Measurement of the Proton $A_1$ and $A_2$ Spin Asymmetries: Probing Color Forces

SANE Results

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June 3, 2015
1 Motivation

2 SANE
   - Overview
   - Apparatus
   - Overview of Detectors
   - Polarized Target

3 Data Analysis
   - Event Reconstruction and Selection
   - Asymmetries
   - Background and Radiative Corrections

4 Results
   - Spin Structure Functions
   - Twist-3 Matrix Element: $d_2^p$

5 Summary
1 Motivation

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5 Summary
Quantum Chromodynamics (QCD)

\[
\bar{\psi}(i \not D - m)\psi - \frac{1}{4} G_{\mu\nu} G^{\mu\nu}
\]

The degrees of freedom are the QCD quark and gluon fields, not the constituent quarks!

The QCD coupling constant \( \alpha_s \) is a function of \( Q^2 \).

Asymptotic freedom → 2004 Nobel prize (Gross, Wilczek, Politzer)

Many successful predictions from pQCD at high energies.

QCD is believed to be the correct theory of the strong force.

QCD should be able to describe the structure of the proton and neutron.

However, perturbative techniques cannot describe the complex bound state of quark and gluon fields composing the proton.
The Strong Force

Quantum Chromodynamics

- $L_{QCD} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4} G_{\mu\nu}G^{\mu\nu}$
- The degrees of freedom are the QCD quark and gluon fields, **not the constituent quarks**!
- The QCD coupling constant $\alpha_s$ is a function of $Q^2$.
- Asymptotic freedom $\rightarrow$ 2004 Nobel prize (Gross,Wilczek,Politzer)
- Many successful predictions from pQCD at high energies.

\[ \text{Deep Inelastic Scattering} \]
\[ \text{e}^+\text{e}^- \text{ Annihilation} \]
\[ \text{Hadron Collisions} \]
\[ \text{Heavy Quarkonia} \]
**Quantum Chromodynamics**

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QCD is believed to be the correct theory of the strong force. QCD should be able to describe the structure of the proton and neutron. However, perturbative techniques cannot describe the complex bound state of quark and gluon fields composing the proton.
What does the nucleon look like?

size

$Q^2$
What does the nucleon look like?

Size $\leftarrow 1 \text{ fm}$

$Q^2 \rightarrow 1 \text{GeV}^2/c^2$
What does the nucleon look like?

size ← 1 fm 0.8 fm

$Q^2$ 1GeV$^2$/c$^2$ 2GeV$^2$/c$^2$
What does the nucleon look like?

Size: 1 fm, 0.8 fm, 0.4 fm

$Q^2$: 1 GeV$^2$/c$^2$, 2 GeV$^2$/c$^2$, 10 GeV$^2$/c$^2$
What does the nucleon look like?

<table>
<thead>
<tr>
<th>Size</th>
<th>1 fm</th>
<th>0.8 fm</th>
<th>0.4 fm</th>
<th>0.1 fm</th>
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Use our understanding of pQCD at high $Q^2$ to begin to test our understanding at lower $Q^2$. 

Operator Product Expansion
What does the nucleon look like?

Use our understanding of pQCD at high $Q^2$ to begin to test our understanding at lower $Q^2 \rightarrow \text{Operator Product Expansion}$
Deep Inelastic Scattering

Inclusive deep inelastic scattering experiments can probe the structure of the nucleon using both unpolarized and polarized targets and beams.

Unpolarized cross section

\[ \sigma_0 = \frac{4\alpha^2 E'^2}{q^4} \left[ 2 \frac{F_1}{M} \sin^2(\theta/2) + \left( \frac{F_2}{\nu} \right) \cos^2(\theta/2) \right] \]

The Bjorken variable

\[ x = \frac{Q^2}{2p \cdot q} = \frac{Q^2}{2M\nu} \]

where \( \nu = E - E' \) and

\[ Q^2 = -q^2 = 4EE' \sin^2(\theta/2) \]

\( x \) is the fraction of the total nucleon momentum carried by the struck quark.

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

\[ F_2(x, Q^2) = 2xF_1(x, Q^2) \]

(Callan-Gross)
Polarized Deep Inelastic Scattering

Retaining the polarization of the initial states and taking the cross section differences for the two electron spin states yields the two measured double spin asymmetries:

\[ 2\sigma_0 A_\parallel = -\frac{4\alpha^2}{Q^2} \frac{E'}{E} [(E + E' \cos \theta) g_1 / M \nu - Q^2 g_2 / M \nu^2] \]

\[ 2\sigma_0 A_\perp = -\frac{4\alpha^2}{MQ^2} \frac{E'^2}{E} \sin \theta \cos \phi [g_1 / M \nu + 2E g_2 / M \nu^2] \]

Why a transverse target is needed

\[ A_\parallel \propto g_1 - \frac{2Mx}{\nu} g_2 \]

\[ \rightarrow g_2 \text{ suppressed by } 1/\nu. \]

\[ A_\perp \propto g_1 + g_2 \]

\[ \rightarrow \text{In DIS region both contribute.} \]

\[ \Rightarrow \text{Directly sensitive to non-perturbative effects!} \]

\[ g_1(x, Q^2) = \frac{1}{2} \sum_i e_i^2 \Delta q_i(x, Q^2) \]

\[ g_2(x, Q^2) = ? \]
A twist-3 sum rule

Using the Operator Product Expansion for the non-local operators showing up in the S matrix, one can arrive a the infinite set of sum rules below. For \( n \geq 3 \) and \( n \) odd, we have

\[
\int_0^1 dx x^{n-1} \{ g_1 + \frac{n}{n-1} g_2 \} = \frac{1}{2} \sum_i \delta_i d_{n-1}^i E_{2,i}^n(Q^2, g) \quad (1)
\]

For \( n = 3 \)

\[
\int_0^1 x^2 \{ 2g_1 + 3g_2 \} dx = d_2 \quad (2)
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Interpretations of $d_2$

- Color Polarizabilities (X.Ji)
- Average Color Lorentz force (M.Burkardt)
Quark-gluon Correlations

M. Burkardt

\[
d_2 = \frac{1}{2MP^2} S_x \langle P, S \mid \bar{q}(0) g G^+ y (0) \gamma^+ q(0) \mid P, S \rangle
\]

but with \( \vec{v} = -c \hat{z} \)

\[
\sqrt{2} G^+ y = -E^y + B^x = -(\vec{E} + \vec{v} \times \vec{B})^y
\]
Quark-gluon Correlations

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\[ \sqrt{2} G^{+y} = -E^y + B^x = - (\vec{E} + \vec{\nu} \times \vec{B})^y \]

\( d_2 \Rightarrow \) average color Lorentz force acting on quark moving backwards (since we are in inf. mom. frame) the instant after being struck by the virtual photon. \(^a\)

\[ \langle F^y \rangle = -2M^2 d_2 \]

Quark-gluon Correlations

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

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**Twist-2 (Wandzura, Wilczek, 1977)**

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

\[ \equiv g_2^{tw2}(x, Q^2) \]
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**Twist-3 (Cortes, Pire, Ralston, 1992)**

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

\[ \equiv g_2^{tw3}(x, Q^2) \]
Quark-gluon Correlations

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

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\[ d_2(Q^2) = 3 \int_0^1 x^2 \bar{g}_2(x, Q^2) dx \]

\[ = \int_0^1 x^2 (2g_1(x, Q^2) + 3\bar{g}_2(x, Q^2)) dx \]
Quark-gluon Correlations

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

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As \( Q^2 \) decreases, when do higher twists begin to matter?
Tangent: Quark OAM

\[ L_q = \int dx \frac{1}{2} (x (H + E)(x, \xi, \Delta) - \bar{\tilde{H}}(x, \xi, \Delta)) \]

\[ L_q = -\int dx xG^2(x, \xi, \Delta) \]

\[ G^2(x, \xi, \Delta) = G_{WW}^2(x, \xi, \Delta) + G_{tw}^3(x, \xi, \Delta) \]

From sum rules: Kiptily and Polyakov (2002)

\[ \int dx x^2 G_{tw}^3(x, 0, 0) = -\frac{2}{3} \bar{\bar{g}}^2 x \tilde{H}(x, 0, 0) - \frac{2}{3} (H + E)(x, 0, 0) \]

\[ G_{WW}^2(x, 0, 0) = \frac{1}{3} x \tilde{H}(x, 0, 0) \]
Tangent: Quark OAM

Ji (1997)

\[ L_q = \int dx \frac{1}{2} \left( x(H + E)(x, \xi, \Delta) - \tilde{H}(x, \xi, \Delta) \right) \]
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Penttinen, et.al.(2000)

\[ L_q = - \int dx \ xG_2(x, \xi, \Delta) \]
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---

**G2 is a twist-3 GPD**

\[ G_2(x, \xi, \Delta) = G_2^{WW}(x, \xi, \Delta) + G_2^{tw3}(x, \xi, \Delta) \]
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From sum rules: Kiptily and Polyakov (2002)

\[ \int dx \ x^2 G_2^{tw3}(x, 0, 0) = -\frac{2}{3} d_2 = -2 \int x^2 \bar{g}_2(x) dx \]

Matching the integrands in the forward limit

\[ G_2^{tw3}(x, 0, 0) = -2\bar{g}_2(x) \]

\[ G_2^{WW}(x, 0, 0) = \frac{1}{3x} \tilde{H}(x, 0, 0) - \frac{2}{3}(H + E)(x, 0, 0) \]
Quark OAM

\[ L_q = \int dx \frac{1}{2} \left( x(H + E)(x, 0, 0) - \tilde{H}(x, 0, 0) \right) \]

\[ L_q = \int dx \left( -\frac{1}{3} \tilde{H}(x, 0, 0) - \frac{2x}{3} (H + E)(x, 0, 0) + 2x\bar{g}_2(x) \right) \]
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\[ L_q = \int dx \left( -\frac{5}{9} \tilde{H}^q(x, 0, 0) - \frac{2}{3} x\bar{g}_2^q(x) \right) \]
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\]

Explicit spin-orbit anti-correlation
Lorcé (2014), Lorcé and Pasquini (2011)

**Extracting \( \bar{g}_2 \)**

Inclusive DIS sensitive to \( \bar{g}_2^q + \bar{g}_2^\bar{q} \)
Need \( \bar{g}_2^q - \bar{g}_2^\bar{q} \)
At high-\( x \) is \( \bar{g}_2^q \sim 0? \)

**Caveats**

Neglects twist \( \geq 3 \)
Need lower \( x \) (not \( x^2 \) weighted)
Quark OAM

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + J_g
\]

\[
= \frac{1}{2} \Delta \Sigma + \mathcal{L}_q + \Delta G + \mathcal{L}_g
\]

\[
L_q = \left( -\frac{5}{9} \Delta \Sigma - \frac{2}{3} \bar{g}_2^q \right)
\]

\[
J_g = \frac{1}{2} + \frac{2}{3} \bar{g}_2^q + \frac{1}{18} \Delta \Sigma
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Quark OAM

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New relation between Ji and J.M. Decompositions

\[ \mathcal{L}_g + \mathcal{L}_q = 5 - 9J_g - \Delta G + 6x \bar{g}_2 \] (3)
Quark OAM

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\frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + J_g
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Need one more relation to experimentally connect Ji and J.M. decompositions.
Quark OAM

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + J_g \]

\[ = \frac{1}{2} \Delta \Sigma + L_q + \Delta G + L_g \]

\[ L_q = \left( -\frac{5}{9} \Delta \Sigma - \frac{2}{3} x \bar{g}_q \right) \]

\[ J_g = \frac{1}{2} + \frac{2}{3} x \bar{g}_q + \frac{1}{18} \Delta \Sigma \]

New relation between Ji and J.M. Decompositions

\[ L_g + L_q = 5 - 9 J_g - \Delta G + 6 x \bar{g}_2 \] \hspace{1cm} (3)

Need one more relation to experimentally connect Ji and J.M. decompositions.

\[ \Delta L = L_q - L_q : \text{ Burkardt (2013)} \]

Difference in angular momentum due to torque as the struck quark is ejected

\[ \Delta L = \int_{x^-}^{\infty} dr^- [\vec{r} \times (\vec{E} - \hat{z} \times \vec{B})]^z \] \hspace{1cm} (4)

See Matthias Burkardt’s talk later today!
Status of the Proton $g_1$ Spin Structure Function

$\propto x^2 g_1^p$

- SLAC E143
- SLAC E155
- EMC
- SMC
- HERMES
- COMPASS
- CLAS

$g_1^p$ for $1.5 < Q^2 < 8.5$

no CLAS data
Status of the Proton $g_1$ Spin Structure Function

$x^2 g_1^p$

- $g_1^p$ for $1.5 < Q^2 < 8.5$
- with CLAS data

More high $x$ data needed

W.R. Armstrong (ANL)
SANE
June 3, 2015

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Status of the Proton $g_1^p$ Spin Structure Function

$x^2g_1^p$

- $g_1^p$ for $1.5 < Q^2 < 8.5$
- More high $x$ data needed
Status of $g_2$ Spin Structure Function

$x^2 g_2^p$

- SLAC E143
- SLAC E155
- SLAC E155x
- SMC
- HERMES

$g_2^p$ for $1.5 < Q^2 < 8.5$
Status of $g_2$ Spin Structure Function

$\chi^2 g_2^p$

$g_2^p$ for $1.5 < Q^2 < 8.5$

More high $x$ data needed
\[ d^C_{2N} = \int_0^1 x^2 \{2g_1 + 3g_2\} \, dx \quad \text{and} \quad d^N_{2Nach} = \int_0^1 \xi^2 \{2\xi g_1 + 3 \left(1 - \frac{\xi^2 M^2}{2Q^2}\right) g_2\} \, dx \]

Recent results from \( d^2_n \) experiment
Posik, et.al. PRL.113.022002[3]

**Lattice QCD**

- Ab initio calculations can be done on the lattice
\[ d_{2}^{CN} = \int_{0}^{1} x^{2} \{ 2g_{1} + 3g_{2} \} \, dx \]

\[ d_{2}^{Nach} = \int_{0}^{1} \xi^{2} \{ 2\frac{\xi}{x}g_{1} + 3 \left( 1 - \frac{\xi^{2}M^{2}}{2Q^{2}} \right) g_{2} \} \, dx \]

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- Agree with proton and (now) neutron results ...
\[ d_2^{CN} = \int_0^1 x^2 \{2g_1 + 3g_2\} dx \]
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- \( d_2 \) lattice results in the quenched approximation (Gockeler, et.al., PRD.63.074506 [1])
- Agree with proton and (now) neutron results ...
- Updated and improved lattice results long overdue

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Physics with $g_2$

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- Polarized DIS is uniquely poised to provide insight into quark-gluon correlations.
- Direct access to higher twist using transversely polarized target.
- $\bar{g}_2$ possibly connected to quark OAM and $d_2$
- Twist-3 matrix element $d^p_2$ proportional to an average Lorentz color force.
- Ab initio QCD calculations (lattice) are tested
Physics with $g_2$

- Polarized DIS is *uniquely* poised to provide insight into quark-gluon correlations.
- Direct access to higher twist using *transversely* polarized target.
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- Twist-3 matrix element $d_2^p$ proportional to an average Lorentz color force.
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Precision measurements of $g_1$ and $g_2$ at JLab provide great insight into the non-perturbative structure of the nucleon and test our understanding of QCD
Motivation

SANE
- Overview
- Apparatus
- Overview of Detectors
- Polarized Target

Data Analysis
- Event Reconstruction and Selection
- Asymmetries
- Background and Radiative Corrections

Results
- Spin Structure Functions
- Twist-3 Matrix Element: $d_2^P$

Summary
Measured Asymmetries
Using Jefferson Lab's polarized electron beam with a polarized ammonia target, we measured the asymmetries $A_{180}$ and $A_{80}$, where the 180 (80) indicates the target polarization is anti-parallel (near perpendicular) to the incoming beam direction. The beam helicity is flipped rapidly (60Hz) allowing for the slowly varying experimental systematics to cancel.
Spin Asymmetries of the Nucleon Experiment (E07-003)

SANE Spokespersons
S. Choi (Seoul), M. Jones (JLab), Z-E. Meziani (Temple), O.A. Rondon (UVa)

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**SANE**

- 4.7 GeV and 5.9 GeV beam energies
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- **Big Electron Telescope Array**

---

**Diagram:**

- BigCal
- Lucite Hodoscope
- Čerenkov Counter
- Forward Tracker
- Polarized Target
- Target Outer Vacuum Chamber
- Superconducting Magnet
Polarized Electron Beam: 4.7, 5.9 GeV

Polarized Proton Target: $\perp$, $\parallel$

Ammonia (NH$_3$) Polarized via DNP in 5T Magnetic Field
Detector Overview

BETA was a unique detector
Detector Overview

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- Large solid angle, about 200 msr
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- Open configuration
Detector Overview

BETA was a unique detector

- Large solid angle, about 200 msr
- Open configuration
- No momentum selecting magnet
SANE used BETA to detect inclusive electrons with a large acceptance at angles around 40° for energies above about 1 GeV.
BigCal

Two Sections

The upper section from Yerevan Physics Institute used during RCS experiment.

- It consists of $4 \times 4 \times 40 cm^3$ lead-glass blocks
- They are arranged in a $30 \times 24$ array

Lower section from IHEP in Protvino, Russia.

- It consists of $3.8 \times 3.8 \times 45 cm^3$ lead-glass blocks
- They are arranged in $32 \times 32$ array

1,744 lead glass blocks total.

Figure: Bigcal lead-glass blocks

Bigcal was previously used in the GEp series of experiments
SANE Gas Čerenkov

Gas Čerenkov is from Temple University.

**Design**

- Filled with nitrogen gas at atmosphere.
- Uses 4 spherical and 4 toroidal mirrors to focus light to photomultiplier tubes.
- Used 3 inch quartz window Photonis PMTs for UV transparency
- Mirror blanks were sent to CERN for special coating for high reflectivity far into the UV.

**Figure:** Gas Čerenkov on Hall C floor
Čerenkov ADCs

- PMT 5
- Spherical mirrors at large scattering angle.

- PMT 4
- Toroidal mirror at small scattering angle.
Lucite Hodoscope

Lucite Hodoscope is from North Carolina A&T State University.

**Design**

- 28 curved Lucite bars with light guides mounted to edges cut at 45°
- PMT with light guide mounted at both ends of each bar.

**Figure:** Lucite Hodoscope in Hall C
Forward Tracker

Forward tracker is from Norfolk State University and University of Regina

Design

- 3 layers of $3 \times 3$ mm$^2$ scintillators.
- 1 horizontally segmented layer closest to the target consisting of 72 segments
- 2 vertically segmented layers consisting of 128 segments each
- WLS fibers glued to each bar with fibers connected to Hamamatsu 64-Channel PMTs

Figure: Forward tracker in position between Čerenkov snout and target OVC
Polarized NH$_3$ Target - UVa Target Group

- 5.1 T magnetic field
- Ammonia beads held by a cup, placed in LHe
- Average polarization was about 69%
1 Motivation

2 SANE
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5 Summary
Neural Network Reconstruction

Three Neural Networks

1. Cluster position correction
   - Corrects cluster position X-Y position
Neural Network Reconstruction

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2. Track deflection correction
   - Returns scattering angles at the target
Neural Network Reconstruction

Three Neural Networks

1. Cluster position correction
   - Corrects cluster position X-Y position
2. Track deflection correction
   - Returns scattering angles at the target
3. Track momentum vector correction
   - Corrections for the momentum vector at the face of BigCal
Neural Network Reconstruction

First moment → position
Second moment → standard deviation
Third moment → skewness
Fourth moment → peakedness
The Measured Asymmetry

\[ A_{\text{exp}} = \frac{N_+ - N_-}{N_+ + N_-} \]

\[ N_\pm = \frac{n_\pm}{Q_\pm L_\pm} \]

- \( n_\pm \) is the raw number of counts
- \( Q_\pm \) is the total incident charge
- \( L_\pm \) is the live time for each helicity.
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\[ A = \frac{A_{\text{exp}}}{fP_B P_T} \]

where \( P_B \) and \( P_T \) are the beam and target polarizations.
**Dilution factor**

**Packing Fraction**
- PF obtained from HMS using F1F209 cross-section model.
- PF determines how much of target-cell volume is ammonia vs He.
- Roughly 60 percent

Byoyoung Kang, Narbe Kalantarians, and Anusha Liyanage

**Dilution**
- Takes into account scattering from unpolarized material in target.
- Need to know target geometry and material.
- Yields from montecarlo are normalized to data from C target of known thickness
- Function of $W$ and $Q^2$

\[
f(W, Q^2) = \frac{N_p \sigma_p(W, Q^2)}{N_p \sigma_p + \sum_i N_i \sigma_i(W, Q^2)}\]
Only 50% of proposal due target magnet failure
Many thanks to JLab staff and others for fixing magnet.
Pair Symmetric Background Corrections

Electroproduction

- Model production cross sections (using Wiser’s fits)
- Run monte carlo to get \( R = \frac{N_{pair}^{e^+}}{N_{total}^{e^-}} \)
- Pion asymmetry from previous SLAC experiments (analysis by Oscar Rondon)

\[
A_{bg cor} = \left( \frac{1}{1 - 2R} \right) A_{raw} - \left( \frac{2R A_{pair}}{1 - 2R} \right) \\
= \frac{1}{f_{bg}} A_{raw} - C_{bg}
\]

Currently working on finalizing background corrections.
Fitting inclusive pion electro- and photo- production.
(Wiser fit is almost 40 years old) → Fit will be very useful for future experiments.

Photoproduction
Background Corrections

R(e+/e-)

1/f_{bg}

N_{pair} and N_{dis}

C_{bg}
Radiative Corrections

New Radiative Correction Code

- **Unpolarized** formalism of Mo and Tsai[2]
  - Includes internal and external radiative corrections.
- **Polarized** formalism of Akushevich, et.al.
- **Written in C++** (part of InSANE)
- **Check and re-checked against existing codes** (RADCOR and POLRAD)
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Formalism Differences
- Polarized formalism treats only internal RCs
- External RCs calculated using beam depolarization term
- Unpolarized formalism does internal and external RCs
Elastic Radiative Tail Subtraction

Elastic
- Largest radiative correction
- Treated with polarization following Akushevich, et.al.
- Correction depends on accurate calculation of radiated inelastic cross section

\[ A_{\text{corr}}^{el} = \frac{A_{\text{bg}}^{bg}}{f_{el}} - C_{el} \]

\[ \frac{1}{f_{el}} = \frac{\Sigma T}{\Sigma_{in}} \]

\[ C_{el} = \frac{\Delta_{el}}{\Sigma_{in}} \]

\[ \Sigma_x = \sigma_x^+ + \sigma_x^- \]

\[ \Delta_x = \sigma_x^+ - \sigma_x^- \]
After all corrections
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Models are showing $g_2^{WW}$. 

$x^2g_1^p$ and $x^2g_2^p$
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$$d_2^{CN} = \int_0^1 x^2 \{2g_1 + 3g_2\} \, dx$$

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

**proton**

**neutron**

Recent results from $d_2^n$ experiment
M. Posik, et.al. [3]

Existing data
\[ d_{2}^{CN} = \int_{0}^{1} x^2 \{ 2g_1 + 3g_2 \} \, dx \]
\[ d_{2}^{Nacht} = \int_{0}^{1} \xi^2 \left\{ 2\frac{\xi}{\lambda} g_1 + 3 \left( 1 - \frac{\xi^2 M^2}{2Q^2} \right) g_2 \right\} \, dx \]

**Preliminary**

**SANE Result**

- \( d_2 \) dips around \( Q^2 \sim 3 \text{ GeV}^2 \) for proton and neutron

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**SANE Result**

- \( d_2 \) dips around \( Q^2 \sim 3 \) GeV\(^2\) for proton and neutron
- Is this a flavor independent average color force?
- Updated Lattice calculations are long overdue!
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Summary
SANE Analysis (nearly) Complete!

- SANE results *significantly* improve world data on $g_2^p$.

The result seems to indicate a negative or zero value around $Q^2 \sim 3 - 6$ GeV$^2$ at the one standard deviation level, consistent with the neutron result.

Comparing to recent $d_2$ results: the average transverse color force appears flavor independent.

Is this result surprising?

The flavor averaged color structure of the nucleon should be flavor independent.

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- JLab 12GeV neutron experiments (Hall C and Hall A) will extend to higher $Q^2$ with more uniform coverage.

A dedicated experiment with a transversely polarized proton target is a worthwhile effort at 12 GeV.

Proposal to match the expected neutron precision.

High $x$ and high $Q^2$ data on $g_1$ and $g_2$ is needed to cleanly extract the leading twist PDFs.

While a future EIC will focus on the sea quarks and gluons, JLab will continue to present a unique opportunity for studying QCD and the structure of the nucleon to high precision in the valence region.
## Conclusion (2/2)

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Thank You!

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Radiated cross sections and asymmetries

\[ A_{180}^p, E=5.9 \text{ GeV} \]

\[ \sigma_{180}, E=5.9 \text{ GeV} \]

\[ A_{80}, E=5.9 \text{ GeV} \]

\[ \sigma_{80}, E=5.9 \text{ GeV} \]

- Born
- Inel. Rad. Tail
- El. Rad. Tail