P-1039:  
**Polarized Target Drell-Yan Single-Spin Asymmetry Measurement to Access Sea Quarks’ Angular Momentum**  
Xiaodong Jiang and Andi Klein, Los Alamos National Laboratory  
June 5th, 2013 @ Fermilab PAC.

- Measure Drell-Yan yield dependence on the target’s spin direction.
- Strong constraints on sea quarks’ angular momentum.
- Add a polarized proton (NH$_3$) target to SeaQuest (E906) setup.

\[
A_N = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \neq 0
\]

\[
A_N \equiv 0 \text{ if } L_{\bar{u}} = 0
\]
Outline:

• Nucleon spin puzzle: ~50% of proton spin is not accounted for. Sea quarks’ orbital angular momentum could be a major part of the “missing spin”.
• Quark orbital angular momentum leads to transverse momentum dependent distributions: Sivers distribution.
• Polarized target Drell-Yan asymmetry at SeaQuest (E906) provides a clean access to sea quark Sivers distribution.
• Experimental setup, polarized target and resources needed.

Drell-Yan yields depend on target’s spin direction?

\[
A_N = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \neq 0
\]

\[
A_{DY}^N \propto \frac{u(x_b) \cdot f_{1T}^{\perp, \bar{u}}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}
\]

\[
A_N \equiv 0 \quad \text{if} \quad L_{\bar{u}} = 0
\]
P-1039 Collaboration:

Co-Spokespersons: A. Klein, X. Jiang
Los Alamos National Laboratory

Collaboration includes experts on
- Drell-Yan: E772, E866, E906
- Polarized target: BNL, SLAC, JLab
- Spin experiments: JLab, HERMES, RHIC

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Nucleon Spin Puzzle: ~50% of spin is missing

The need for a major breakthrough in understanding the origin of the nucleon spin

Nucleon’s ½ spin:

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma_q + L_q + \Delta g + L_g \]

Many years of spin experiments since 1988:

Quark polarization from all flavor:

\[ \Delta \Sigma_q \approx 0.25 \pm ... \]

Gluon polarization (RHIC):

\[ \int_{0.05}^{0.2} dx \Delta g(x) = 0.1 \pm 0.06 \]

about half of the nucleon’s spin is not accounted for

Orbital angular momentum? Sea quarks’ angular momentum could be a major part of the “missing spin”.


\[ \Delta \Sigma_q \approx 25\% \]

\[ 2 \, L_q \approx 46\% \text{ (0\% (valence) + 46\% (sea))} \]

\[ 2 \, J_g \approx 25\% \]

\[ L_u \approx - L_d \]
Drell-Yan at SeaQuest (E906): a Clean Access to Sea Quark

Strong flavor asymmetry in the sea.

Could sea quarks carry a significant amount of angular momentum?
The meson cloud model explains the flavor asymmetry in the sea, and requires quarks to carry angular momentum.

\[ |p\rangle = p + N\pi + \Delta\pi + \ldots \]

Pions $J^p=0^-$ Negative Parity
Need $L=1$ to get proton’s $J^p=\frac{1}{2}^+$

Sea quarks should carry orbital angular momentum.
Quark Orbital Momentum and the Sivers Function

The Sivers function is the distribution of unpolarized quarks in a transversely polarized proton

\[ L = \vec{b} \times \vec{k} \]

\[ f_{q/P^+} (x, k_\perp, S) = f_1 (x, k_\perp^2) - \frac{S \cdot (\hat{P} \times k_\perp)}{M} f_{1T} (x, k_\perp^2) \]

Sivers distribution was believed to vanish until 2002!
- Imaginary piece of interference \( L_q=0 \times L_q=1 \) quark wave functions.

Sivers function = 0 \( \iff \) \( L_q=0 \)

Sea quark Sivers function = 0 ?
Accessing the quark Sivers distribution

**Polarized target experiments**

Left-right asymmetry in Semi-Inclusive Deep Inelastic Scattering (SIDIS) on a polarized nucleon

\[ e_p^\uparrow \rightarrow e' \pi X \]

Left-right asymmetry in Drell-Yan di-muon production (DY) on a polarized nucleon

\[ pp^\uparrow \rightarrow \mu^+ \mu^- X \]

**Cornerstone prediction of QCD**

The same quark Sivers distribution in both processes, but with **opposite sign**

\[ f_{1T}^{\perp q} \bigg|_{SIDIS} = - f_{1T}^{\perp q} \bigg|_{DY} \]
Asymmetry in Semi-Inclusive DIS

\[ e p^\uparrow \rightarrow e' \pi X \]

\[ d\sigma^{\uparrow\downarrow} = d\sigma_0 \pm \sum q e_q^2 f_{1T}^q(x) \otimes D_1^q(z) \]

- Involves quark to hadron frag. func.
- Valence and sea quarks are mixed.

\[ A_N = \frac{\sum_q e_q^2 f_{1T}^q(x) \otimes D_1^q(z)}{\sum q e_q^2 f_1^q(x) \otimes D_1^q(z)} \]

Asymmetry in Drell-Yan

\[ p p^\uparrow \rightarrow \mu^+ \mu^- X \]

\[ d\sigma^{\uparrow\downarrow} = d\sigma_0 \pm \sum q e_q^2 [f_1^q(x_1) \cdot f_{1T}^{\bar{q}}(x_2) + 1 \leftrightarrow 2] \]

- No quark frag. func. involved.
- Valence and sea quarks can be isolated
  - Pol. Beam \(\rightarrow\) valence quark (P-1027)
  - Pol. Target \(\rightarrow\) sea quark (P-1039)

\[ A_N = \frac{\sum_q e_q^2 [f_1^q(x_1) \cdot f_{1T}^{\bar{q}}(x_2) + 1 \leftrightarrow 2]}{\sum_q e_q^2 [f_1^q(x_1) \cdot f_{1T}^{\bar{q}}(x_2) + 1 \leftrightarrow 2]} \]
Quark Sivers Distribution Leads to Left-Right Bias

\[ p \, p^\uparrow \rightarrow \pi X \]

Valence quarks have a clear left-right bias due to orbital angular momentum.

Sea quark Sivers distribution =0 ?
Hints of Non-Vanishing Sea Quark Sivers Distribution?

BRAHMS Preliminary (arXiv:0908.4551)

$p^+p \rightarrow h X \sqrt{s} = 200 \text{ GeV}$

Sea quark generates left-right bias?

Secondary string-breaking?

Left-right bias generated through fragmentation process?
Quark Sivers Distributions: fit to HERMES and COMPASS data (2009)
Semi-Inclusive Deep-Inelastic Scattering on transversely polarized targets

\[ A_N = \frac{\sum_q e_q^2 f_{1T}^{\perp q}(x) \otimes D_1^q(z)}{\sum_q e_q^2 f_{1}^{q}(x) \otimes D_1^q(z)} \]

- Involves quark fragmentation functions.
- Valence quark overwhelmingly dominate.
- Limited sensitivity to sea quark leads to zero sea quark Sivers distribution.

\[ N^\uparrow(l, l' h) \]

→ large uncertainties in Sivers distribution

• up-quark favors left (L_u>0),
• down-quark favors right (L_d<0).

\[ L_u \approx -L_d \]
Quark Sivers Distributions: a new fit includes new data (2013)

Sun and Yuan:
arXiv:1304.5037

- Include new COMPASS proton target data (2010) and earlier transverse distribution data.
- Take $Q^2$-evolution effects into account.
- Allow contributions from sea quarks which lead to non-zero $u\bar{u}$ Sivers distribution, however with large error bars.
- Predict Drell-Yan target single-spin asymmetry for SeaQuest.

\[
A_{N}^{DY} \propto \frac{u(x_b) \cdot \frac{1}{f_{1T}} \bar{u}(x_t)}{u(x_b) \cdot \bar{u}(x_t)}
\]
Projected Precision with a Polarized Target at SeaQuest

Exis:ng data do not put enough constraints on the sea quark Sivers distribution, neither in sign nor value.

If $A_N \neq 0$, major discovery:
- "Smoking Gun" evidence for $L_{ubar} \neq 0$
- Determine sign and value of $ubar$
- Sivers distribution
- Confirm Lattice QCD and Meson Cloud Model expectations
- Help shape physics direction at EIC

If $A_N = 0$:
- $L_{ubar} = 0$, spin puzzle more dramatic?
- Sea flavor asymmetry hard to explain.
- In contradiction to Lattice QCD and Meson Cloud Model.

Sta:s:cs shown for one calendar year of running:
\[ L = 1.4 \times 10^{43} / \text{cm}^2 \quad \leftrightarrow \quad \text{POT} = 2.1 \times 10^{18} \]

Request for two calendar years of beam time
### COMPASS, P-1027 and P-1039

<table>
<thead>
<tr>
<th></th>
<th>Beam Pol.</th>
<th>Target Pol.</th>
<th>Favored Quarks</th>
<th>Physics Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COMPASS</strong></td>
<td>×</td>
<td>✔</td>
<td>Valence quark</td>
<td>Sign change and size of Sivers distribution for valence quark</td>
</tr>
<tr>
<td>$\pi^- p^\uparrow \rightarrow \mu^+ \mu^- X$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>P-1027</strong></td>
<td>✔</td>
<td>×</td>
<td>Valence quark</td>
<td>Sign change and size of Sivers distribution for valence quark</td>
</tr>
<tr>
<td>$p^\uparrow p \rightarrow \mu^+ \mu^- X$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>P-1039</strong></td>
<td>×</td>
<td>✔</td>
<td>Sea quark</td>
<td>Size and sign of Sivers distribution for Sea quarks, if DY $A_N \neq 0.$</td>
</tr>
<tr>
<td>$p p^\uparrow \rightarrow \mu^+ \mu^- X$</td>
<td></td>
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</tbody>
</table>
Physics Summary

- We know almost nothing about sea quarks angular momentum.
- Quark orbital angular momentum leads to quark Sivers distribution.
- Identifying a non-vanishing sea quark Sivers distribution could lead to a major breakthrough in nucleon structure.
- Polarized target D-Y at Fermilab’s SeaQuest provides an unique opportunity to pin down sea quark’s angular momentum.
- Dedicated group of theorists at LANL to support this effort: I. Vitev, Z. Kang, C Lee, R. Gupta, B. Yoon

Does Drell-Yan yield depend on target’s spin direction?

\[ A_N = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \neq 0 \]

\[ A_N^{DY} \propto \frac{u(x_b) \cdot f_{1T}(x_t)}{u(x_b) \cdot \bar{u}(x_t)} \]

\( (A_N \equiv 0 \text{ if } L_{\bar{u}} = 0) \)
The Polarized Target Installation and Support Needed

- Why here at FNAL
- Current spectrometer and Integration
- Polarized Target Overview
- Special Requirements for Polarized Target Experiments
- Yield and Precision
- Support needed
- Time Line
- Summary
New LANL polarized target & E906 Spectrometer

The right place for this experiment

- 4 scintillator hodoscope stations (x and y)
- 4 tracking stations (x and stereos)
- Setup close to E906 (see later)
- $1 \times 10^{13}$ p/spill
- Kinematic Range $4 < M < 8$ GeV

Why at FNAL and why now
- Can perform world’s highest luminosity polarized target
- Drell-Yan measurement at Fermilab’s 120 GeV proton beam
- Perfect spectrometer for study of sea quarks
- Only small modifications required
- Pol target work aligns well with schedule
**Principle of Dynamic Nuclear Polarization:**

\[ P_i = \left[ \frac{\mu_i g_i H}{2 k_B T} \right] \]

Thermal Equilibrium TE

\[ \text{TE: } T=1 \text{K}, \quad H=5 \text{T} \]

\[ P_e = 0.998 \]

\[ P_p = 0.005 \]

1. Create paramagnetic centers through irradiation
2. Use dipole-dipole interaction \( \Rightarrow \) Hyperfine Splitting
3. Pump on electrons with 140 GHz
4. \( \tau_e \ll \tau_p \Rightarrow \) Large Polarization (\( \tau \) Relaxation times)

**Polarization Measurement**

Keith et al. NIM A 501 (2003), 327 JLAB

Well established technology: SLAC, JLAB, PSI ...
The Polarized Target System

Magnet from LANL

Measure polarization

Roots pump system used to pump on $^4$He vapor to reach 1K

Superconducting Coils for Magnet: 5T
Rotation needed

Target material: frozen NH$_3$
Irradiation @ NIST

Microwave: Induces electron spin flips
• Tube + Power equip:

Cryostat: UVa
NH\textsubscript{3} Target Parameters:

- Cylinder \( \Phi : 4\text{cm} \) (x,y), length 8cm (z)
- \( \rho = 0.91 \text{ g/cm}^3 \) frozen NH\textsubscript{3}
- Packing Fraction = 0.6
- Dilution Factor = 3/17 NH\textsubscript{3}
- 5.1 g/cm\(^2\) (NH\textsubscript{3}) + 0.44 g/cm\(^2\) He
- 3 \times 10^{24} \text{nucleons/cm}^2

\mu\text{-}wave horn

Requirements and Running conditions:

- \( \frac{dB}{B} < 10^{-4} \) field uniformity over cell
- \( \mu\text{-}wave: 2.2 \text{ W} + \text{beam: } 370\text{mW} \)
- Total heat load 2.6 W
- 100 liter liquid He/day
- Requires **10,000 m}^3/hr** pumping capacity

Soft Iron Plate to clamp field from 15G to 5 G
Beam effects on polarized Target

- Anneal every 24 hours ~ 1hr at 80K (yellow line)
- Replace target material every 10 days (two active targets), will take one shift
  - Replace target stick
  - Cool down
  - perform TE measurement
  - Turn on microwave, measure again

Polarization as a function of accumulated beam dose 2.5T target
(D. Crab private communication)

Systematics control:
- Reverse Polarization Direction once a day
- Reverse magnet field of Fmag and Kmag every two days
- Reverse magnetic field of target magnet every target replacement
- Background measurements every shift with target out

Systematic errors:
- **Absolute: 1%** (Luminosity precision on different pol directions)
- ΔA/A ~ 4% (Dominant effect polarization measurement)
**Yield and Beam Time Request**

**Yield Calculation**
- beam: $1 \times 10^{13}$ p/spill
- Target: $3.1 \times 10^{24}$ N/cm$^2$
- One year $L = 1.4 \times 10^{43}$/cm$^2$
- POT = $2.1 \times 10^{18}$
- $4<M<8$ GeV

**Assumed Efficiencies:**
- Beam and Experiment availability from E906 = .5
- Additional efficiency due to pol target = .8 (conservative)

<table>
<thead>
<tr>
<th>Cuts</th>
<th>Efficiency</th>
<th>Yield/ calendar year</th>
</tr>
</thead>
<tbody>
<tr>
<td>All DY in the kinematic range</td>
<td>100%</td>
<td>1.34E+08</td>
</tr>
<tr>
<td>$\mu^+\mu^-$ accepted by all detectors</td>
<td>2%</td>
<td>2.78E+06</td>
</tr>
<tr>
<td>Accepted by trigger</td>
<td>50%</td>
<td>1.39E+06</td>
</tr>
<tr>
<td>$\mu^+\mu^-$ pair reconstructed (with target/dump separation cut)</td>
<td>8%</td>
<td>1.11E+05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bin</th>
<th>$x_t_{\text{min}}$</th>
<th>$x_t_{\text{max}}$</th>
<th>$&lt;x_{\text{target}}&gt;$</th>
<th>$N_{\text{evt}}$</th>
<th>$\sigma_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>0.17</td>
<td>0.137</td>
<td>34761</td>
<td>0.039</td>
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<tr>
<td>2</td>
<td>0.17</td>
<td>0.24</td>
<td>0.201</td>
<td>37472</td>
<td>0.036</td>
</tr>
<tr>
<td>3</td>
<td>0.24</td>
<td>0.50</td>
<td>0.324</td>
<td>38853</td>
<td>0.036</td>
</tr>
</tbody>
</table>

measuring time for given $\Delta A$

$t^{-1} \propto \rho \left( f \cdot P \right)^2$
- $f = .6$
- $P = .8$

Request for two calendar years of beam time
Changes to E906 Target Cave and Support

Changes and Support needed

• lift roof of cave (36”) 0.2M$
• new hoist in cave (2 ton)
• He and LN fill lines 0.5M$
• He lines installation 1M$
• beam collimator to prevent magnet quenches
• beam position monitors
• Safety infrastructure for Oxygen deficiency
• Liquid Helium needs for 2 years:
  A) Helium liquefier system/recovery
    • running and maintaining system
    • According to A. Klebaner too expensive
  B) Buying liquid Helium
    • storage system for exhaust
    • 100 lt *600 = 60,000 lt gas = 420K$
    • Might be able to sell back to vendor

TOTAL: ~2.1 M$ (including labor) (very preliminary)

Negotiation: FNAL, DOE and collaboration
Summary

- First Measurement of p-p Drell Yan with a polarized target.
- Measure Single Spin Asymmetry for Sea Quarks
- Access Quark Angular momentum through Sivers Distribution.
- Help solve the nucleon spin puzzle
- Establish sign of Sivers Distribution, if nonzero

- Request 2 calendar years of beam time
- FNAL and E906 ideally situated for this experiment
- Aligns well with current E906 beam time
- Spectrometer already in place, largely unchanged
- Replace cryogenic targets with polarized target
- Provide new facility for FNAL nuclear spin physics
- Requires only modest support from FNAL

\[ A_N \equiv 0 \quad \text{if} \quad L_{\bar{u}} = 0 \]
Backup slides
## SeaQuest(E906), P-1027 and P-1039 using a Similar Setup

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<tr>
<td><strong>SeaQuest</strong></td>
<td></td>
<td></td>
<td></td>
<td>Unpolarized sea quark flavor asymmetry $d\bar{b}/u\bar{b}$.</td>
</tr>
<tr>
<td>$pN \rightarrow \mu^+ \mu^- X$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$-$</td>
<td></td>
</tr>
<tr>
<td><strong>P-1027</strong></td>
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<td></td>
<td>Sign change and size of Sivers distribution for valence quark</td>
</tr>
<tr>
<td>$p^\uparrow p \rightarrow \mu^+ \mu^- X$</td>
<td>$\checkmark$</td>
<td>$\times$</td>
<td>Valence quark</td>
<td></td>
</tr>
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<td>Size and sign of Sivers distribution for Sea quarks, if $DY A_N \neq 0$.</td>
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<tr>
<td>$p^\uparrow p \rightarrow \mu^+ \mu^- X$</td>
<td>$\times$</td>
<td>$\checkmark$</td>
<td>Sea quark</td>
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</table>
NH$_3$

E143 SLAC, 1993

$T = 1K, B=5T$
Possible improvements in near future.

A high rate front tracking station (GEM) to improve vertex and momentum resolution. 
Adiabatic passage for spin reversal.
Target material, 7LiH, improve dilution factor.
Magnetic field reconfiguration, change acceptance to focus on lower x2.
New tracking stations with larger detectors.
$$A_{meas} = \frac{N_+ - N_- \frac{L_+}{L_-}}{N_+ + N_- \frac{L_+}{L_-}}$$

$$\left( \delta A_{meas} \right)_{sys} = \frac{N_- \cdot \delta \left( \frac{L_+}{L_-} \right)}{N_+ + N_- \cdot \frac{L_+}{L_-}} \cdot (1 + A_{meas})$$

for small Asymmetry

$$\frac{N_+}{L_+} \approx \frac{N_-}{L_-}$$

$$\left( \delta A_{meas} \right)_{sys} \approx \frac{1}{2} \left( 1 + A_{meas} \right) \cdot \delta \left( \frac{L_+}{L_-} \right) \cdot \frac{\frac{L_+}{L_-}}{\frac{L_+}{L_-}}$$

Systematic error
• Geant 4 MC from E906
• DY cross section from pythia using CETQ5M PDF
• added simple field from pol target
• E906 life time: .75, beam .66 = .5 overall

\[
p_T \begin{cases} \text{if flag1} > 0 \land \text{flag2} > 0 \land \text{mass} > 4 \land \text{mass} < 8 \land pT > 0.2 A & \text{& abs}(py1/pz1*z0) > 2.54*2.25 \land \text{& abs}(py1/pz2*z0) > 0.52*2.25) \\
\end{cases}
\]
JLab Hall A E08-027

Offline Polarization Results for E=2.2 GeV, 5T, Longitudinal

Polarization

Run #