Precision Measurement of Neutron Asymmetry A_1^n at Large x_{Bj}

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BNL Spin Discussion, May 21, Upton, NY

OUTLINE

- Introduction - Polarized DIS and Spin Structure Functions
- Theories about A_1^n
- Experiment E99-117
  - Experimental Setup
  - Jefferson Lab Hall A Polarized ^{3}He Target
  - Data Analysis – From ^{3}He to Neutron
- Preliminary Results
- Discussion, Summary and Outlook

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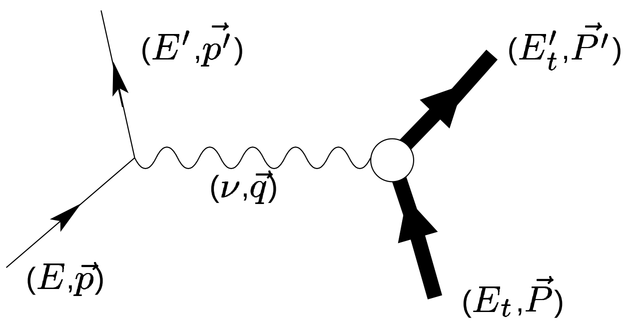
Polarized Deep Inelastic Scattering

POLARIZED DIS



STRUCTURE FUNCTIONS

- Unpolarized Target:

$$\frac{d^2\sigma_{\uparrow\Uparrow}}{d\Omega dE'} + \frac{d^2\sigma_{\uparrow\Downarrow}}{d\Omega dE'} = \frac{8\alpha^2 E'^2}{mQ^4}[2\sin^2\frac{\theta}{2}F_1(x,Q^2) + \frac{m^2}{\nu}\cos^2\frac{\theta}{2}F_2(x,Q^2)]$$

$$F_1(x,Q^2) = \frac{F_2(x,Q^2)(1+\gamma^2)}{2x(1+R(x,Q^2))}$$

- Longitudinally Polarized Target:

$$\frac{d^2\sigma_{\uparrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma_{\uparrow\Downarrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{E\nu Q^2}\left[(E+E'\cos\theta)g_1(x,Q^2) - 2xmg_2(x,Q^2)\right]$$

- Transversely Polarized Target:

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

Structure Functions in QPM

Within the Quark-Parton Model,

$$F_1(x) = \frac{1}{2} \sum_i e_i^2 \left[q_i^{\uparrow}(x) + q_i^{\downarrow}(x) \right]$$

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

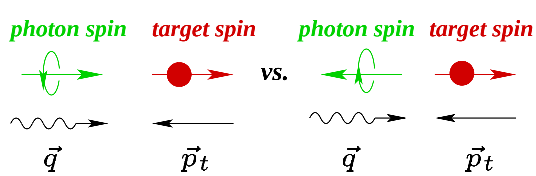
Ignoring quark mass effects,

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

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

Virtual Photon Asymmetries

$$A_1 = \frac{\sigma_{\frac{1}{2}} - \sigma_{\frac{3}{2}}}{\sigma_{\frac{1}{2}} + \sigma_{\frac{3}{2}}}$$



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

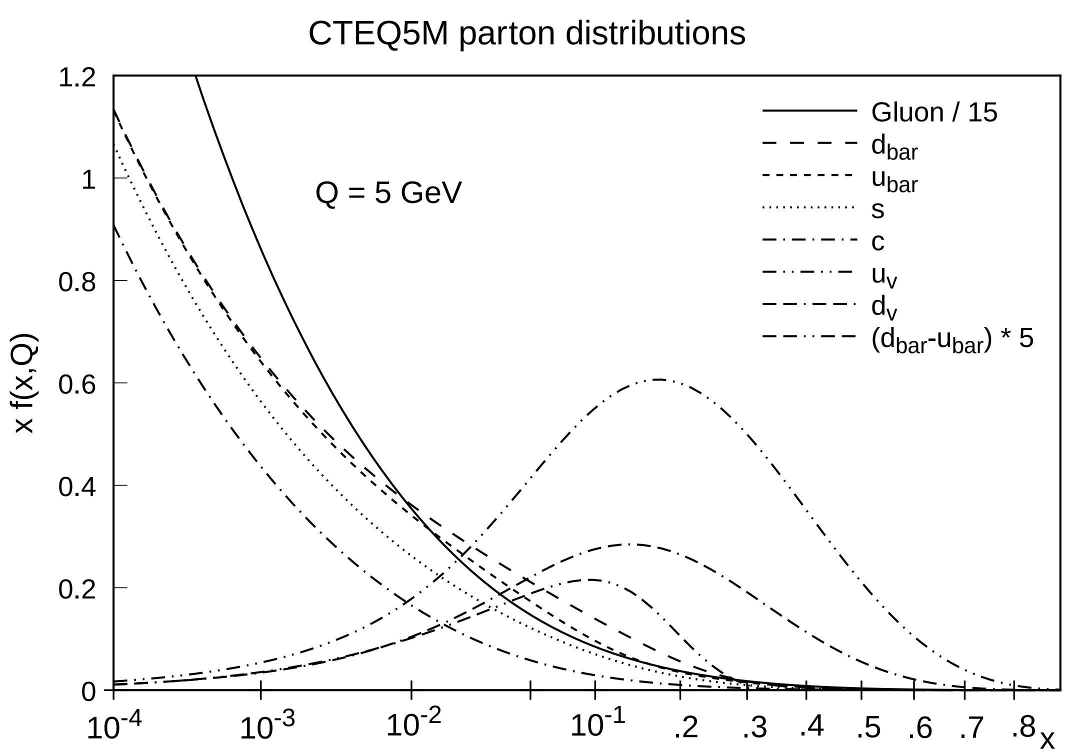
A_1^n *at high* x_{Bj}

Why at high x_{Bj}?

- Valence quarks dominate;
- Constituent quark models

  - Is our understanding of valence quark picture correct?
- pQCD

  - how solid it is and to how low x it can apply;



Theories about A_1^n

- SU(6): $A_1^n = 0$
- SU(6) Broken: $A_1^n \rightarrow 1$ as $x \rightarrow 1$;

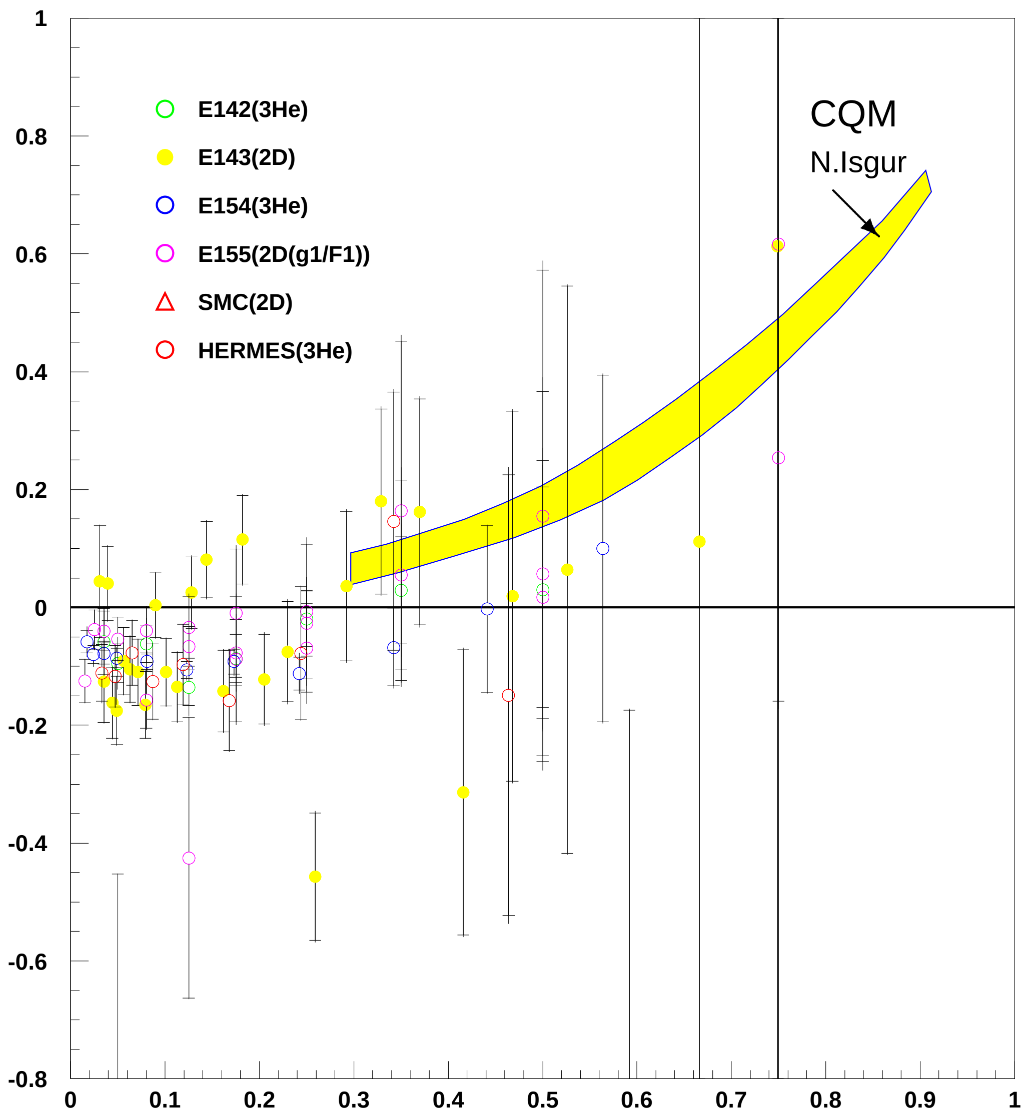
- Constituent quark models (CQM): N.Isgur $A_1^n \rightarrow 1$ as $x \rightarrow 1$;
- pQCD at $Q^2 \rightarrow \infty$, $A_1^n \rightarrow 1$ as $x \rightarrow 1$;

- Statistical model, C.Bourrely, J. Soffer ;
- Duality: W. Melnitchouk;

- Chiral Quark-Soliton Model, H. Weigel, $A_1^n < 0$ for $x > 0.5$;
- Instanton Model, N.I.Kochelev, $A_1^n \sim 0$ or $A_1^n < 0$;

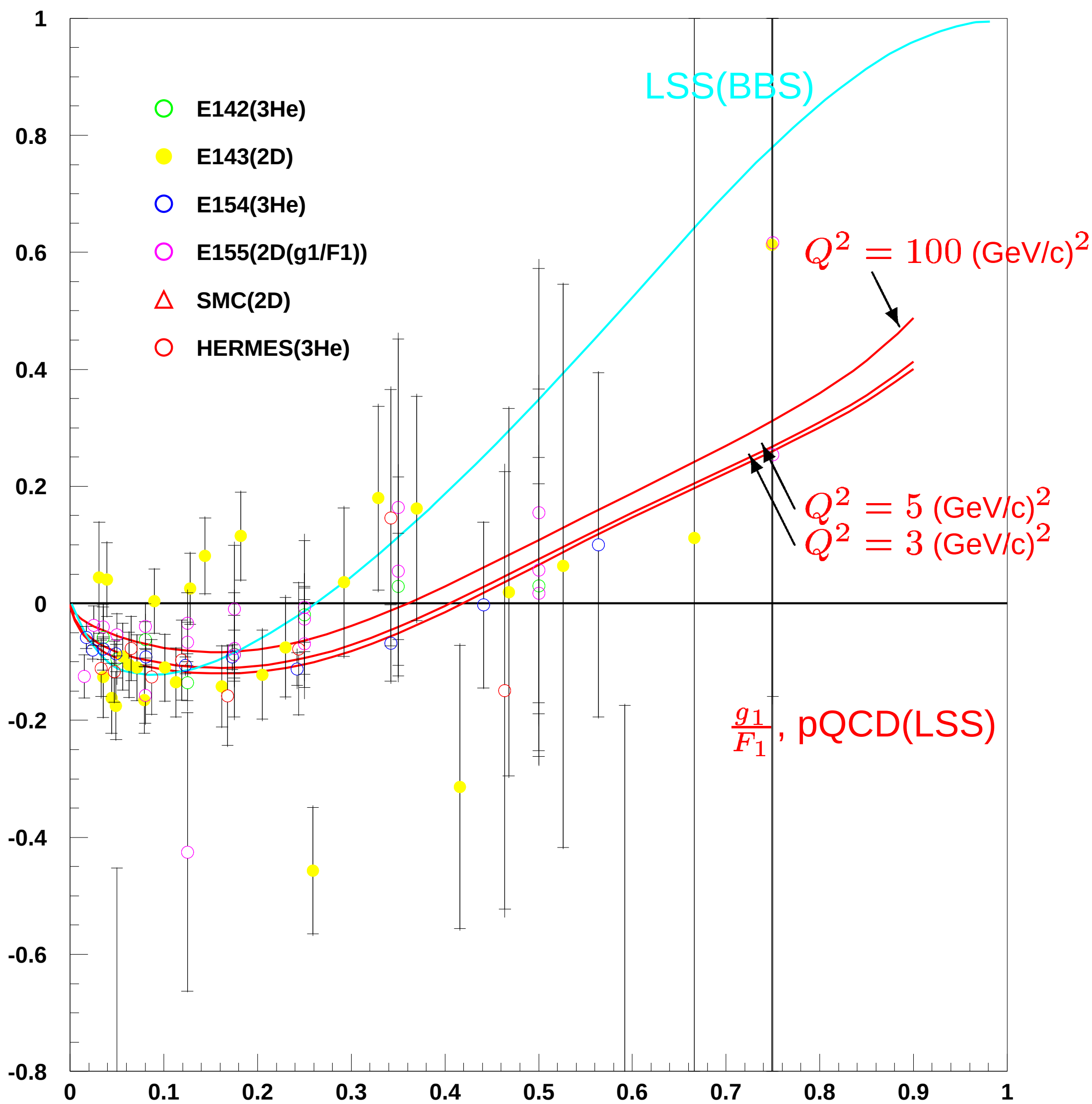
- **CQM**: N.Isgur, Phys.Rev. **D59** (1999) 034013
  - Hyperfine perturbed
  - A (simple) parameterization: $\frac{d(x)}{u(x)} \approx \kappa(1-x)$ as $x \to 1$, $\kappa \approx 0.5 \sim 0.6$
    $c_A(x) = nx(1-x)^n$, $n = 2 \sim 4$
  - $A_1^n(x) = \frac{4\Delta d_v(x)+\Delta u_v(x)}{4d_v(x)+u_v(x)}$ $A_1^p(x) = \frac{4\Delta u_v(x)+\Delta d_v(x)}{4u_v(x)+d_v(x)}$
  - A_1^n and $A_1^p \to 1$ as $x \to 1$.

World data on A_1^n and prediction from CQM



- pQCD (LSS-BBS): E. Leader, A.V.Sidorov, D.B.Stamenov, hep-ph/9708335
  - Polarized & unpolarized parton densities by Brodsky, Burkhardt and Schmidt (BBS);
  - $\frac{\Delta u}{u} \to 1$, $\frac{\Delta d}{d} \to 1$ at $x \to 1$.
- pQCD (LSS2001): E. Leader, A.V.Sidorov, D.B.Stamenov, hep-ph/0111267
  - A new evaluation of NLO polarized parton densities in the nucleon;
  - calculation done for g_1/F_1 at Q^2= 3, 5, 100 (GeV/c)^2.

World data on A_1^n and pQCD predictions

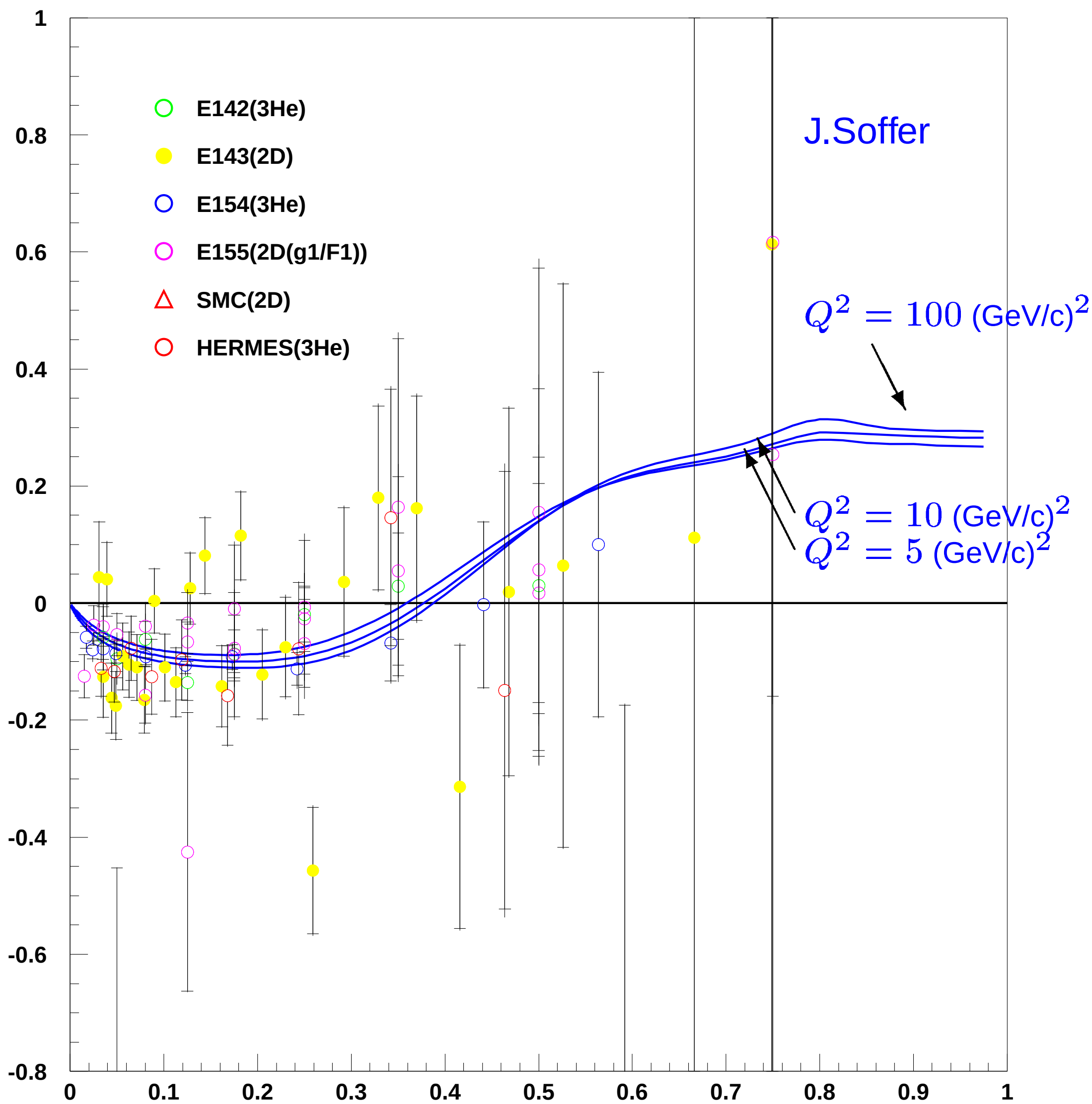


- Statistical Model: C.Bourrely, J. Soffer, hep-ph/0109160
  - global NLO QCD analysis of unpolarized and polarized DIS data;
  - parton distributions constructed in a statistical physical picture of the nucleon:

$$p(x) \propto [\exp{(x - X_{0p})/\bar{x}} \pm 1]^{-1}$$

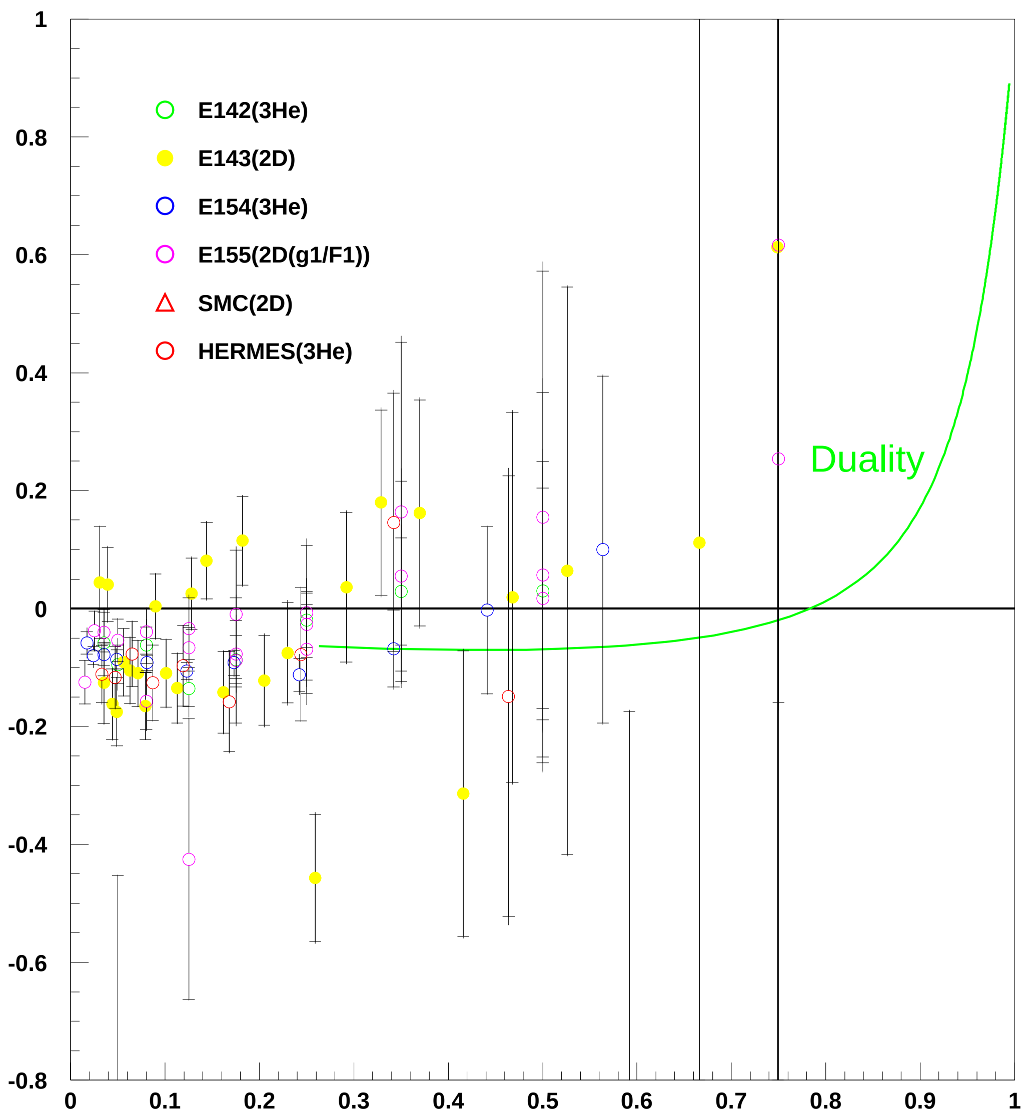
  - calculation done for A_1 at Q^2=5, 10, 100 (GeV/c)^2, ($g_2 = g_2^{ww}$)

World data on A_1^n and Soffer's statistical model



- **Duality**: W. Melnitchouk, Phys. Rev. Lett. **86**, 35 (2001)
  - local quark-hadron duality;
  - predict $x \sim 1$ behavior of A_1 from available data on G_E,G_M;

World data on A_1^n, Prediction from Duality



- Chiral Quark-Soliton Model:

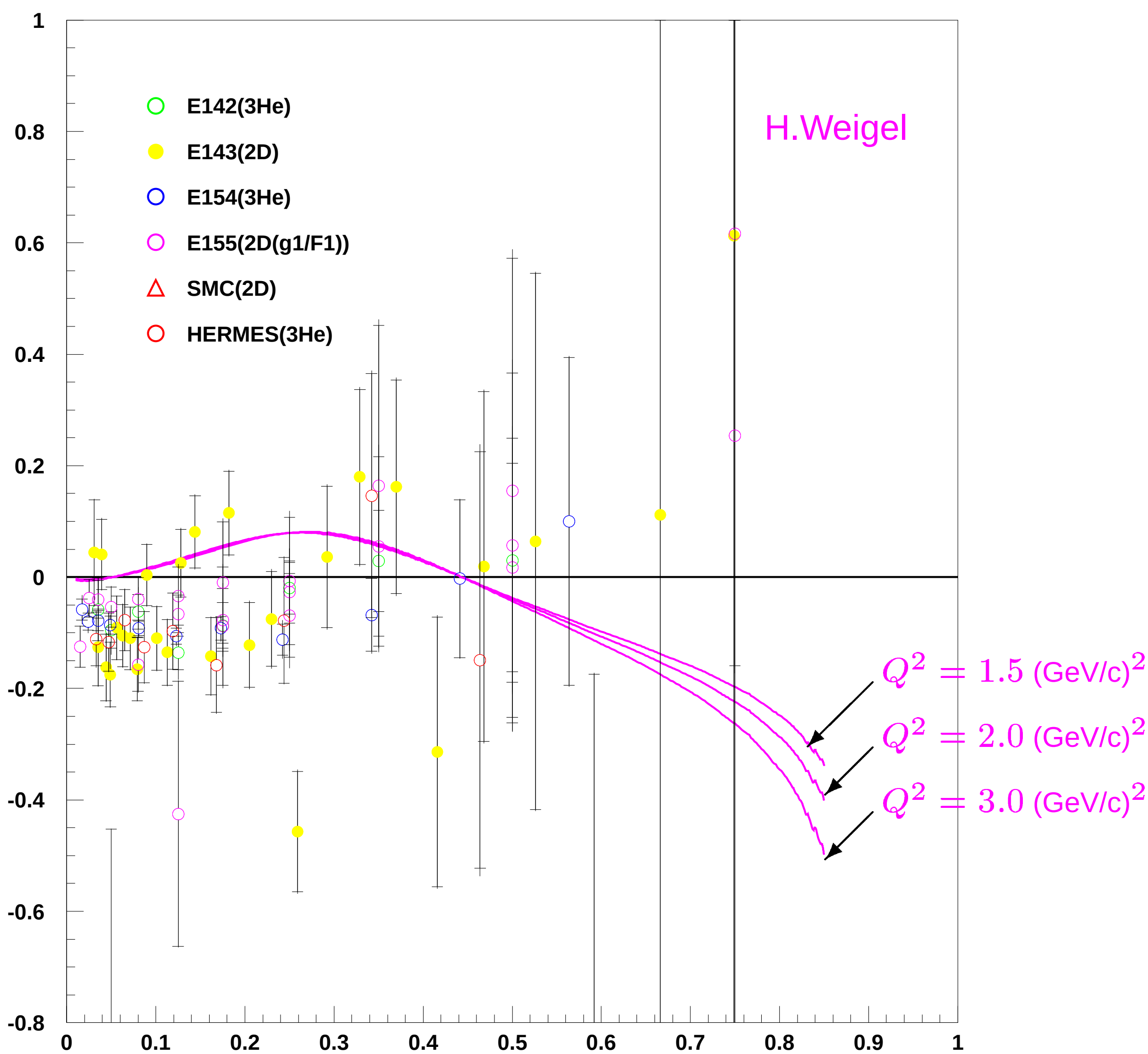
  H.Weigel, L.Gamberg and H.Reinhardt, Phys. Lett. **B399**, 287 (1997), Phys. Rev. **D55**, 6910 (1997).

  – Two flavor chiral soliton approach to baryons, based on the Bosonized Nambu-Jona-Lasinio (NJL) model;

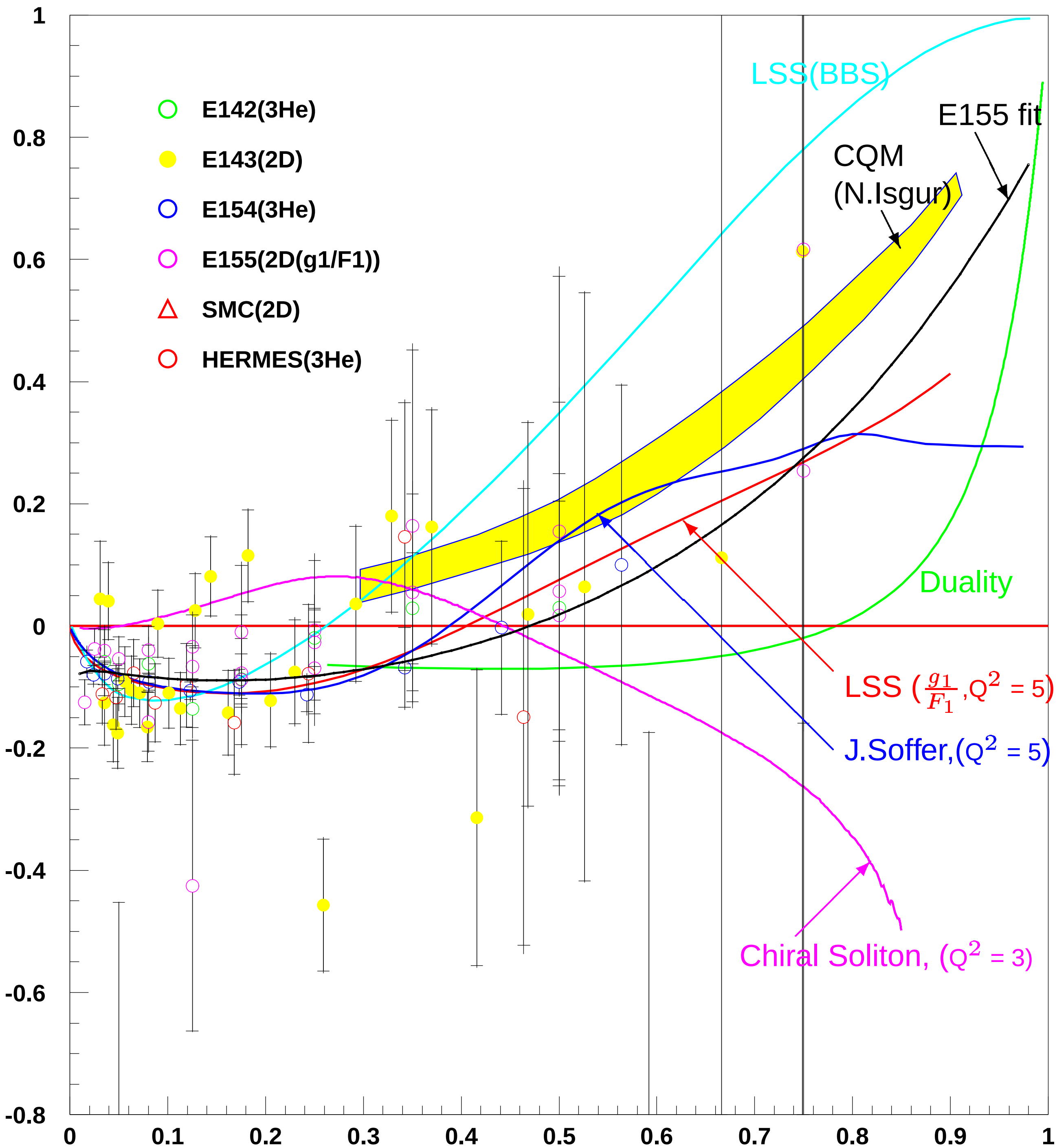
  – Model degrees of freedom are effective constituent quarks;

  – Tentative calculation done for $\frac{g_1}{F_1}$ at Q^2=1.5, 2.0, 3.0 (GeV/c)^2.

World data on A_1^n and chiral quark-soliton model



A_1^n World Data and Theoretical Predictions



Experiment E99-117

Measured A_1^n at

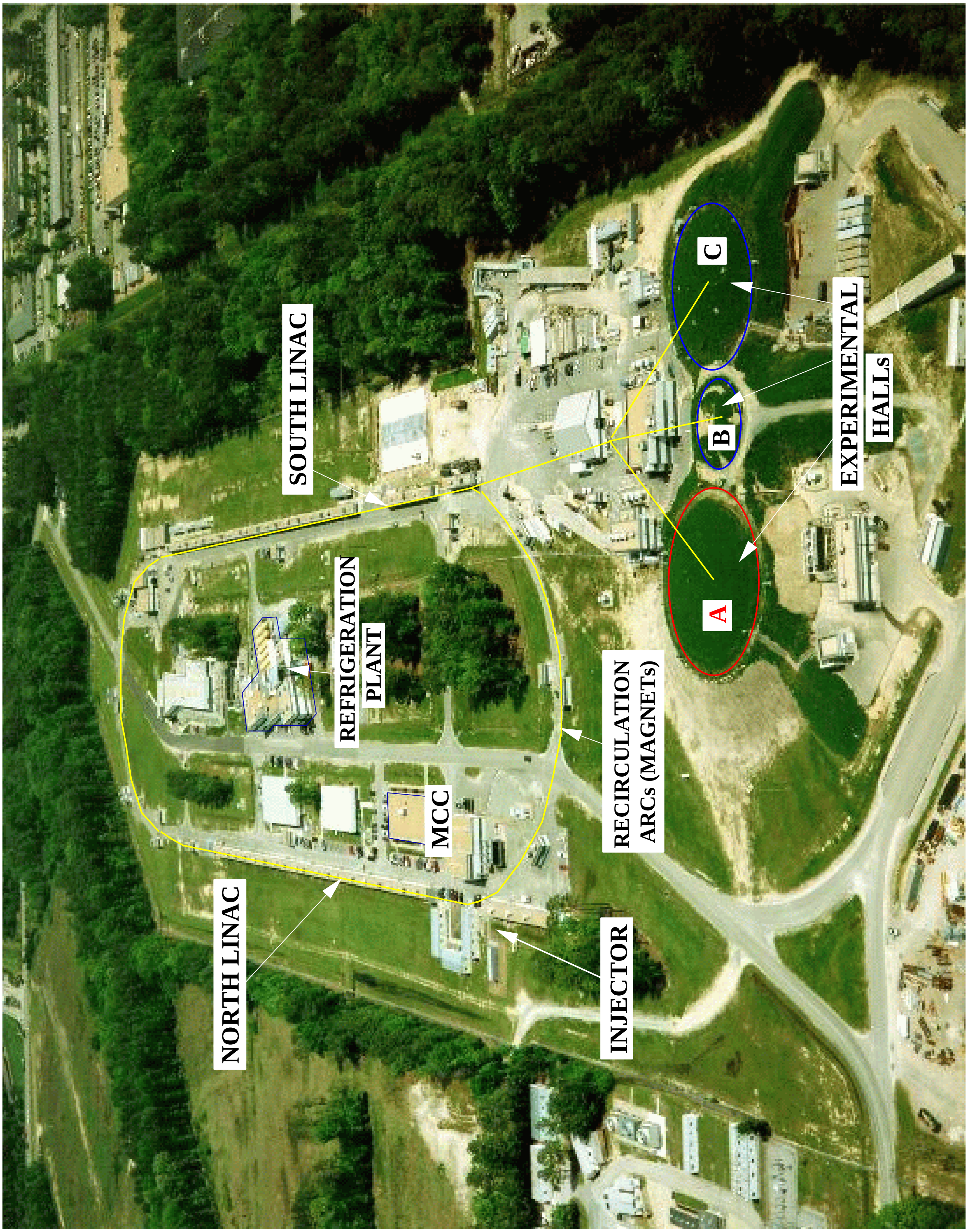
x_{Bj}	0.331	0.474	0.609
Q^2 $(GeV/c)^2$	2.738	3.567	4.887
W^2 $(GeV/c)^2$	6.426	4.846	4.023

through e^- asymmetries $A_\parallel$ and $A_\perp$ in inclusive $\vec{e}^- - {}^3\vec{He}$ DIS;

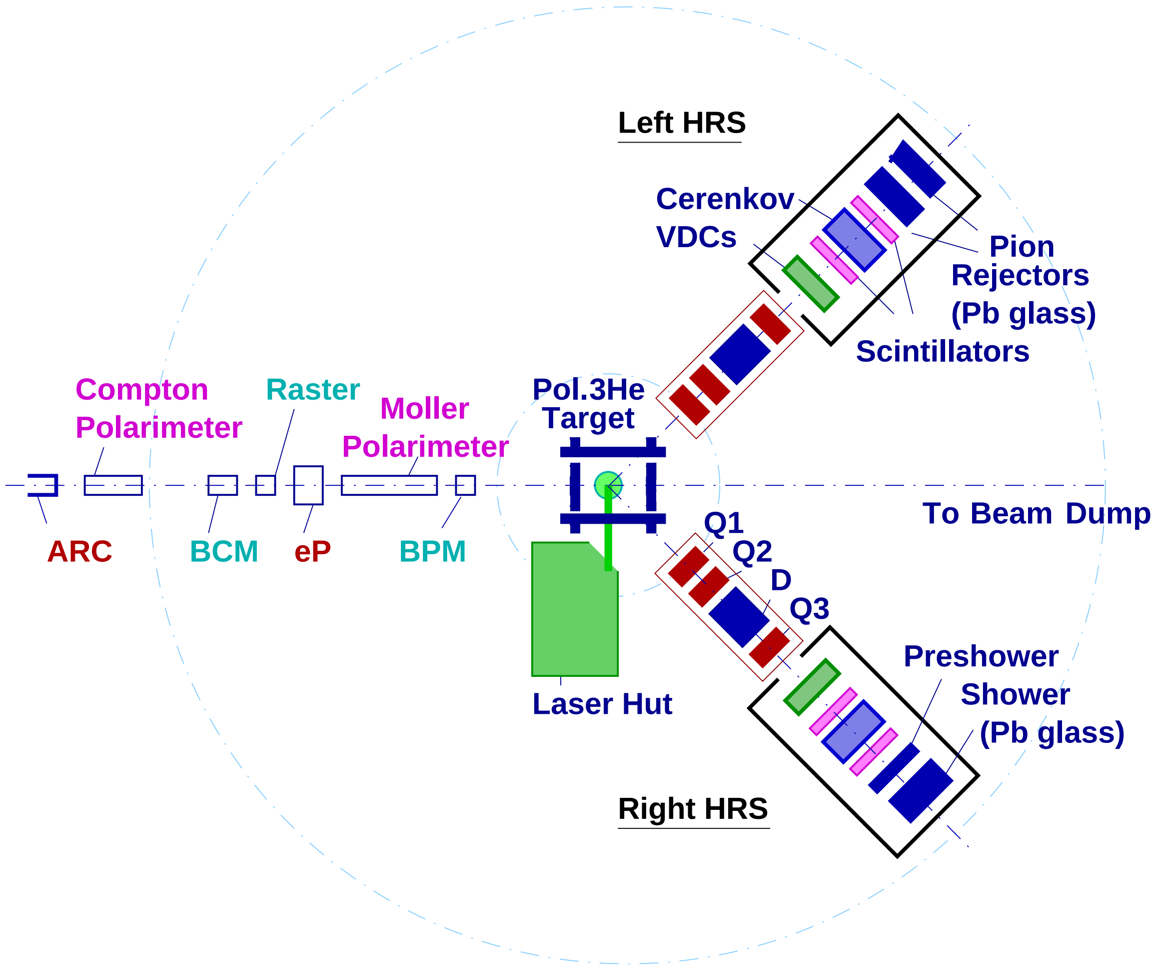
Experimental setup

- Jefferson Lab(JLab) polarized e^- beam, 5.734 GeV, $P_{beam} = 81\%$, 12 μA
- Hall A polarized ${}^3He$ target, $\sim$ 10 atm, $P_{targ} = 40\%$
- Two Hall A High Resolution Spectrometers (HRS) at symmetric positions

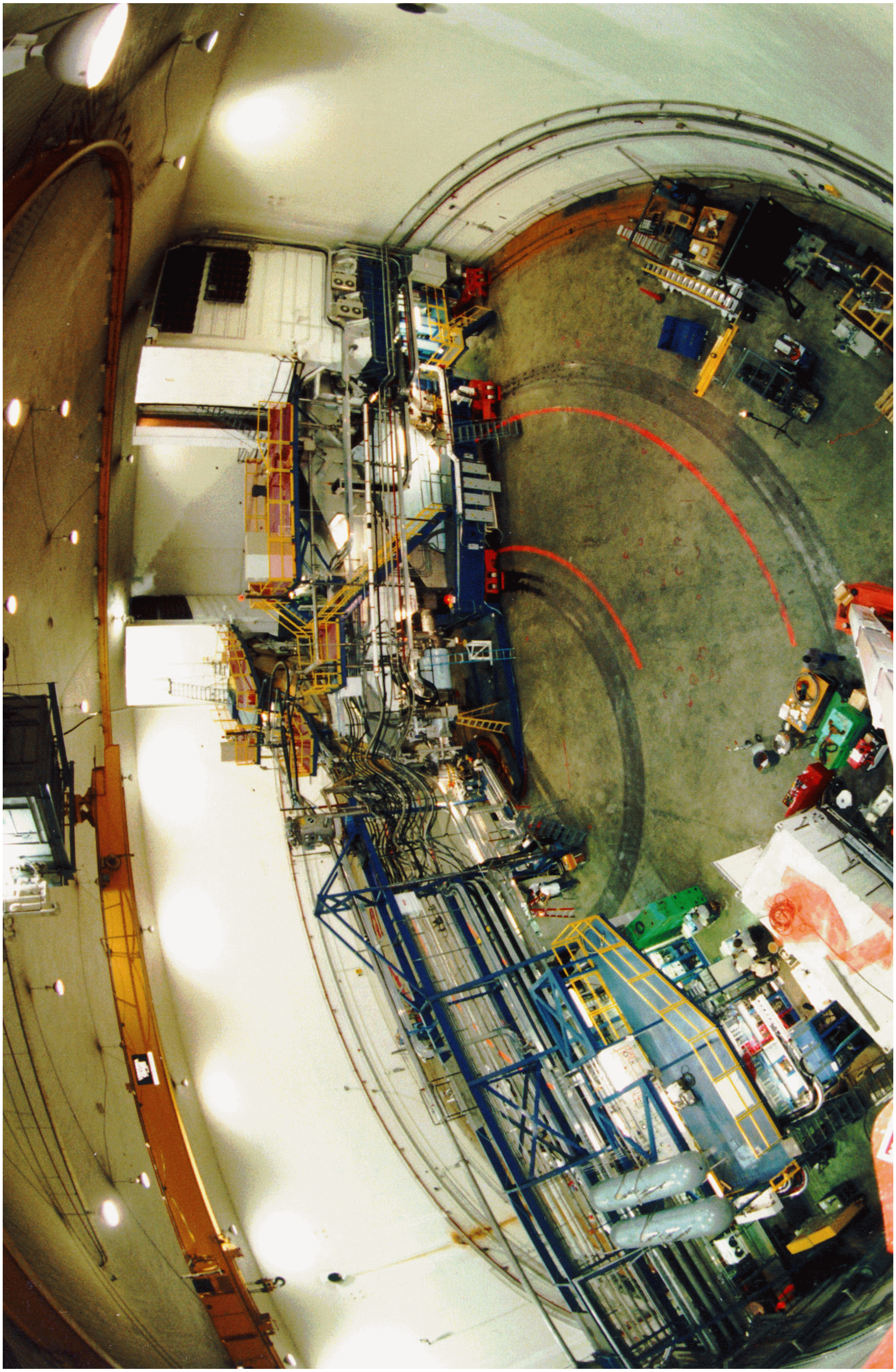
The Jefferson Lab Accelerator



EXPERIMENTAL HALL A



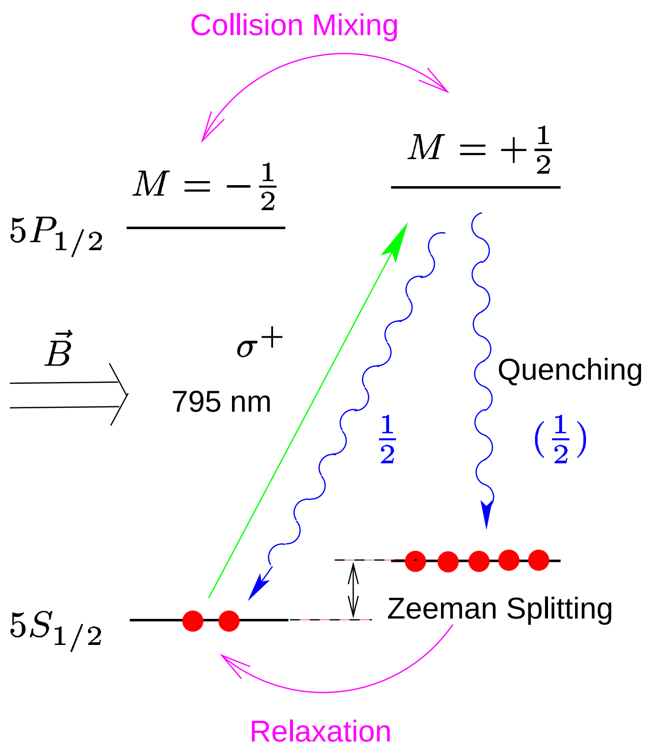
- *Two VDCs* for tracking;
- *Sets of scintillators* for triggering on charged particles;
- *Gas cherenkov detector* for pion rejection;
- *Two layers of lead glass counters* for additional PID;
- *Pion rejection efficiency:* better than 10^{-4} with electron efficiency 99%.



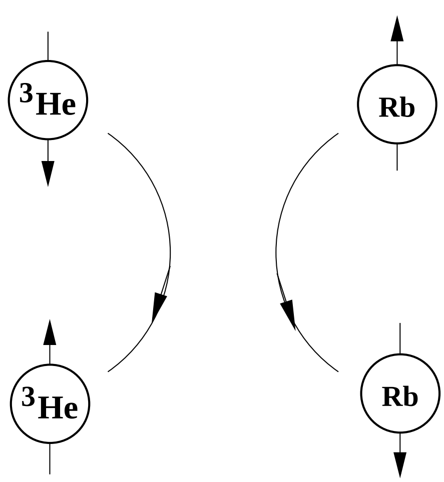
Polarzied ^3He Target

PRINCIPLE OF POLARIZING

- Optical pumping of Rb by circularly polarized light



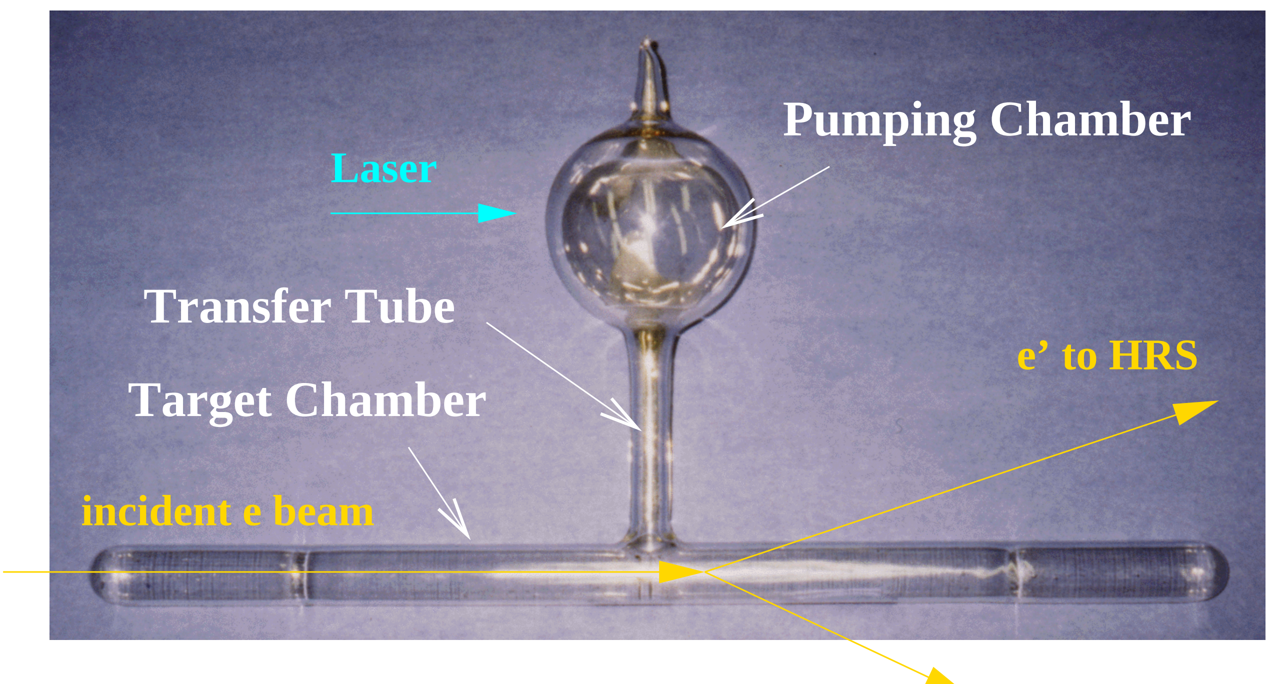
- Spin exchange through Rb-^3He collisions



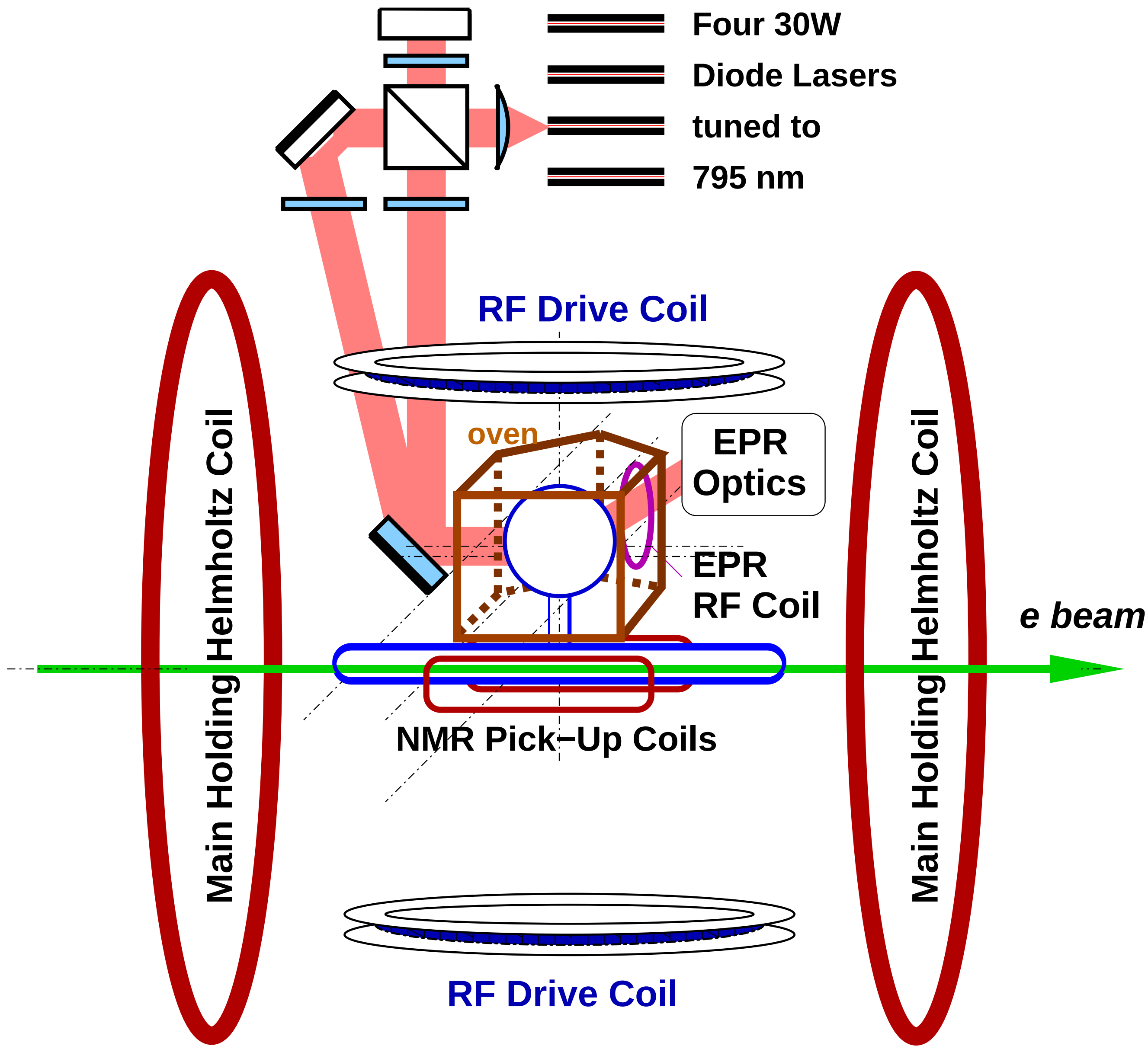
The Cell

- Cell density: 7.5∼10 amg.
- Maximum polarization: ∼40% (in beam) - NMR, EPR Polarimetries
- Cell lifetime: $\Gamma = \Gamma_{He} + \Gamma_{wall} + \Gamma_{beam} + \Gamma_{\Delta B}$

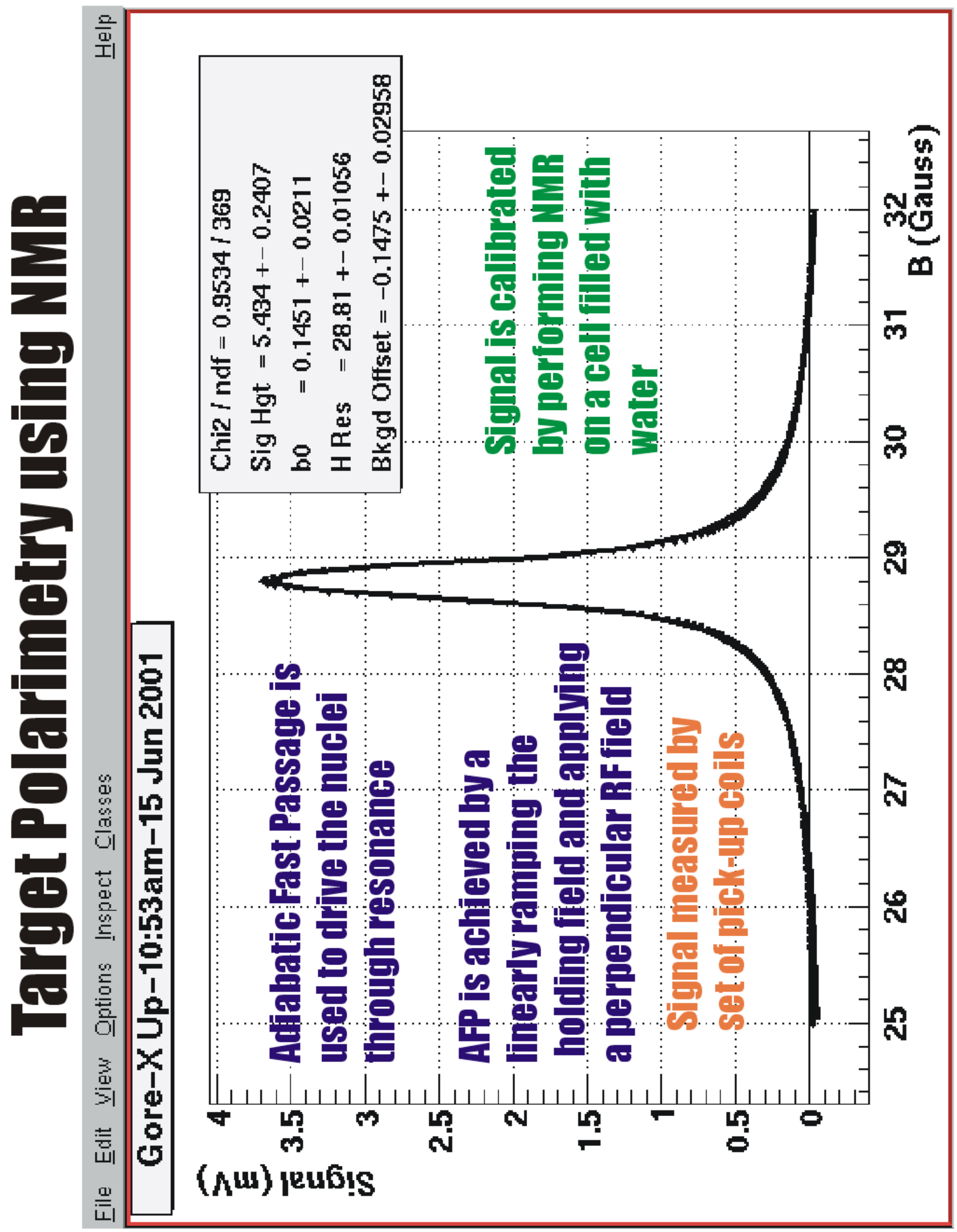
  $\sim (40)^{-1} = (744/[He])^{-1} \quad (90)^{-1} \quad (655/I)^{-1} \quad (1700)^{-1}$ (hours)$^{-1}$
- Cell end windows 100μm, wall thickness $\sim$ 130 mm
- Polarization diffusion: $P_p - P_t \sim 1\%$



TARGET SETUP

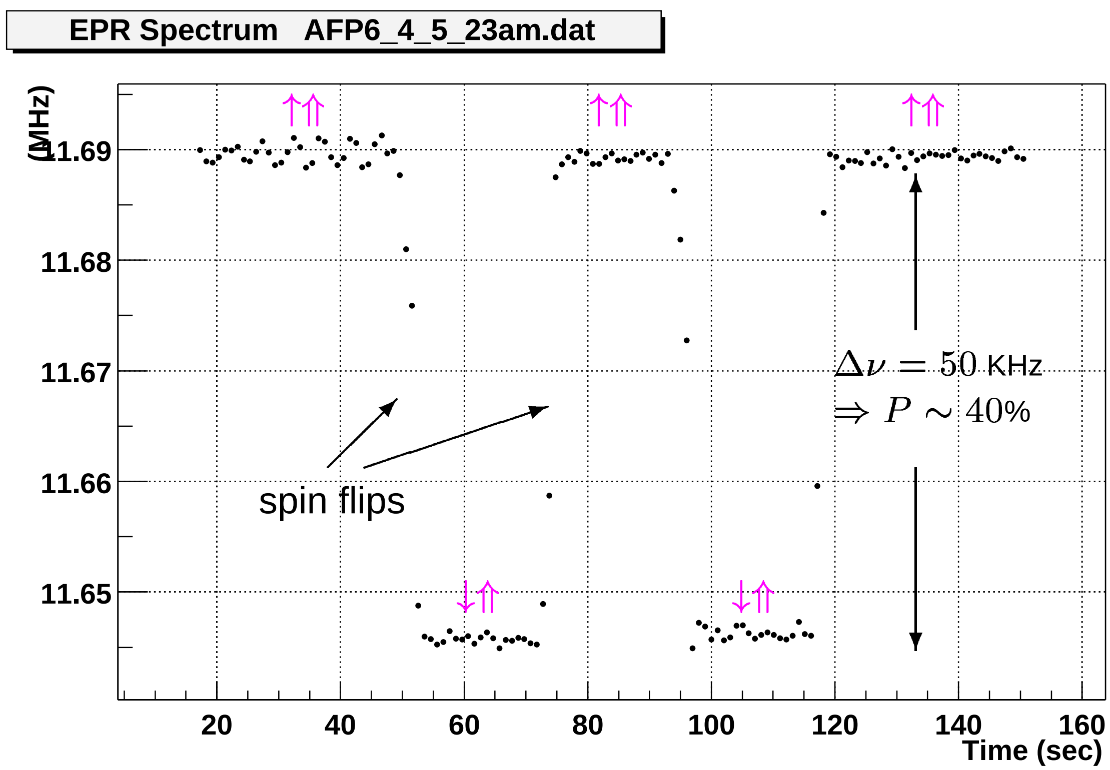


NMR POLARIMETRY (K.Kramer, PST2001)

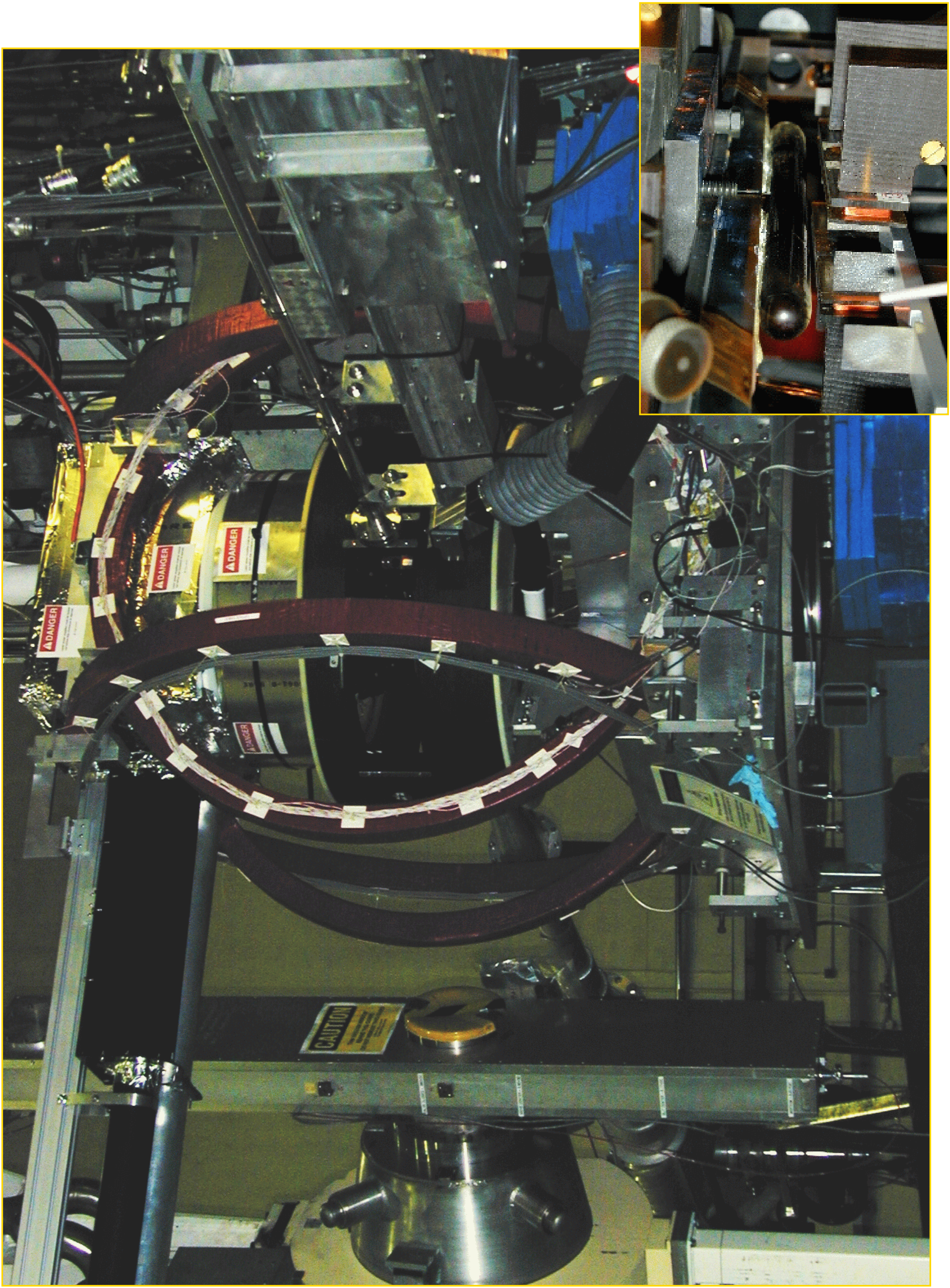


EPR Polarimetry

- Rb Zeeman splitting $\propto$ Magnetic field magnitude $\vec{B}$;
- $P_{^3He}$ induce a small $\vec{B}_{^3He}$, $\vec{B} = \vec{B}_{^3He} + \vec{B}_{main}$;
- Measure Rb resonance frequency shift due to $P_{^3He}$

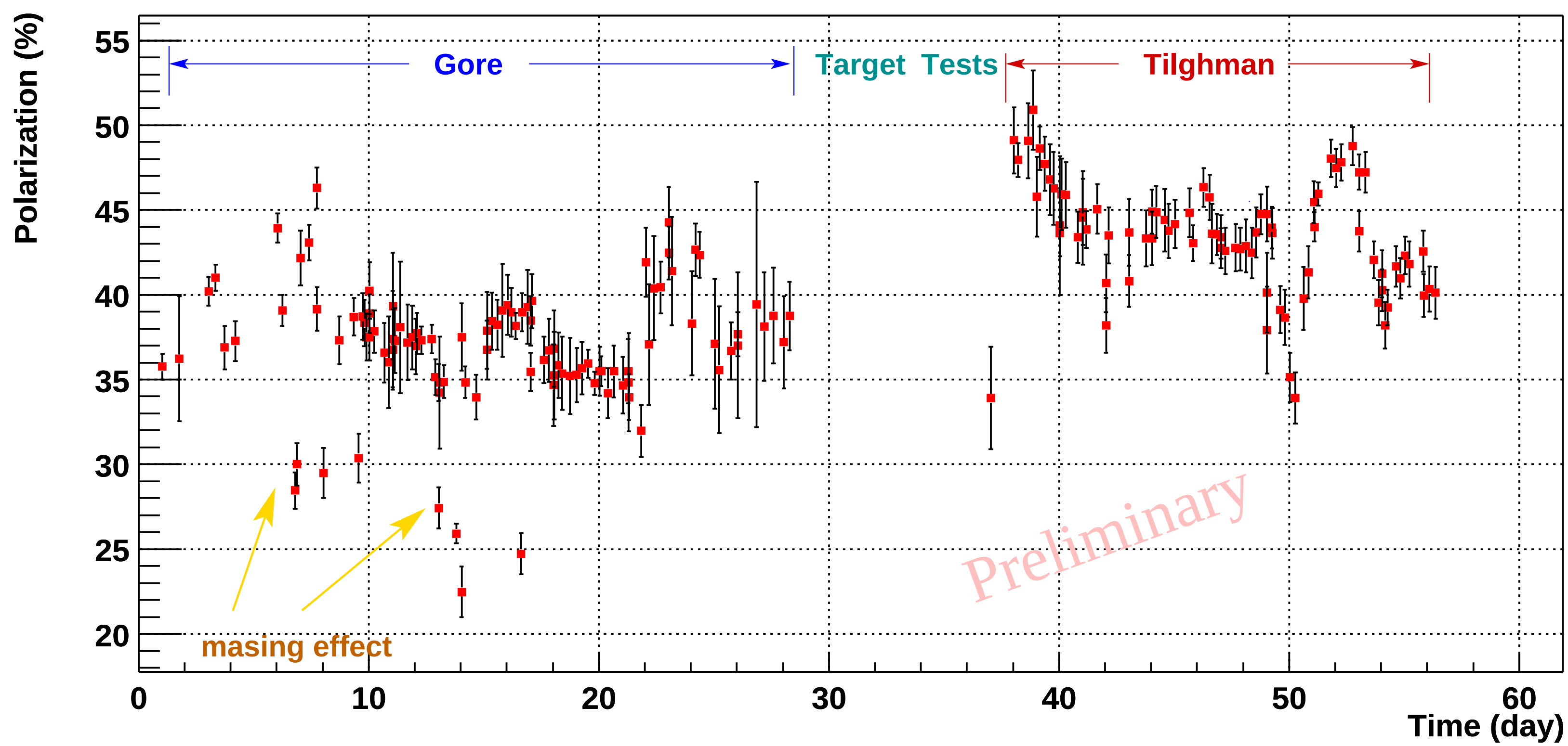


Target In Situ



Polarized ^{3}He Target Performance During E99–117

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



Asymmetry Analysis

Electron asymmetries

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

$$A_{\parallel,\perp} = \frac{A_{raw}}{f P_b P_t}$$

^{3}He asymmetries

$$A_1 = \frac{A_\parallel}{D(1+\eta\xi)} - \frac{\eta A_\perp}{d(1+\eta\xi)}$$

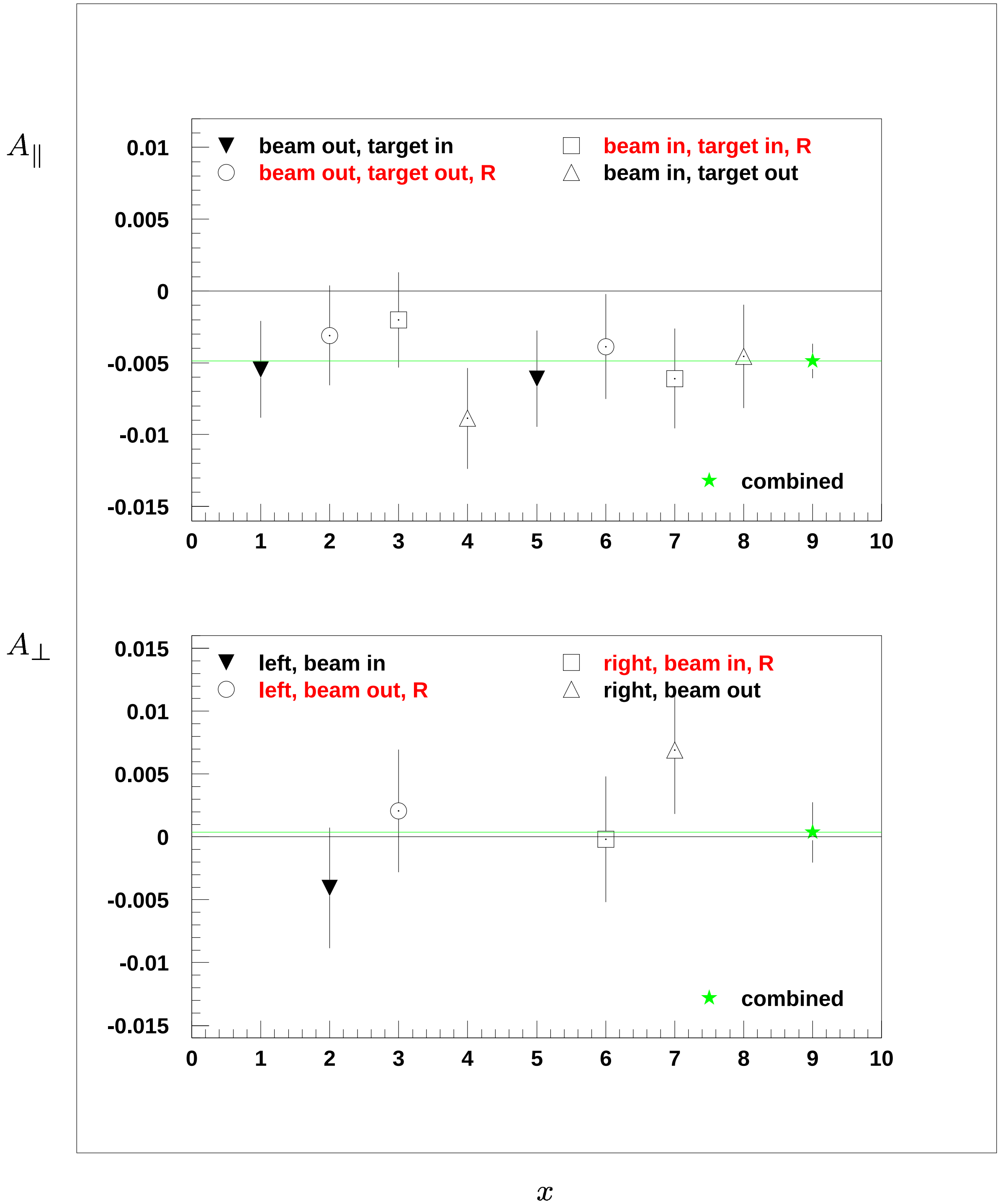
$$A_2 = \gamma\Big\{\frac{1-\frac{y}{2}}{D'}A_\parallel + \frac{1}{D'}\Big[\tan(\theta/2) + \frac{y}{2\sin\theta}\frac{1+(1-y)\cos\theta}{1-y}\Big]A_\perp\Big\}$$

$$g_1(x,Q^2) = \frac{F_1(x,Q^2)}{D'}\Big[A_\parallel + \tan(\theta/2)\cdot A_\perp\Big]$$

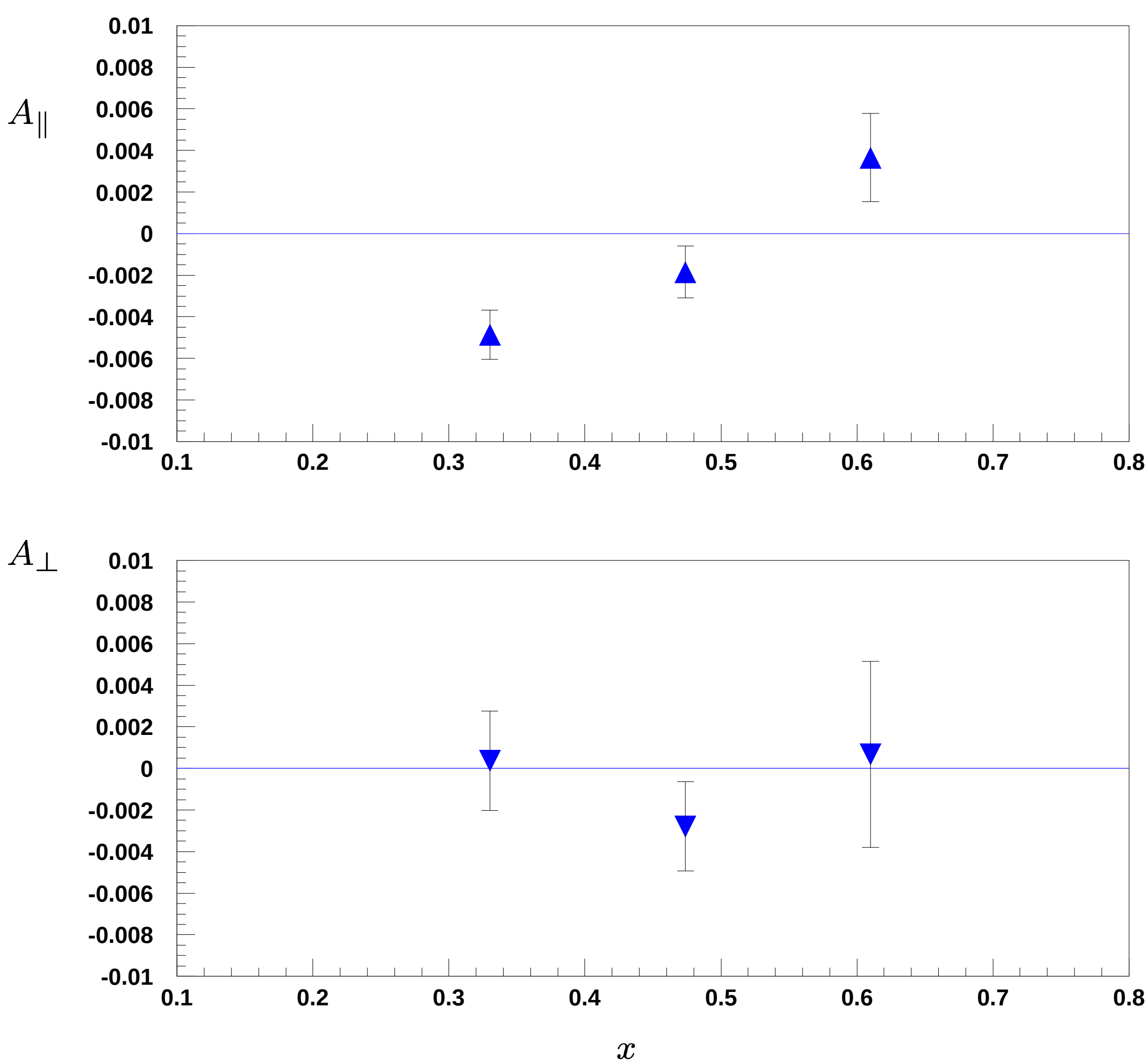
$$g_2(x,Q^2) = \frac{F_1(x,Q^2)}{2D'y\sin\theta}\Big[\frac{E+E'\cos\theta}{E'}A_\perp - \sin\theta\cdot A_\parallel\Big]$$

Asymmetries

^{3}He Raw Asymmetries

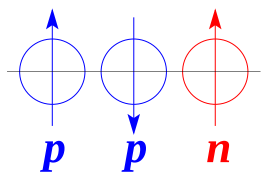


^{3}HE PHYSICS ASYMMETRIES



From ^{3}He to Neutron

$^3\vec{He}$ AS EFFECTIVE $\vec{n}$



$^3\vec{He} \approx \vec{n}$

CONVOLUTION APPROACH

Ciofi degli Atti et.al., Phys.Rev.**C48**, 968(1993); Phys. Lett., **B404**, 223(1997)

- ^3He consists S, S', D
- Three body calculation using Fadeev wavefunction

$$\tilde{g_1^n} = \frac{1}{\rho_n}(g_1^{^3\mathrm{He}} - 2\rho_p g_1^p)$$

$$\tilde{A_1^n} = \frac{W_1^{^3\mathrm{He}}}{W_1^n}\frac{1}{\rho_n}(A_1^{^3\mathrm{He}} - 2\frac{W_1^p}{W_1^{^3\mathrm{He}}}\rho_p A_1^p)$$

COMPLETE ANALYSIS

F. Bissey et. al., hep-ph/0109069

- S, S', D, Δ isobar in ^3He wavefuntion

$$A_1^n = \frac{F_2^{^3He}}{P_n F_2^n(1+\frac{0.056}{P_n})}[A_1^{^3He} - 2\frac{F_2^p}{F_2^{^3He}}P_p A_1^p(1 - \frac{0.014}{2P_p})]$$

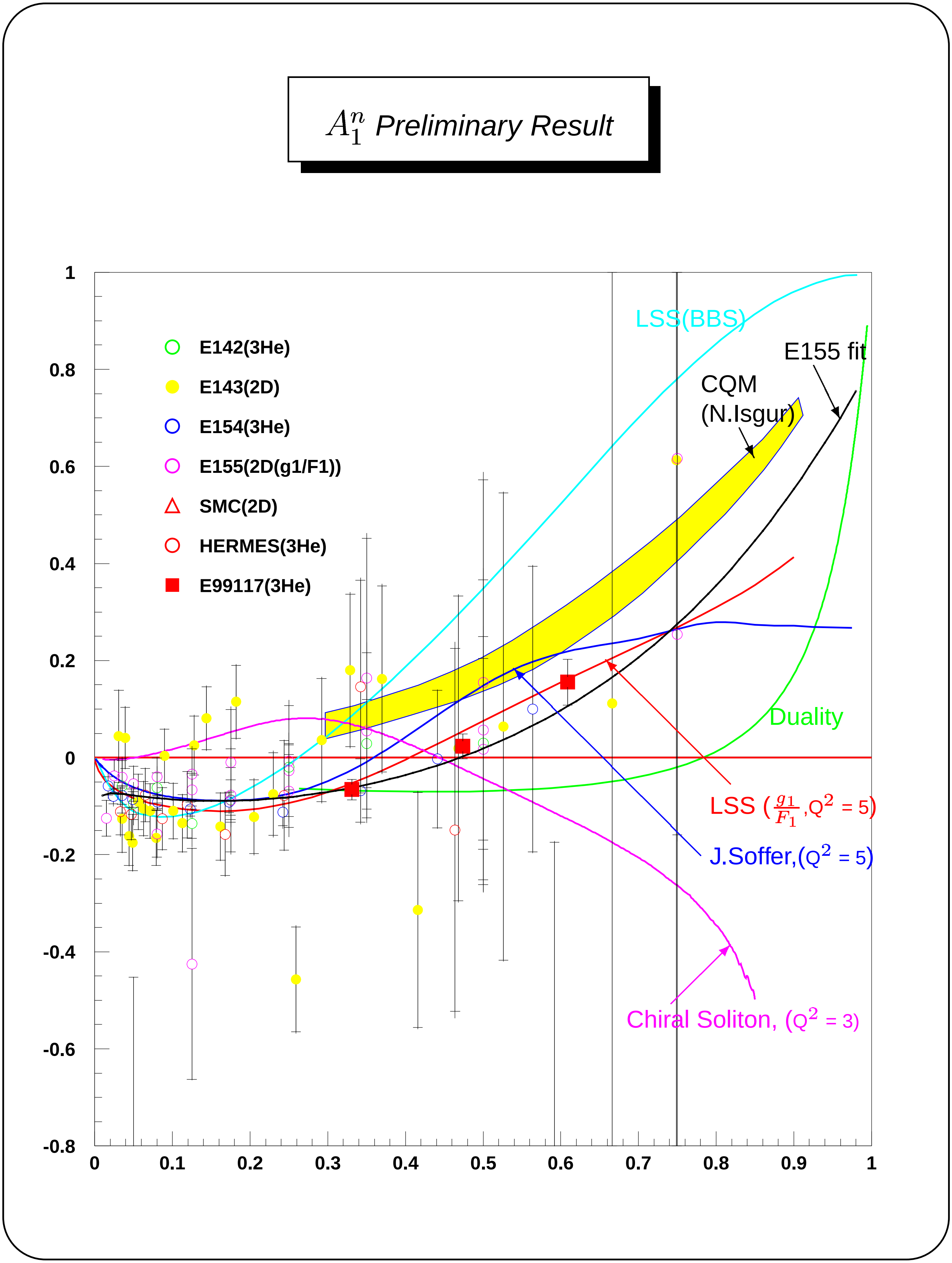
OTHER INPUTS

- $R(x, Q^2)$ - E143, K. Abe et. al., hep-ex/9808028
- F_2^p, F_2^D - NMC95, M. Arneodo et. al., hep-ph/9509406,
- EMC $F_2^{^3He} = \mathcal{R}^{3He}(2F_2^p + F_2^n)$, $F_2^n = \frac{F_2^D}{\mathcal{R}^D} - F_2^p$, W. Melnitchouk, pri.comm.
- Effective nucleon polarization P_p, P_n
  - $P_p = -0.028 \pm 0.004$,$P_n = 0.86 \pm 0.02$

    C. Ciofi degli Atti et.al.,*Phys.Rev.***C48**, R968(1993)
  - $P_p = -0.021$,$P_n = 0.879$

    PEST5, F. Bissey et. al., *Phys. Rev.* **C64**, 024004(2001)
  - $P_p = -0.018$,$P_n = 0.897$

    CD-Bonn2000 + TM (Tucson-Melbourne) 3NF, A. Nogga, Ph.D. thesis, (2001)
- A_1^p - E155 fit, P. L. Anthony et. al., *Phys.Lett.***B493**:19-28,(2000) (hep-ph/0007248)
- g_2, using g_2^{ww} (E155x)



A_1^n Preliminary Result
E142(3He)
E143(2D)
E154(3He)
E155(2D(g1/F1))
SMC(2D)
HERMES(3He)
E99117(3He)
LSS(BBS)
E155 fit
CQM
(N.Isgur)
Duality
LSS ($\frac{g_1}{F_1}$,Q^2 = 5)
J.Soffer,(Q^2 = 5)
Chiral Soliton, (Q^2 = 3)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

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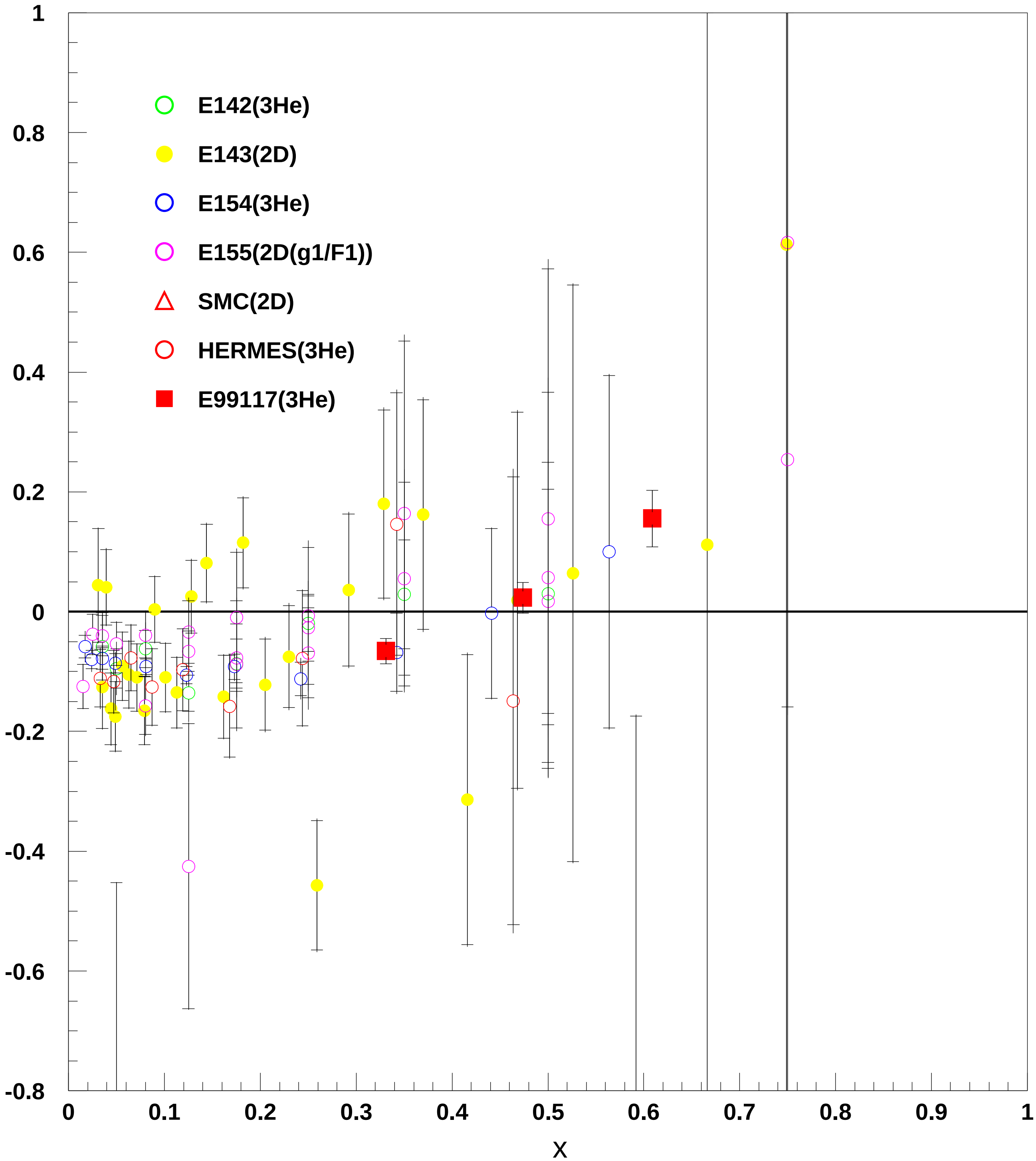
A_1^n *Preliminary Result*



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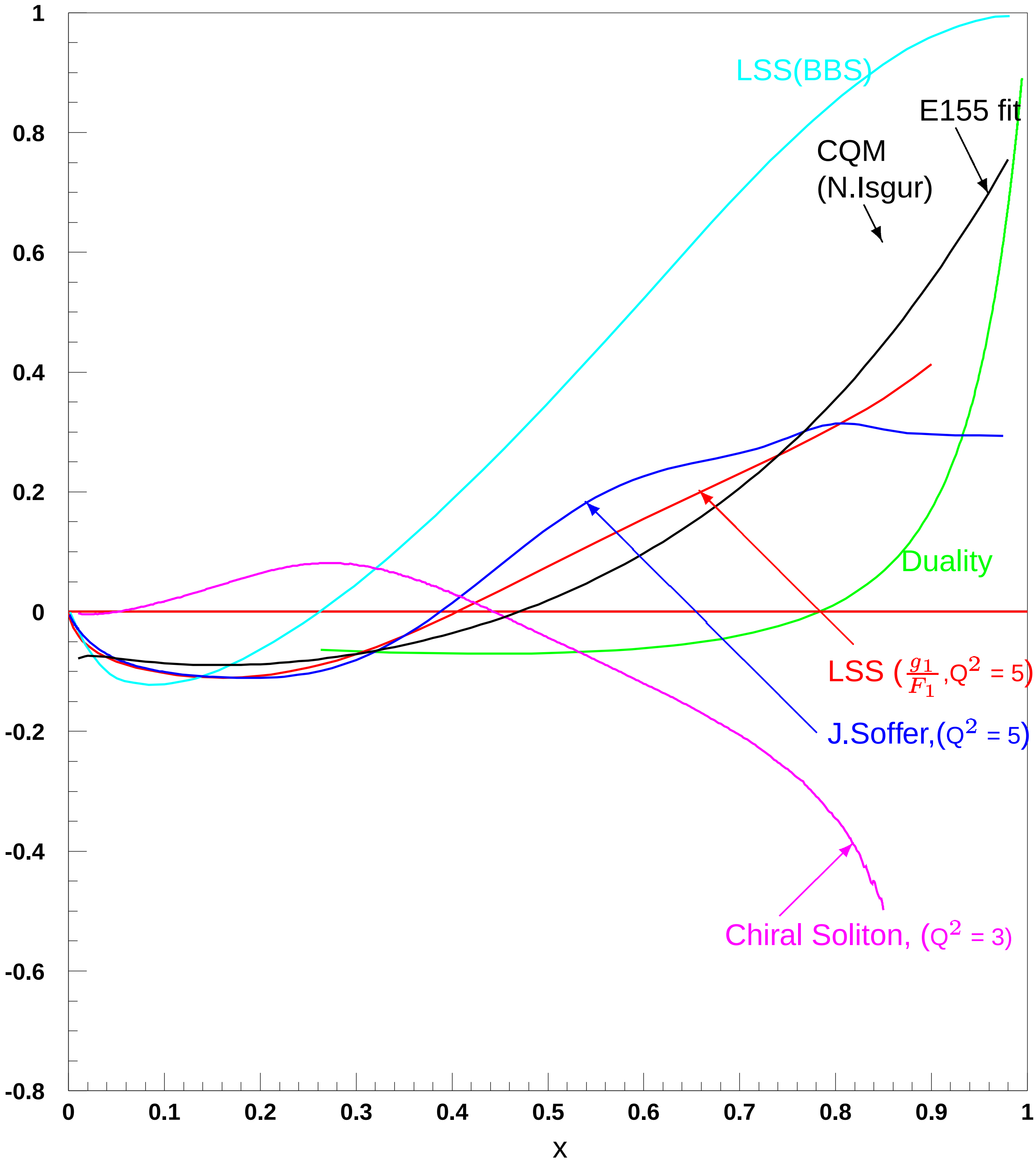
A_1^n Preliminary Result



Error Analysis

STATISTICS

- ΔA_1^n =5% at $x = 0.61$;

EXPERIMENTAL SYSTEMATICS

- Beam energy: 5.734 GeV, $\frac{\Delta E_b}{E_b} < 5 \times 10^{-4}$;
- Spectrometer momentum: $\frac{\Delta E_e}{E_e} < 5 \times 10^{-4}$;
- Spectrometer angle: $\Delta\theta_e < 0.1^\circ$;
- Beam polarization: 81%, $\frac{\Delta P_b}{P_b}$ <3%;
- Target polarization: 40%, $\frac{\Delta P_t}{P_t}$ <4%;
- Target spin orientation: $\Delta\theta_{targ}$ <1°;

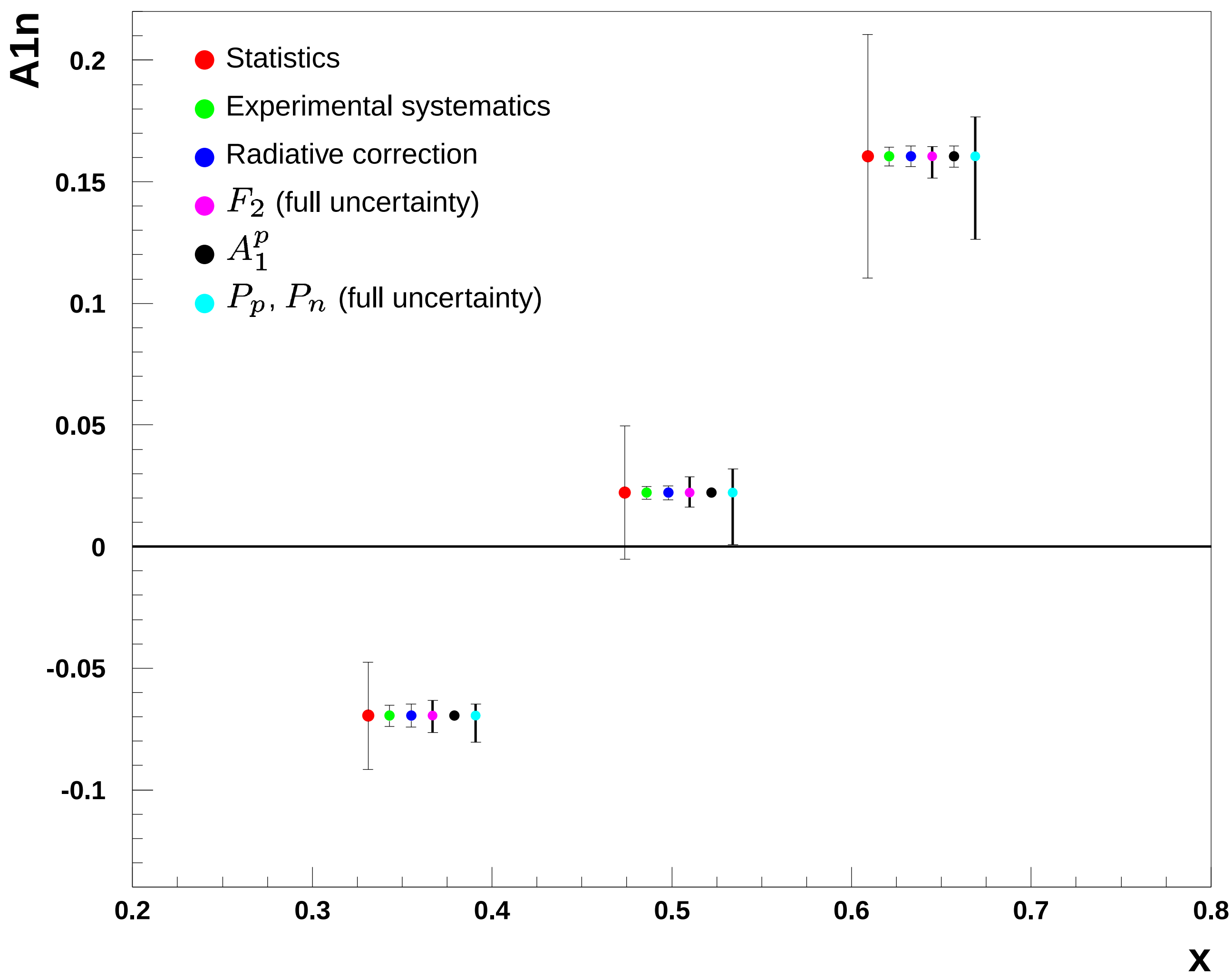
RADIATIVE CORRECTION

- Correct $A_{\parallel}^{^3He}$, $A_{\perp}^{^3He}$ directly;
- F_2 variation (5 models), $F_2^{p,\mathrm{res}}$ (2);
- g_1 variation, g_1/F_1 variation (3), $g_1^{^3He,\mathrm{res}}$ variation;
- g_2 variation (g_2^{ww} vs. $g_2 = 0$);

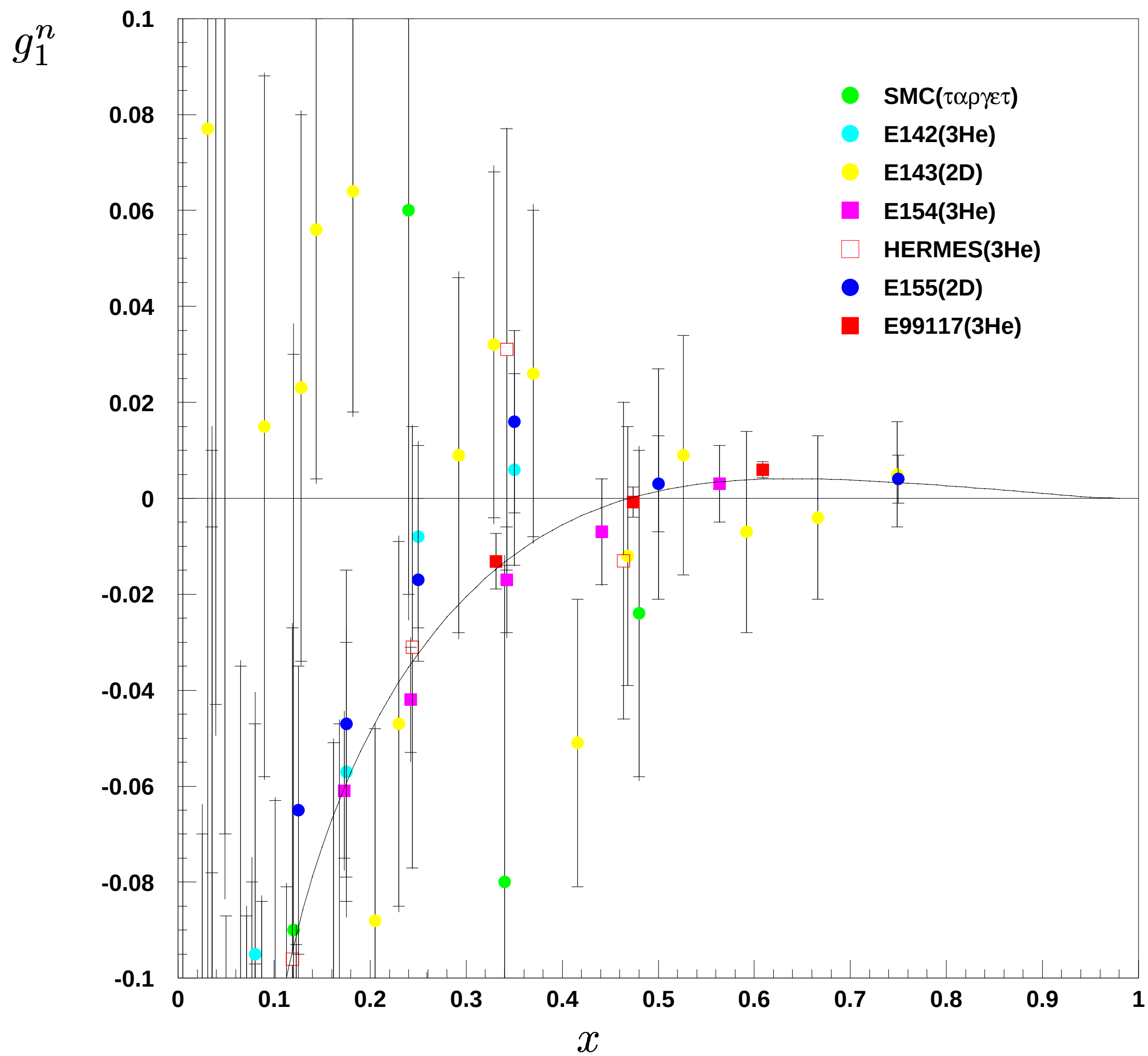
NUCLEAR CORRECTION

- F_2^p, F_2^d; $\mathcal{R}^{^3He}$, $\mathcal{R}^D$; A_1^p; P_p, P_n

Error Analysis

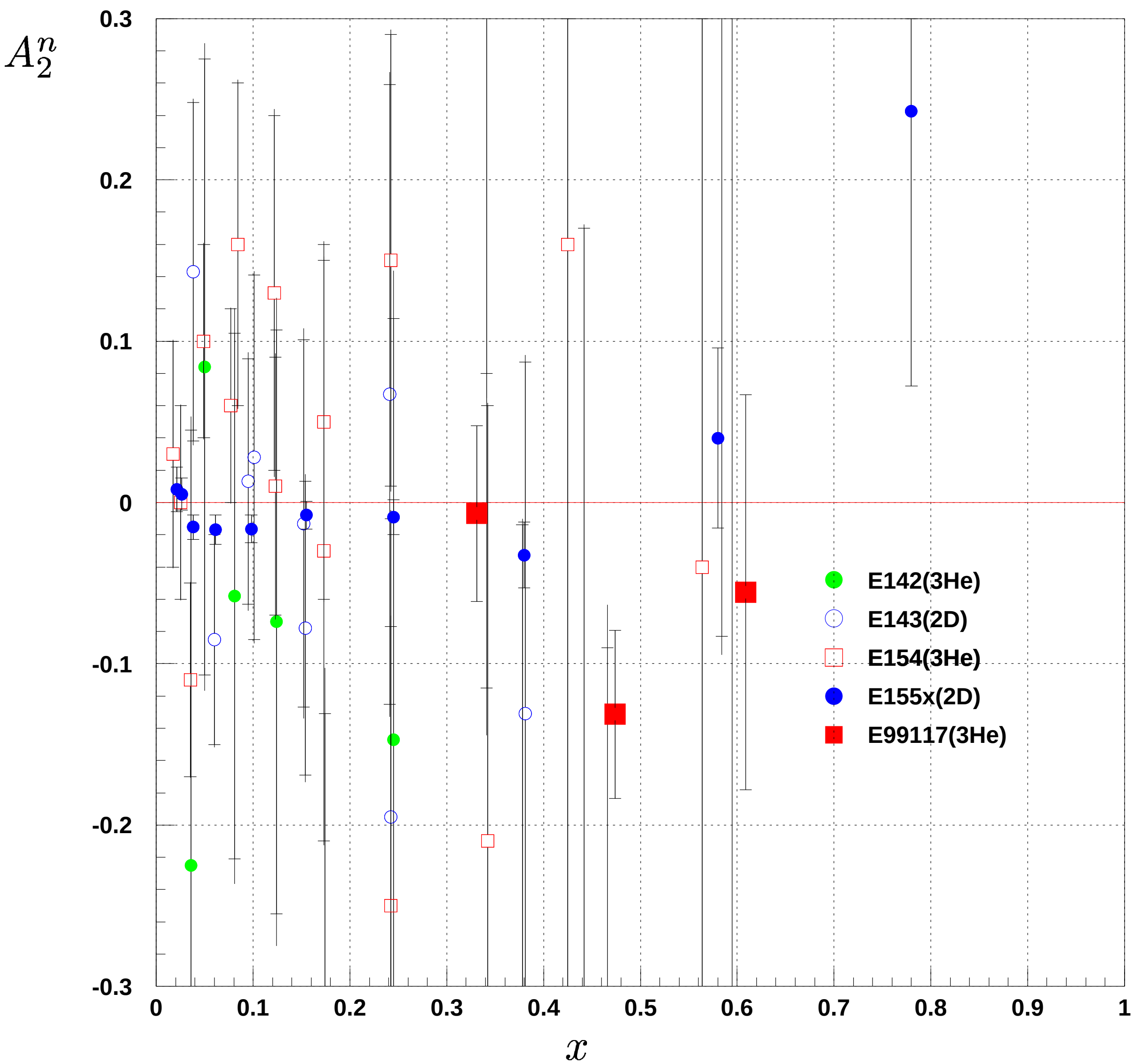


Preliminary Result

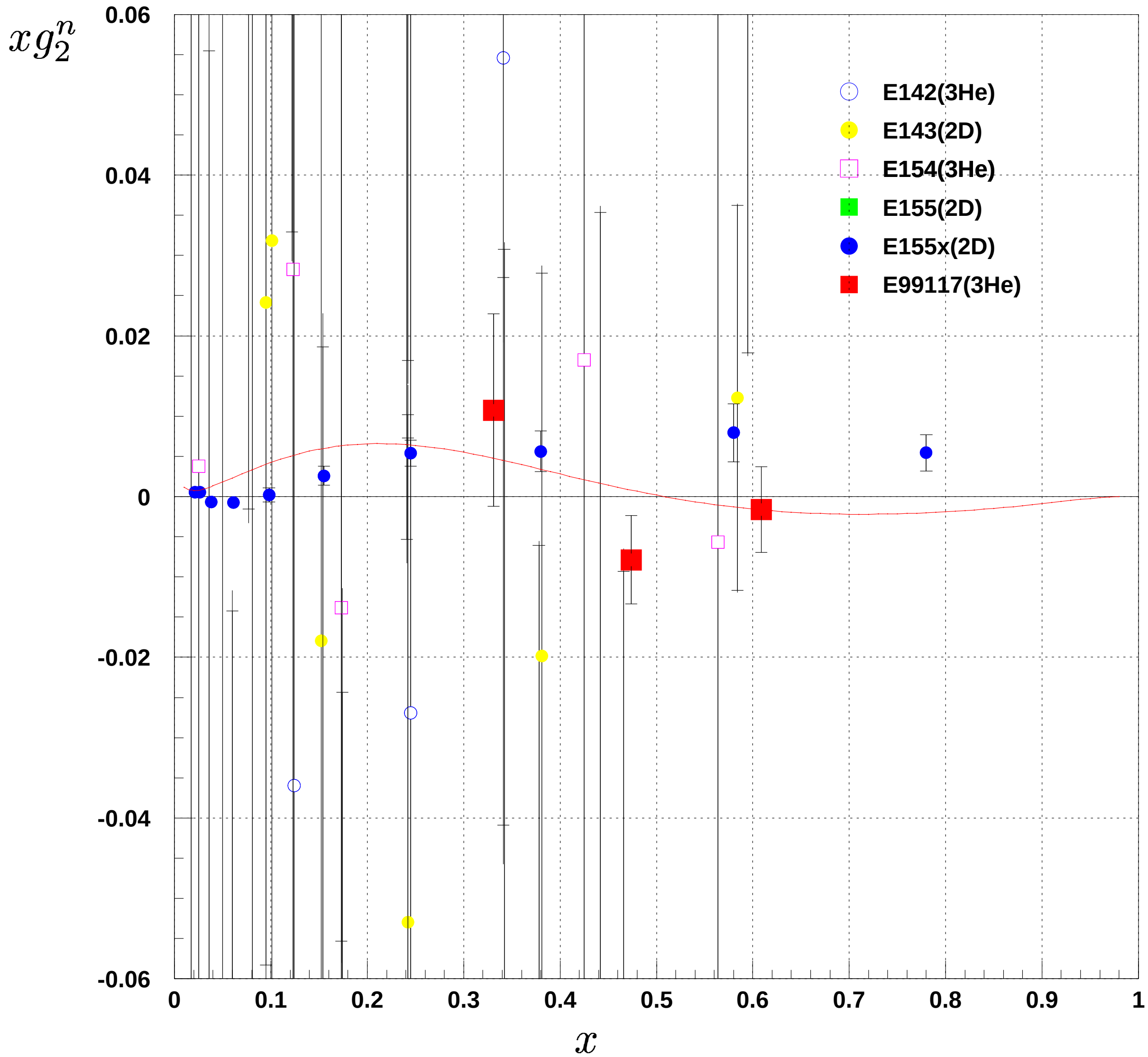


black solid curve: g_1^n obtained from E155 fit for $\frac{g1}{F1}$ and NMC95 fit for F_1, at $Q^2 = 4.0$ (GeV/c)^2

Preliminary Result



Preliminary Result



red solid curve: xg_2^{ww} obtained from E155 fit for $\frac{g1}{F1}$ and NMC95 fit for F_1, at $Q^2 = 4.0$ (GeV/c)^2

X. Zheng, M.I.T

Discussions

A_1^n and Spin Crisis

- Proton spin 'crisis': $\Sigma = \Sigma_v + \sum \Delta(q+\bar{q})_{sea} \sim 0.3 \pm 0.1$
- Current understanding of nucleon spin:
  - $\Sigma_v = 0.75$ from rCQM;
  - $\sum \Delta(q+\bar{q})_{sea} = -0.45$ from data;
  - $1 = \underbrace{\Sigma_v + \sum \Delta(q+\bar{q})_{sea}}_{\Sigma=0.3\pm0.1} + 2L_q + \Sigma_G$
- Spin physics programs have been planned at HERMES, RHIC and CERN to study $\Delta\bar{q}$ and ΔG;
- Measuring $\Delta\bar{q}$ and ΔG is also based on the knowing of contribtuion from valence quarks;
- A_1^n and A_1^p at large x will check our valence quark picture of $\Sigma_v = 0.75$. A negative A_1^n will bring a great doubt at this assumption and thus start a new search for resolution of 'spin crisis'.

- Can also check pQCD at valence quark region. ($\frac{\Delta d}{d} \rightarrow$? 1, $-\frac{1}{3}$)

Summary

EXPERIMENT E99-117

- Provides the first precise data of A_1^n and g_1^n at $x > 0.4$;
- Data on A_2^n, g_2^n also available;
- Check current understanding of nucleon spin;
- Help to understand constituent quark models;
- Provide new constraint on other models, PDFs.

Summary

Neutron Spin Structure Program at JLab Hall A

(Using Polarized ^3He)

Sum Rules

- ● E94010 A Connection between Bjorken and GDH Sum Rules, (Nov∼Dec 1998)
- ○ E97110 The Generalized GDH Sum Rule for Nearly Real Photons (Sep 2002)

Spin Structure Functions

- ● E99117 Neutron Asymmetry A_1^n at larget x_{Bj} (June $\sim$ July 2001)
- ● E97103 Search for Higher Twist Effect in g_2^n (Aug $\sim$ Sep 2001)
- ○ E01012 Neutron Spin Structure in the Resonance Region (approved)

A_1^n @ JLAB 12 GEV UPGRADE

- Precision measurement of spin asymmetry in valence quark region
- Decisive test of pQCD vs quark model, insight to quark-gluon wavefunctions