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

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OUTLINE

- Physics Motivation
  - A long introduction

- Theories - $A_1^n$ at Large $x_{Bj}$

- The Experiment
  Overview Experimental Setup Polarized $^3$He Target Data Analysis

- Results and Discussion

- Summary and Outlook
**Introduction**

**The Four Interactions of Our Nature**

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Strength</th>
<th>Force Type</th>
<th>Well Understood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational</td>
<td>$10^{-38}$</td>
<td>General Relativity</td>
<td>Well understood (at large scale)</td>
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<tr>
<td>Electromagnetic</td>
<td>$1/137$</td>
<td>SU(2)×U(1) gauge theory</td>
<td>Well understood</td>
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<tr>
<td>Weak</td>
<td>$10^{-5}$</td>
<td>SU(2)×U(1) gauge theory</td>
<td></td>
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<tr>
<td>Strong</td>
<td>$\lesssim 1$</td>
<td>SU(3), QCD</td>
<td>Not well understood yet</td>
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</tbody>
</table>

**Strong Interaction**

- Has its characteristics of
  - asymptotic freedom
  - confinement
- Is mostly non-perturbative – difficult to handle theoretically;
- Where and how can we verify that QCD is the correct theory for strong interaction?
  - Hadron structure as an ideal laboratory to study strong interaction
  - Deep inelastic scattering (DIS) – testing ground of QCD in the perturbative regime.
EXPLORING NUCLEON STRUCTURE USING ELECTROMAGNETIC PROBE

The One-Photon Exchange Approximation

\[ k' = (E', k') \quad P' = (E'_t, P') \]

\[ q = (\nu, q) \]

\[ k = (E, \vec{k}) \quad P = (M, \vec{0}) \]

- The four momentum transfer \( Q^2 \equiv -q^2 \)
- The invariant mass \( W^2 = M^2 + 2M\nu - Q^2 \)
  \[ \nu = E - E', \quad y = \nu/E \]

The cross section

\[ \frac{d\sigma}{d\Omega dE'} = \sigma_{Mott} \left[ \alpha W_1(Q^2, \nu) + \beta W_2(Q^2, \nu) \right] \]

for point like target
RESPONSES OF ELECTRON-NUCLEUS SCATTERING

Cross section

\[ W = 2 \text{ GeV} \] (elastic)

\[ W = M_T \] (quasi-elastic)

\[ W > 2 \text{ GeV} \] (deep inelastic)

\[ W = M \]

\[ Q^2 (\text{GeV/c})^2 \]
1950’s: Nucleons are not point-like particles, Hofstadter et al.

1968: First DIS data from SLAC, Friedman, Kendall, Taylor et al.
   – Nucleons have hard point-like scattering centers (partons);

1969:
   – Bjorken – scaling behavior:
     In the limit of $Q^2 \rightarrow \infty, \nu \rightarrow \infty$ and $Q^2/\nu$ fixed,
     
     $$MW_1(Q^2, \nu) \rightarrow F_1(x), \quad \nu W_2(Q^2, \nu) \rightarrow F_2(x);$$
     
     Bjorken limit and scaling variable $x_{Bj} \equiv \frac{Q^2}{2M\nu}$
   – Bloom et al., Breidenbach et al., observed scaling experimentally;
   – Feynman – Quark-Parton model (QPM);
     DIS is the incoherent sum of electron scattering off asymptotically free quarks;
     In the Bjorken Limit, $x_{Bj}$ is the fraction of the nucleon momentum carried by the
     struck quark.

1972-1973: ’t Hooft, Gross and Wilczek and Politzer
   Asymptotic freedom of QCD:
   $$\alpha_s(Q^2) = \frac{4\pi}{\beta_0 \ln(Q^2/\Lambda^2)}$$
   QCD – possible theory to describe strong interaction

Since then, DIS continue to serve as the major experimental tool to study nucleon
structure and a testing ground for perturbative QCD.
Formalism

\[
\frac{d^2 \sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{MQ^4} \left[ 2 \sin^2 \frac{\theta}{2} F_1(x, Q^2) + \frac{M^2}{\nu} \cos^2 \frac{\theta}{2} F_2(x, Q^2) \right]
\]

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

After 35 Years of Study

\[
F_2(x, Q^2)
\]

NMC data

\[
x = 0.0045 (x = 4.8)
x = 0.008 (x = 4.0)
x = 0.0125 (x = 3.2)
x = 0.0175 (x = 2.5)
x = 0.025 (x = 2.0)
x = 0.035 (x = 1.5)
x = 0.05 (x = 1.2)
x = 0.07 (x = 1.0)
\]

\[
x = 0.09 (x = 7.5)
x = 0.11 (x = 5.2)
x = 0.14 (x = 3.7)
x = 0.18 (x = 2.5)
x = 0.225 (x = 1.7)
x = 0.275 (x = 1.2)
x = 0.35 (x = 1.0)
x = 0.50 (x = 1.0)
\]
Scaling Violation in QCD

- Bjorken limit, $Q^2 \to \infty$, one photon exchange

- No $Q^2$ dependence $\to$ scaling;

- High $Q^2$, soft gluon emission

  - $Q^2$ evolution and DGLAP equations;
  - $\log Q^2$ dependence $\to$ mild scaling violation;

- Low $Q^2$, hard gluon emission

  - Operator Product Expansion and higher twist effects;
  - $\frac{1}{(Q^2)^{t-2}}$ dependence $\to$ strong scaling violation;
STRUCTURE FUNCTIONS IN QPM

Within the Quark-Parton Model,

The Callan-Gross Relation: \( F_2(x) = 2x F_1(x) \)

\[
F_1(x) = \frac{1}{2} \sum_i e_i^2 [q_i(x)]
\]

After 35 years of DIS experiments, the unpolarized structure of the nucleon is reasonably well understood (for moderate \( x \) region).
In 1980's, development of polarized beam and polarized target allow people to study the spin structure of the nucleon through polarized DIS.

- Spin observables provide new testing ground of QCD.
Polarization data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection.

– J.D. Bjorken


- 1988-1989, the Proton “Spin Crisis”
AFTER TWO DECADES

- Current Understanding of the Nucleon Spin –

\[ \frac{1}{2} = S_N^z = S_z^q + L_z^q + J_z^q; \]

Quarks contribute \( \sim 30\% \) to the nucleon spin

- “Surprise” instead of “Crisis”

- However, lot of problems remain
  - \( L_z^q \) ? \( J_z^q \) ?
  - Higher twist effect?
  - Deep valence region \( (x_{Bj} > 0.4) \) poorly explored.
POLARIZED STRUCTURE FUNCTIONS

- Longitudinally Polarized Target:

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

- Transversely Polarized Target:

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

INTERPRETATION OF \( g_1 \) IN QPM

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

\( g_2 \) AND HIGHER TWIST

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

\[
g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{g_1(y, Q^2)}{y} dy
\]
VIRTUAL PHOTON ASYMMETRIES

\[ A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \]

\[ A_1 = \frac{g_1 - \gamma^2 g_2}{F_1} \quad \text{with} \quad \gamma^2 = \frac{Q^2}{\nu^2} = \frac{4M^2 x^2}{Q^2} \]

\[ \approx \frac{g_1}{F_1} \quad \text{at large} \ Q^2 \]

\[ A_2 = \frac{\sigma_{LT}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{\gamma[g_1 + g_2]}{F_1} \]
**What Makes the Large $x$ Region Interesting?**

- At large $x$, valence quark dominate;
- Less contribution from $q - \bar{q}$ sea and gluons;
- A relatively clean region to study the nucleon structure.
After 20 years of Polarized DIS study, the large $x$ region stays poorly explored.
EXPERIMENTAL DIFFICULTIES

- High luminosity is required;
  Rate = luminosity \times cross section;
  At large $x$, $\sigma_{Mott}$ $\downarrow$ and $q(x)$ $\downarrow$ $\Rightarrow$ small cross section

- No dense free neutron target.
**EXPERIMENTAL DIFFICULTIES**

- High luminosity is required;
  Rate = luminosity $\times$ cross section;
  At large $x$, $\sigma_{Mott}$ $\downarrow$ and $q(x)$ $\downarrow$ $\Rightarrow$ small cross section

  – 1997, JLab CW Polarized $e^-$ Beam

- No dense free neutron target.

  – 1998, Hall A Polarized $^3$He as an Effective $\bar{n}$ Target
Theoretical Predictions of $A_{1}^{n}$

**MODELS**

- SU(6) CQM
- Broken SU(6) CQM – N.Isgur
- pQCD (HHC) – S. J. Brodsky, M. Burkardt, I. Schmidt (BBS) ;
  - E. Leader, A.V.Sidorov, D.B.Stamenov, LSS(BBS) ;
- Chiral Quark-Soliton Model – H. Weigel, L. Gamburg;
- Instanton Model – N.I.Kochelev, $A_{1}^{n} \sim 0$ or $A_{1}^{n} < 0$;
- Local Duality – W. Melnitchouk;

**PARTON DISTRIBUTION FUNCTIONS FROM WORLD DATA**

- LSS(BBS) – E. Leader, A.V.Sidorov, D.B.Stamenov, with pQCD (HHC) imposed ;
- LSS 2001 – E. Leader, A.V.Sidorov, D.B.Stamenov ;
- Statistical model - C.Bourrely, J. Soffer .
\[ |n \uparrow\rangle = \frac{1}{\sqrt{2}} |d \uparrow (ud)_{S=0}\rangle + \frac{1}{\sqrt{18}} |d \uparrow (ud)_{S=1}\rangle - \frac{1}{3} |d \downarrow (ud)_{S=1}\rangle - \frac{1}{3} |u \uparrow (dd)_{S=1}\rangle - \frac{\sqrt{2}}{3} |u \downarrow (dd)_{S=1}\rangle \]

\[ A_1^n = 0, \quad A_1^p = \frac{5}{9} \]
However, SU(6) symmetry is well known to be broken:

\[ \text{In SU(6)} \quad R^{nP} \equiv \frac{F_2^n}{F_2^p} = \frac{2}{3} \]

- Nucleon is made of three valence quarks;

- Hyperfine interaction $\vec{S}_i \cdot \vec{S}_j \delta^{(3)}(r_{ij}) \Rightarrow S = 1$ diquark state suppressed

$$|n \uparrow\rangle \rightarrow |d \uparrow (ud)_{S=0}\rangle \text{ as } x \rightarrow 1;$$

$$A^p_1$$ and $$A^P_1 \rightarrow 1 \text{ as } x \rightarrow 1.$$

- The large $x$ region is where CQM is supposed to work.
Perturbative QCD:

- Hadron helicity conservation (HHC) – based on the assumption that the orbital angular momentum of the quarks is zero
  * At \( x \to 1 \), \( S_Z = 1 \) diquark state suppressed;
  * \( \frac{\Delta u}{u} \to 1 \), \( \frac{\Delta d}{d} \to 1 \) at \( x \to 1 \);
  * \( A_1^n \) and \( A_1^P \) \( \to 1 \) as \( x \to 1 \).

- BBS  S. J. Brodsky, M. Burkardt, I. Schmidt, hep-ph/9401328v2
Curves: (1) LSS(BBS); (2) BBS; (3) CQM; (4) LSS 2001 \((g_1^n/F_1^n, Q^2 = 5)\);
(5) E155 experimental fit; (6) Stat Model \((Q^2 = 4)\);
(7) Chiral Soliton \((g_1^n/F_1^n, Q^2 = 0.4)\); (8) Local Duality;
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Experiment E99-117

Measure $A_1^n$ at

<table>
<thead>
<tr>
<th>$x_{Bj}$</th>
<th>0.327</th>
<th>0.466</th>
<th>0.601</th>
</tr>
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<tbody>
<tr>
<td>$Q^2 , (\text{GeV/c})^2$</td>
<td>2.709</td>
<td>3.516</td>
<td>4.833</td>
</tr>
<tr>
<td>$W^2 , (\text{GeV/c})^2$</td>
<td>6.462</td>
<td>4.908</td>
<td>4.090</td>
</tr>
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</table>

Measure electron asymmetries $A_\parallel$ and $A_\perp$ in inclusive $e^- - ^3\text{He}$ DIS

$$A_\parallel \equiv \frac{\sigma_{\downarrow \uparrow} - \sigma_{\uparrow \uparrow}}{\sigma_{\downarrow \uparrow} + \sigma_{\uparrow \uparrow}}$$

$$A_\perp \equiv \frac{\sigma_{\downarrow \Rightarrow} - \sigma_{\uparrow \Rightarrow}}{\sigma_{\downarrow \Rightarrow} + \sigma_{\uparrow \Rightarrow}}$$

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

Run Successfully from June 1 to July 31, 2001
Experimental Setup

\[ ^3\text{He}(e^-, e') \]

- \( e^- \): Jefferson Lab (JLab) polarized \( e^- \) beam
  
  \[ 5.734 \text{ GeV}, \ P_{\text{beam}} = 80\% \]

- \( ^3\text{He} \): Hall A polarized \( ^3\text{He} \) target
  
  \[ \sim 14 \text{ atm @ } 50^\circ\text{C}, \ P_{\text{targ}} = 40\% \]

- \( e' \): Two Hall A High Resolution Spectrometers (HRS).
# Development of $^3\bar{He}$ Target Technology

<table>
<thead>
<tr>
<th>Lab/Exp</th>
<th>year</th>
<th>beam</th>
<th>$I[\mu A]$</th>
<th>$\rho[\text{cm}^{-2}]$</th>
<th>$\mathcal{L}[\text{s}^{-1}\text{cm}^{-2}]$</th>
<th>$P_{\text{targ}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT/Bates(I)</td>
<td>90</td>
<td>$e^-$</td>
<td>6</td>
<td>$7.5 \times 10^{20}$</td>
<td>$2.8 \times 10^{34}$</td>
<td>0.19</td>
</tr>
<tr>
<td>MIT/Bates(IIa)</td>
<td>90</td>
<td>$e^-$</td>
<td>11</td>
<td>$1.1 \times 10^{19}$</td>
<td>$7.6 \times 10^{32}$</td>
<td>0.30</td>
</tr>
<tr>
<td>TRIUMF</td>
<td>91</td>
<td>$p$</td>
<td>$3.5 \times 10^{-3}$</td>
<td>$20 \times 10^{21}$</td>
<td>$4.4 \times 10^{31}$</td>
<td>0.60</td>
</tr>
<tr>
<td>SLAC(E142)</td>
<td>92</td>
<td>$e^-$</td>
<td>1.5</td>
<td>$7 \times 10^{21}$</td>
<td>$6.6 \times 10^{34}$</td>
<td>0.35</td>
</tr>
<tr>
<td>MIT/Bates(IIb)</td>
<td>93</td>
<td>$e^-$</td>
<td>25</td>
<td>$3.3 \times 10^{18}$</td>
<td>$5.1 \times 10^{32}$</td>
<td>0.38</td>
</tr>
<tr>
<td>IUCF</td>
<td>93</td>
<td>$p$</td>
<td>70</td>
<td>$1.5 \times 10^{14}$</td>
<td>$6.6 \times 10^{28}$</td>
<td>0.46</td>
</tr>
<tr>
<td>HERMES</td>
<td>95</td>
<td>$e^+$</td>
<td>$20 \times 10^{3}$</td>
<td>$3.3 \times 10^{14}$</td>
<td>$4.1 \times 10^{31}$</td>
<td>0.46</td>
</tr>
<tr>
<td>NIKHEF</td>
<td>95</td>
<td>$e^-$</td>
<td>$80 \times 10^{3}$</td>
<td>$7 \times 10^{14}$</td>
<td>$3.5 \times 10^{32}$</td>
<td>0.50</td>
</tr>
<tr>
<td>SLAC(E154)</td>
<td>95</td>
<td>$e^-$</td>
<td>1.5</td>
<td>$8 \times 10^{21}$</td>
<td>$7.5 \times 10^{34}$</td>
<td>0.38</td>
</tr>
<tr>
<td>MAMI</td>
<td>97</td>
<td>$e^-$</td>
<td>7</td>
<td>$5 \times 10^{20}$</td>
<td>$2.2 \times 10^{32}$</td>
<td>0.50</td>
</tr>
<tr>
<td>JLab</td>
<td>98~</td>
<td>$e^-$</td>
<td>12</td>
<td>$1 \times 10^{22}$</td>
<td>$1 \times 10^{36}$</td>
<td>0.35~ 0.45</td>
</tr>
</tbody>
</table>
**EXPERIMENTAL HALL A**

**Detector Package**

- *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%.
**OPTICAL PUMPING OF Rb**

\[ m_S = -\frac{1}{2} \quad \Rightarrow \quad m_S = +\frac{1}{2} \]

Collision Mixing

\[ \vec{B} \quad \Rightarrow \quad 795 \text{ nm} \]

Non-Radiative Quenching (~96%) through Rb-N\(_2\) collisions

Zeeman Splitting

**SPIN EXCHANGE DURING Rb-\(^3\text{He}\) COLLISIONS**
**TARGET SETUP**

Four 30W Diode Lasers tuned to 795 nm

Main Holding Helmholtz Coil

RF Drive Coil

NMR Pick-Up Coils

RF Drive Coil

EPR Optics

EPR RF Coil

oven

**e beam**
**NMR Polarimetry**

- Adiabatic Fast Passage (AFP) is used to flip the nuclei spin;
- $^3\text{He}$ spin flip induces a signal in the pick-up coils;
- Signal height is proportional to the $^3\text{He}$ polarization;
- Signal is calibrated by performing NMR on a water cell – the thermal polarization of the proton.

![Signal from NMR Polarimetry](image)
**EPR Polarimetry**

- Rb Zeeman splitting $\propto$ Magnetic field magnitude $\vec{B}$;
- $P_{3\text{He}}$ induces a small component:
  \[ \vec{B} = \vec{B}_{\text{main}} + \vec{B}_{3\text{He}} \]
  \[ 25 + 0.1 \text{ Gauss} \]
- $^3\text{He}$ spin flipped by AFP: $\vec{B}_{3\text{He}} \rightarrow -\vec{B}_{3\text{He}}$;
- Measure Rb resonance frequency shift: $\Delta \nu \propto B_{3\text{He}} \propto P_{3\text{He}}$.

**EPR Spectrum AFP6_4_5_23am.dat**

![EPR Spectrum](data:image/png;base64,iVBORw0KGgoAAAANSUhEUgAAAACAAAAbwAAABAMh0zvAAAAGXRFWHRTb2Z0d2FyZQBBZG9iZSBJbWFnZVJlYWR5ccllPAAAA3JREFUeNrs3KMD2ACEvAAAAQjP%eB%k+KAAAAAElFTkSuQmCC)
- Average in beam polarization:
  - ~35% during 1998-1999 run;
  - ~40% during 2001 run;
Asymmetry Analysis

**Analysis Procedure**

1. **Data**
   - Detector cuts
   - PID cuts
   - HRS acceptance cuts

2. **Relative yield N^±**
   - Elastic analysis
   - Sign convention
   - Δ(1232) asymmetry

3. **A_{raw}**
   - $P_{beam}$
   - $f_{N_2}$
   - $P_{targ}$

4. **Radiative corrections**

5. **A_{II}**, **A_{I}**
   - **A_{I}**
   - **A_{II}**
   - **A_{n}**
   - **A_{II}^n**
   - **A_{I}^n**

6. **Nuclear correction**
   - $g_1/F_1$
   - $g_2/F_1$
   - $g^n_1/F^n_1$
   - $g^n_2/F^n_1$

**Detector cuts**, **PID cuts**, **HRS acceptance cuts**

**Elastic analysis**, **Sign convention**, **Δ(1232) asymmetry**

**Radiative corrections**
Asymmetry Analysis

**Electron Asymmetries**

\[
A_{raw} = \frac{N^+}{\eta_{LT} Q^+} - \frac{N^-}{\eta_{LT} Q^-}
\]

\[
A_{\parallel, \perp} = \pm \frac{A_{raw}}{f_{N_2 P_b P_t}} + \Delta A^{RC}_{\parallel, \perp}
\]

**\(^3\)He Asymmetries**

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

\[
A_2 = \frac{\xi}{D(1 + \eta \xi)} A_{\parallel} + \frac{1}{d(1 + \eta \xi)} A_{\perp}
\]

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

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

**From \(^3\)He to Neutron**
ARE WE CONFIDENT ABOUT OUR MEASUREMENT?

- To check the “sign convention”, and to fully understand the system
  - Measured elastic $\vec{e}^+ - 3^7\text{He}$ longitudinal asymmetry and cross section;
  - Measured $\Delta(1232)$ transverse asymmetry;
- False asymmetry check.
**Summary**

**Experiment E99-117**
- Provide the first precise data of $A_1^n$ and $g_1^n$ at $x > 0.4$;
- Data on $A_2^n$ and $g_2^n$ also available;
- Polarized PDF $\Delta u/u$ and $\Delta d/d$ extracted from $g_1^n / F_1^n$ results;

**Impact**
- Check current understanding of nucleon spin in the valence quark region;
- Check pQCD (HHC) – quark orbital angular momentum;
- Provide constraints to other models;
**WHAT I DID**

- Test runs - rate and PID efficiency
- Run plan optimization
- Target
  - Laser alignment
  - EPR polarimetry
- Data Analysis ...
FALSE ASYMMETRY CHECK

- Polarized beam and unpolarized $^{12}$C target;
- Kinematics: $E = 5.7$ GeV, $E' = 1.72$ GeV, $\theta = 35^\circ$.

- The false asymmetry is negligible compared to the statistical error of measured $^3$He asymmetries.
ELASTIC ASYMMETRY ANALYSIS

![Graph showing elastic asymmetry analysis with data points and error bars for left and right arm run numbers.](image-url)
$\Delta(1232)$ Transverse Asymmetry

- $A_\parallel^\Delta < 0$ and $A_\perp^\Delta > 0$
- E94010 data

![Graphs showing asymmetry measurements for left and right arm run numbers.](image)
Asymmetries

$^3$He Raw Asymmetries

$A_{\parallel}$

$A_{\perp}$

$x$
$^3$He Physics Asymmetries

(w/o radiative correction)
Radiative Corrections

- Correct $A_{\parallel}^{3}\text{He}$, $A_{\perp}^{3}\text{He}$;
- POLRAD 2.0 and Single Arm Monte-Carlo simulation;
- Update $F_2$, $R$, $g_1$, $\frac{g_1}{F_1}$;
- Uncertainty studied by variation in S.F.'s.
$F_2$ variation in Radiative Corrections

- $\Delta A_{\text{par}} = A_{\text{born}} - A_{\text{obs}}$ (%)

Data points:
- E99117 data ($A_{\text{par}}/D$)
- Aobs
- Aborn

Graphs showing variations in $F_2$ with $x$.
$^3$He Results
$^3\text{He Results (cont.)}$
Polarized $^3$He as an effective neutron target

Effective nucleon polarizations:

$P_n = 86\%, P_p = -2.8\%$

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

Effective Neutron Target
From $^3\text{He}$ to Neutron (cont.)

**CONVOLUTION APPROACH**


- $^3\text{He}$ consists $S$, $S'$, $D$

- Three body calculation using Fadeev wavefunction

\[ g_1^n = \frac{1}{\rho_n}(g_1^{^3\text{He}} - 2\rho_pg_1^p) \]

\[ A_1^n = \frac{W_1^{^3\text{He}}}{W_1^n}\frac{1}{\rho_n}(A_1^{^3\text{He}} - 2\frac{W_1^p}{W_1^{^3\text{He}}\rho_p A_1^p}) \]

**COMPLETE ANALYSIS**

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

- S, S', D, $\Delta$ isobar in $^3\text{He}$ wavefunction

\[ A_1^n = \frac{F_2^{^3\text{He}}}{P_n F_2^n(1 + \frac{0.058}{P_n})}[A_1^{^3\text{He}} - 2\frac{F_2^p}{F_2^{^3\text{He}}}P_p A_1^p(1 - \frac{0.014}{2P_p})] \]
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 \( P_p, P_n \)
  \[ P_n = 0.86^{+0.036}_{-0.02}, P_p = -0.028^{+0.094}_{-0.004} \]
  - C. degli Atti et.al., Phys. Rev. C48, R968(1993);
- \( A_1^p \)
  - fit to world proton data;
- \( g_2 \), using \( g_2^{WW} \) since our \( Q^2 \) is reasonably large; (E155x)
COMPARISON BETWEEN TWO METHODS

\[(A_1^n)_{\text{compl}} - (A_1^n)_{\text{conv}} \approx \frac{F_2^n}{F_2} \frac{0.056}{P_n^2} A_1^{3\text{He}} - \frac{0.014 F_2^p}{P_n F_2^n} A_1^p.\]

- \((A_1^n)_{\text{compl}} - (A_1^n)_{\text{conv}} = 1 \sim 2\% \text{ for } 0.2 < x < 0.7\)
Result

$A_1^n$
Error Analysis

STATISTICS

- $\Delta A^n_1 = 2.4\%, 2.6\%, 4.8\%$ at $x=0.33, 0.48, 0.61$, respectively;

EXPERIMENTAL SYSTEMATICS

- Beam energy: $\frac{\Delta E_b}{E_b} < 5 \times 10^{-4}$, $5728.94 \pm 1.52$ MeV;
- Spectrometer momentum: $\frac{\Delta E_e}{E_e} < 5 \times 10^{-4}$;
- Spectrometer angle: $\Delta \theta_e < 0.06^\circ$;
- Beam polarization: $P_b = 79.73 \pm 2.4\%$;
- Target polarization: $40\%$, $\frac{\Delta P_t}{P_t} < 4\%$;
- Target spin orientation: $\Delta \theta_{targ} < 1^\circ$;

RADIATIVE CORRECTION

- $F_2, g_1$ and $g_2$ variation;

NUCLEAR CORRECTION

- $F^p_2, F^D_2, R^{3\text{He}}, R^D, A^p_1, P_p, P_n$. 
$A_1^n$ Error Analysis (cont.)
Results (cont.)

Curve: $g_1^n = \frac{q_1}{F_1}(E155) \times F_1(NMC95)$ at $Q^2 = 4.0 \text{(GeV/c)}^2$
Results (cont.)

Curve: $A_2^{WW}$ from E155 fit, at $Q^2 = 4.0$ (GeV/c)$^2$
Results (cont.)

Curve: $xg_2^{WW}$ from E155 fit, at $Q^2 = 4.0 \text{ (GeV/c)}^2$
– The ultimate goal of polarized DIS is to understand how different quarks and gluons contribute to the nucleon spin, how are they polarized along the nucleon spin direction? – $\Delta q/q$

- Recall that

$$F_1(x) = \frac{1}{2} \sum_i e_i^2 [q_i(x)] \quad \text{and} \quad g_1(x) = \frac{1}{2} \sum_i e_i^2 [\Delta q_i(x)]$$

- Assuming $s, \bar{s}(x)$ are negligible

$$\frac{g^n_1}{F^n_1} = \frac{\Delta u + 4\Delta d}{u + 4d}, \quad \frac{g^p_1}{F^p_1} = \frac{4\Delta u + \Delta d}{4u + d}$$

- Can extract $\frac{\Delta q}{q}$ as:

$$\frac{\Delta u}{u} = \frac{4}{15} A^p_1(4 + \frac{d}{u}) - \frac{1}{15} A^n_1(1 + 4\frac{d}{u})$$
$$\frac{\Delta d}{d} = \frac{4}{15} A^n_1(4 + 1/\frac{d}{u}) - \frac{1}{15} A^p_1(1 + 4/\frac{d}{u})$$

$A_1^n$ and $\Delta q/q$ (cont.)
$A_{1}^n$ and $\Delta q/q$ (cont.)
**Pion Photoproduction Asymmetries**

What can we learn from asymmetries in meson photoproduction?

- Sensitive to $\Delta G$, $\Delta q$, and to differences among the existing models;
  
  $\uparrow \uparrow$

  (moderate $p_T$) (high $p_T$)

  A. Afanasev, C.E.Carlson and C. Wahlquist, hep-ph/9706522

- No calculation available for the JLAB kinematics range ($p_T \sim 1$ GeV/c)
Discussions (cont.)

\[ \frac{g_1^n}{F_1^n} \]

- E99117\(^{(3}\text{He})\)
- E143\(^{(2}\text{H})\)
- E155\(^{(2}\text{H})\)

LSS 2001
\[ \left( g_1^n/F_1^n, Q^2 = 5 \right) \]