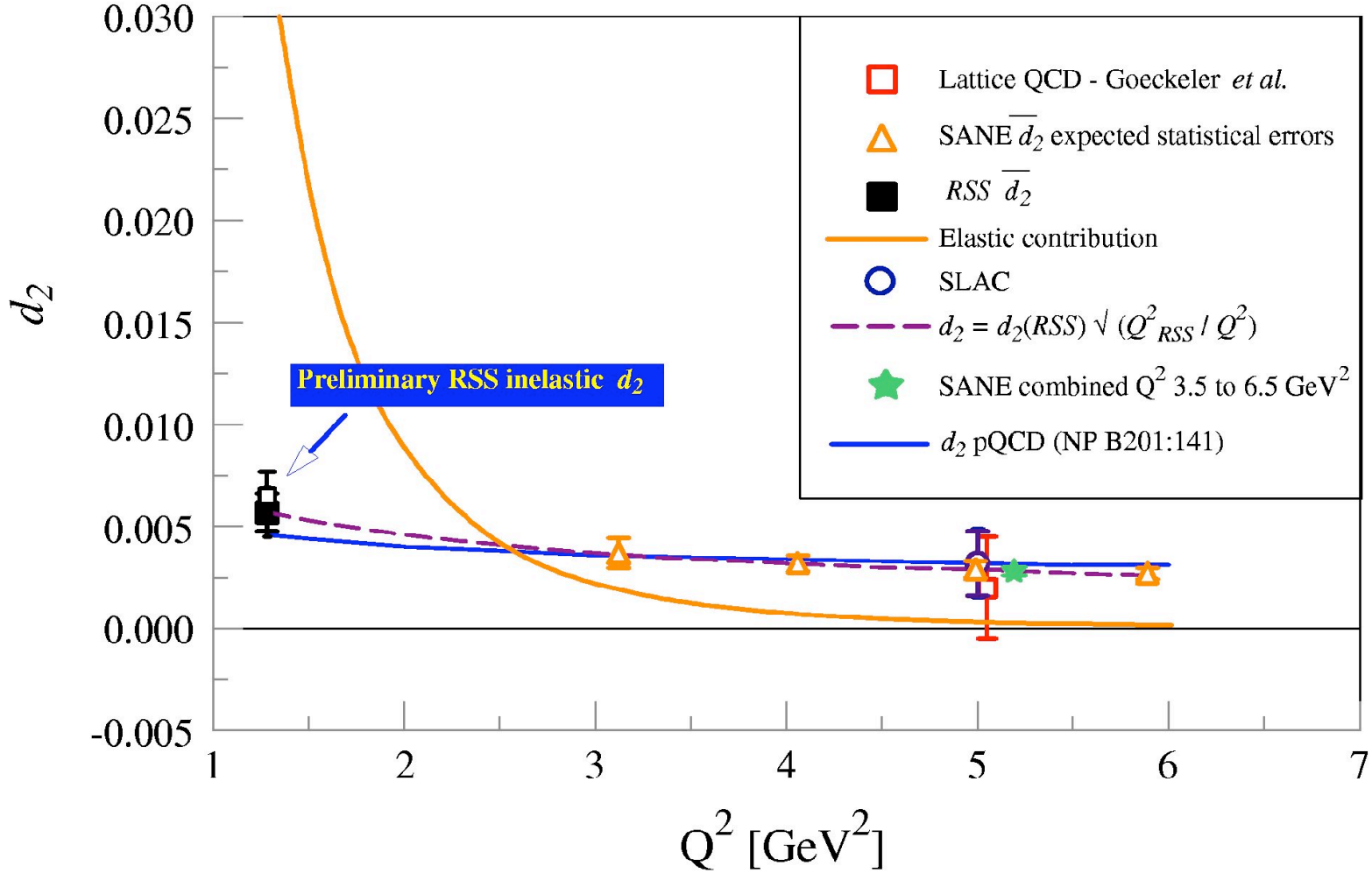


SANE experiment g_2, g_1 projected errors

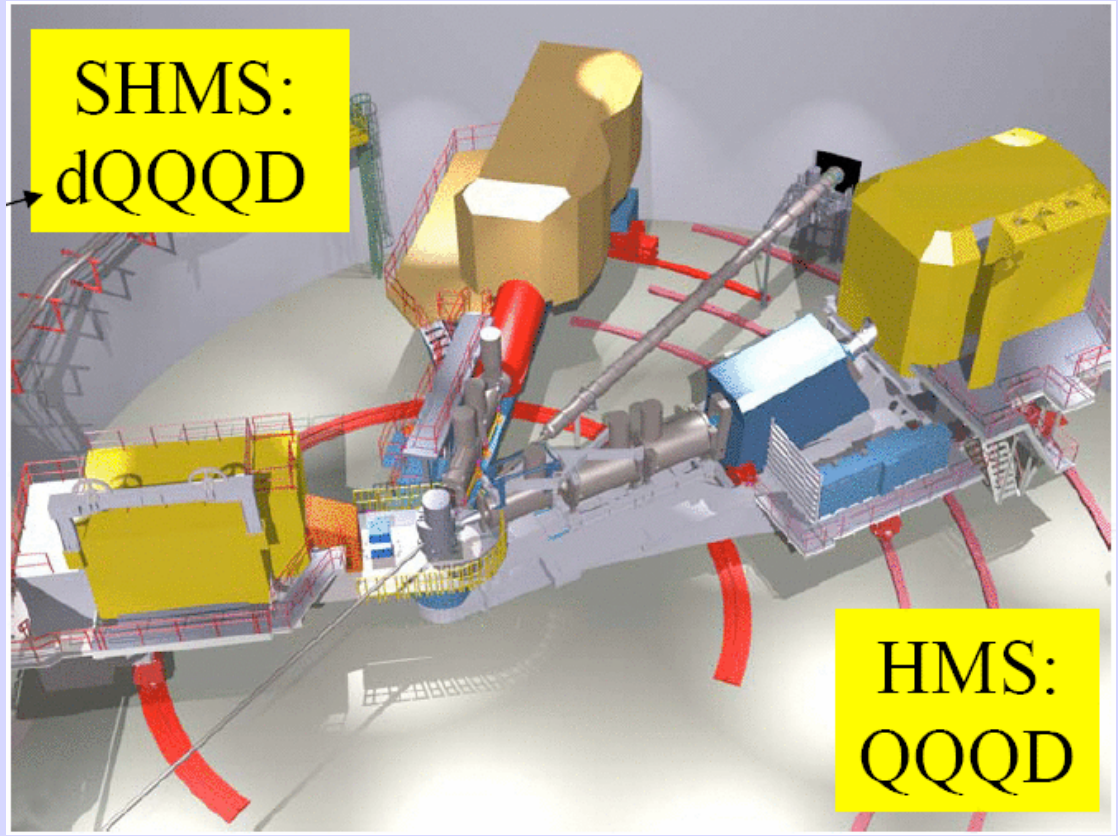


d_2^p RSS and SANE d_2^p projection in Hall C

RSS spokesperons: M. Jones, O. Rondon
SANE spokespersons: S. Choi, M. Jones, O. Rondon, Z.-E. M



Floor layout for Hall C

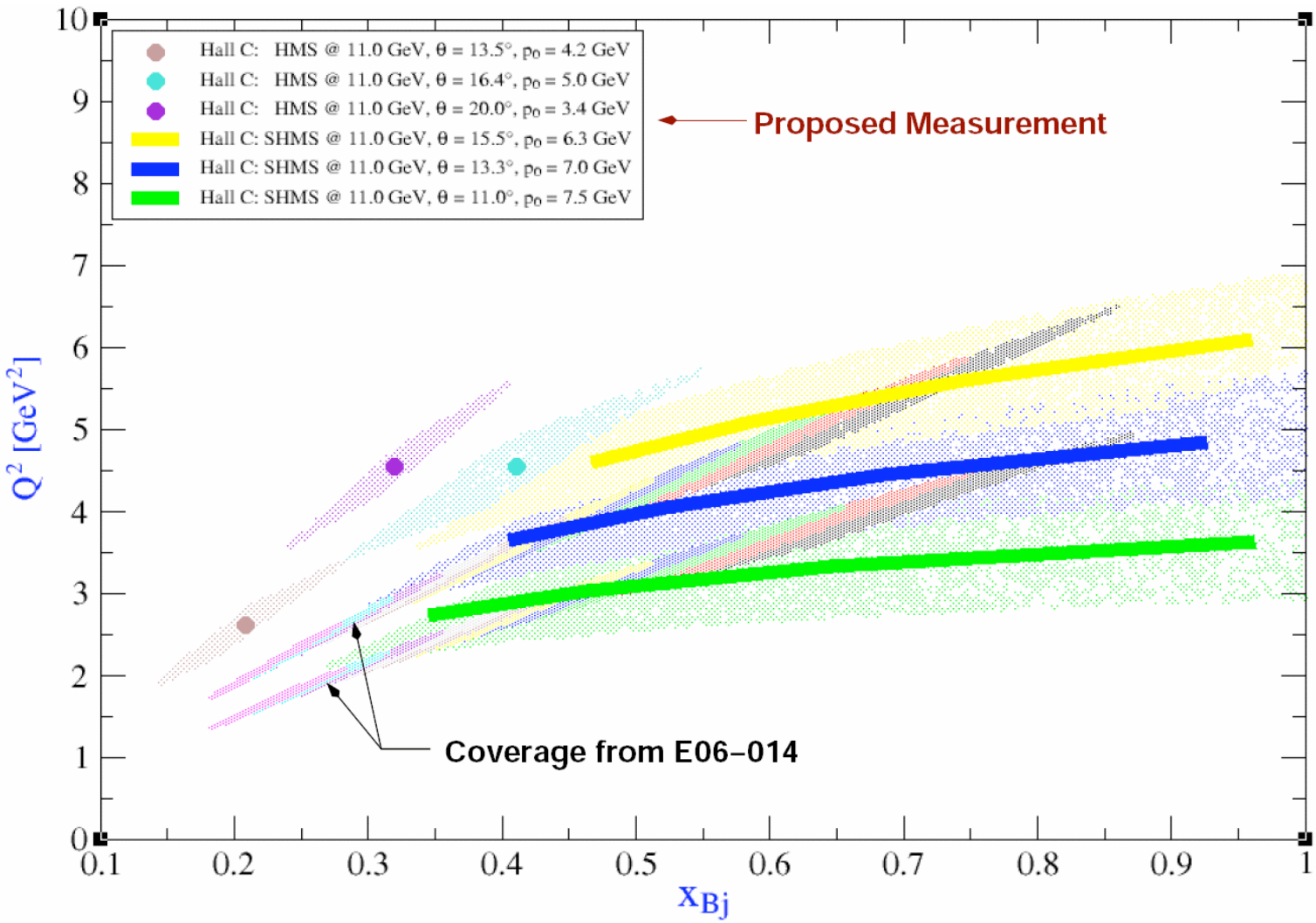


Hall C

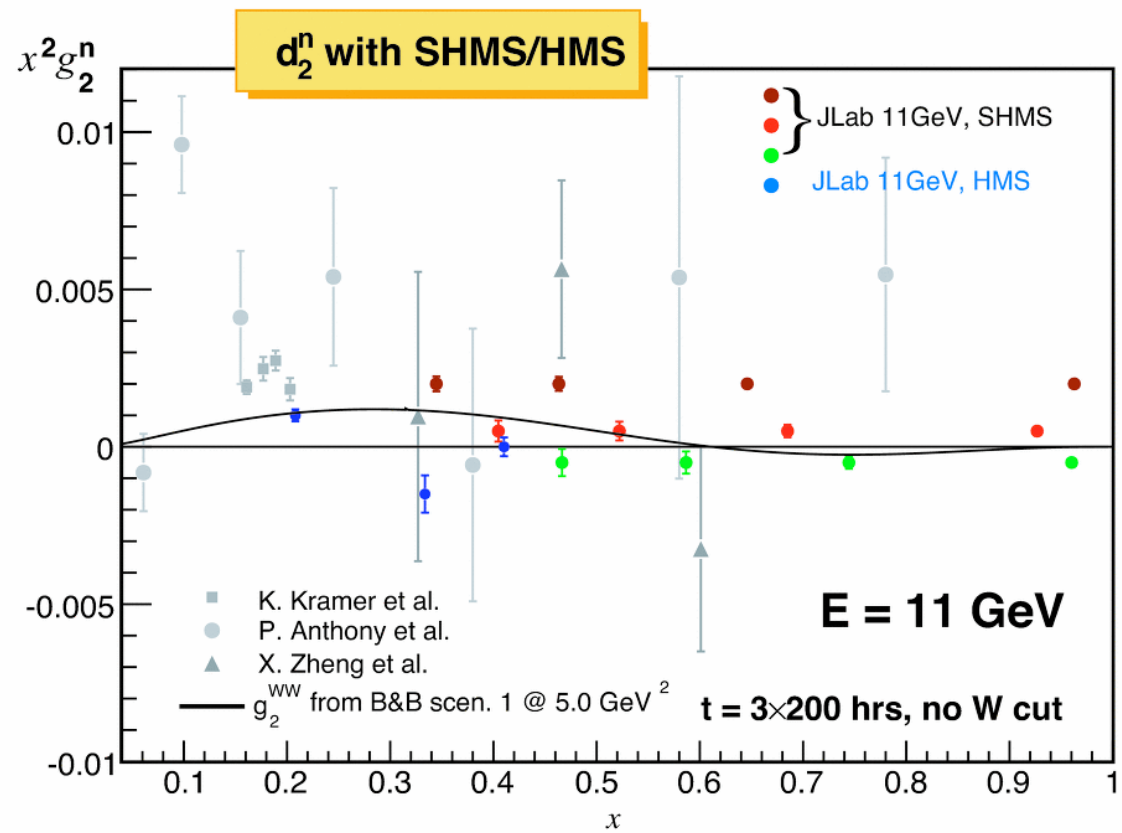
- One beam energy
  - 11 GeV
- Each arm measures a total cross section independent of the other arm.
- Experiment split into three pairs of 200 hour runs with spectrometer motion in between.

- SHMS collects data at Θ = 11°, 13.3° and 15.5° for 200 hrs each
  - data from each setting divided into 4 bins
- HMS collects data at Θ = 13.5°, 16.4° and 20.0° for 200 hrs each

Kinematics for Hall C



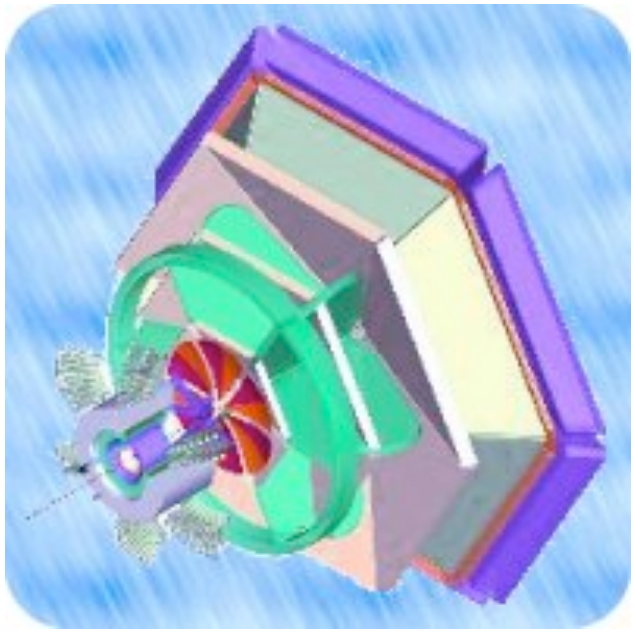
Projected $x^2g_2(x,Q^2)$ results for Hall C

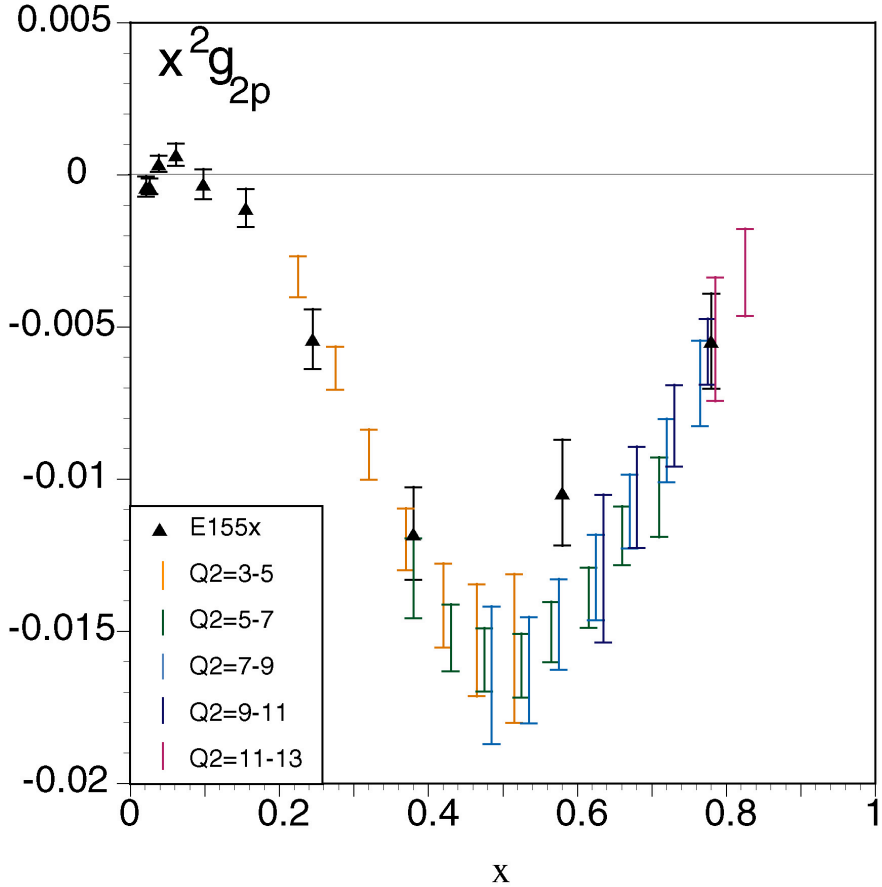


Projected points are vertically offset from zero along lines that reflect different (roughly) constant Q^2 values from 2.5—6 GeV^2.

- g_2 for ^{3}He is extracted directly from L and T spin-dependent cross sections measured within the same experiment.
- Strength of SHMS/HMS:
  nearly constant Q^2 (but less coverage for $x < 0.3$)

g_2 in CLAS 12 Hall B





Summary

- Large x is a good ground for testing our understanding of nucleon structure

- Access to some dynamics like quark-gluon correlations is also possible using higher moments of g2 and g2 accessible at large x.

- Stay tuned for results on d2p and d2n coming soon at a workshop near you!