E1039 @ FNAL:
Measuring the Sea Quark Sivers Asymmetry

Andi Klein
Los Alamos National Laboratory
Where are we today

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

Quark contribution

Gluon contribution

Angular Momentum of q,g

Quark Polarization from all flavors

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

\[
\int_{0.05}^{0.2} dx \Delta g(x) = 0.1 \pm 0.06 = 50\%
\]
**Indication of Angular Momentum:**

**Results from E866**

Gottfried Sum Rule: \( I_G = \frac{1}{3} \neq 0 \)

\[
I_G = \frac{1}{x} \int_0^1 \left[ F_2^p(x, Q^2) - F_2^n(x, Q^2) \right] / dx = \frac{1}{3} + \frac{2}{3} \int_0^1 [\bar{u}(x) - \bar{d}(x)] dx
\]

\( \bar{d}(x) / \bar{u}(x) \neq 1 \)

\[
I_G^{E866} (.100) < I_G^{NMC} (.148)
\]

Why not symmetric:
- Pion cloud model
Non perturbative approach to QCD; formulated on a grid of points in space and time

- When including disconnected diagrams, most orbital angular momentum (OAM) from sea

How measure quark OAM?

- GPD: Generalized Parton Distribution
- TMD Transverse Momentum Distribution

\[ \Delta \Sigma_q \approx 25\% \]
\[ 2 \, L_q \approx 46\% \text{ (0\%(valence)+46\%(sea))} \]
\[ 2 \, J_g \approx 25\% \]
\[ L_u \approx - L_d \]
Quark Orbital Momentum and the Sivers Function

The Sivers function is the distribution of unpolarized quarks in a transversely polarized proton, one of 8 Transverse Momentum Distributions (TMDs)

\[ f(x, p_T, S) = f_1(x, p_T^2) - \frac{[p_T \times P] \cdot S_T}{M} \cdot f_{1T}^\perp(x, p_T^2) \]

- **S**: nucleon spin
- **p_T**: Transverse momentum

First proposed to explain E704

\[ f_{1T}^\perp(x, p_T^2) \propto f_1(x, p_T, S) - f_1(x, p_T, -S) \]

E704 \( \sqrt{s} = 20 \text{ GeV}. \) PLB 264 (1991) 462.

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

Sivers effect: quark’s transverse motion generates a left-right bias. up-quarks favor the left, down-quarks favor the right (\( L_u \approx -L_d \))
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. function.
- Valence and sea quarks are mixed.

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

\[ f_{1T}^q \mid_{SIDIS} = - f_{1T}^q \mid_{DY} \]

Asymmetry in Drell-Yan

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

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

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

\[ A_N = \frac{\sum_q e_q^2 [f_1^q(x_1) \cdot f_{1T}^\perp q(x_2) + 1 \leftrightarrow 2]}{\sum_q e_q^2 [f_1^q(x_1) \cdot f_{1T}^\perp q(x_2) + 1 \leftrightarrow 2]} \]

Result of repulsive initial state (DY) vs attractive final state (SIDIS) interaction
Drell Yan

\[
\frac{d^2\sigma}{dx_b\, dx_t} = \frac{4\pi\alpha^2}{9x_b\, x_t\, s} \sum_{q} e_q^2 \left[ \bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b) \right]
\]

\(x_F = x_b - x_t\)

Through kinematics choose quark from beam and antiquark from target

\(x_F \gg 0\)

800 GeV beam
\(\sqrt{s}: \) 40 GeV
120 GeV:
\(\sqrt{s}: \) 15.5 GeV
cross section scales as \(s^7\) times higher
Where are we?

- We know very little about sea quarks angular momentum.
- E866 might point to OAM
- 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.

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

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

\[
(A_N \equiv 0 \text{ if } L_{\bar{u}} = 0)
\]

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

D. Geesaman, P. Reimer
Argonne National Laboratory, Argonne, IL 60439
C. Brown, D. Christian
Fermi National Accelerator Laboratory, Batavia IL 60510
M. Diefenthaler, J.-C. Peng
University of Illinois, Urbana, IL 61081
W.-C. Chang, Y.-C. Chen
Institute of Physics, Academia Sinica, Taiwan
S. Sawada
KEK, Tsukuba, Ibaraki 305-0801, Japan
T.-H. Chang
Ling-Tung University, Taiwan
Los Alamos National Laboratory, Los Alamos, NM 87545
E. Beise, K. Nakahara
University of Maryland, College Park, MD 20742
C. Aidala, W. Lorenzon, R. Raymond
University of Michigan, Ann Arbor, MI 48109-1040
T. Badman, E. Long, K. Slifer, R. Zielinski
University of New Hampshire, Durham, NH 03824
R.-S. Guo
National Kaohsiung Normal University, Taiwan
Y. Goto
RIKEN, Wako, Saitama 351-01, Japan
L. El Fassi, R. Gilman, K. Myers, R. Ransome, A. Tadepalli, B. Tice
Rutgers University, Rutgers NJ 08544
J.-P. Chen, C. Keith
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606
K. Nakano, T.-A. Shibata
Tokyo Institute of Technology, Tokyo 152-8551, Japan
D. Crabb, D. Day, D. Keller, O. Rondon
University of Virginia, Charlottesville, VA 22904
N. Doshita, Y. Miyachi
Yamagata University, Yamagata 990-8560, Japan
How do we measure the Sivers A

- $1 \times 10^{13}$ p/spill, one 5s spill/minute
- Kinematic Range $4 < \mathrm{M} < 8$ GeV
Mass = 7.0 GeV \ x_r = .0, .2, .4

- 4 scintillator hodoscope stations (x and y)
- 4 tracking stations (x and stereos) MWPC
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

Microwave Input 140 GHz

NMR Signal Out

To Pumps

10,000 m$^3$/hr

To Pumps

LH$_2$

4K Liquid Helium

LN$_2$

Liquid Helium

Target (inside coil) 1° K

NMR Coil

He

B 5T

Target material: frozen NH$_3$

Irradiation @ NIST
The magnet

\[ \frac{dB}{B} < 10^{-4} \]

FMag fringe field at \( x = y = 0 \)

- Measured at downstream end
- Required inhomogeneity: \( 10^{-4} \times 5 = 5 \) Gauss
- Current field difference: \( \sim 15 \) Gauss

8 cm NH₃ target
**Principle of Dynamic Nuclear Polarization:**

Polarization $P$ for paramagnetic materials:

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

Thermal Equilibrium TE TE:

$T=1K$, $H=5T$

$P_e = .998$

$P_p = .005$ since $\mu_N / \mu_B \sim 10^{-3}$

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Polarization Measurement $P \sim 92\%$

Keith et al. NIM A 501 (2003), 327 JLAB
Well established technology: SLAC, JLAB, PSI ...

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Electron transitions in Hydrogen:

$V_e = 140$GHz

Protons

Electrons

Hydrogen

Micro wave

$V_e + V_p$

$V_e - V_p$
NH₃ Target Parameters

- Cylinder Φ: 2cm (x,y), length 8cm (z)
- \( \rho = 0.82 \text{ g/cm}^3 \) NH₃
- Packing Fraction = 0.6
- Dilution Factor = 3/17 NH₃
- 5.1 g/cm² (NH₃) +
- 0.44 g/cm² He
- \( 4.2 \times 10^{23} \text{ H/cm}^2 \)
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)
- $\Delta A/A \sim 4\%$ (Dominant effect polarization measurement)
Target and Beam Performance

Target
• Polarization: 88%
• Packing fraction .6
• Dilution factor: .176
• Density: .82 g/cm$^3$

Beam
• Beam: $1 \times 10^{13}$ p/spill; spill is 5 s
• Luminosity: $4 \times 10^{35}$ /cm$^2$/sec
• 120 GeV protons
• KTeV beam line
• $\sqrt{s} = 15$ GeV
• One year $\mathcal{L} = 1.1 \times 10^{43}$/cm$^2$
• POT = $2.7 \times 10^{18}$

Mass Resolution

Reconstructed Vertex
### Yield and Asymmetry estimates

<table>
<thead>
<tr>
<th>Cuts</th>
<th>Efficiency</th>
<th>Yield</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>33%</td>
<td>4.59E+05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Range $x_2$</th>
<th>Mean $x_2$</th>
<th>N events</th>
<th>$\Delta A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1-0.14</td>
<td>0.123</td>
<td>159097.2</td>
<td>0.016</td>
</tr>
<tr>
<td>0.14-0.17</td>
<td>0.154</td>
<td>136557.6</td>
<td>0.017</td>
</tr>
<tr>
<td>0.17-0.21</td>
<td>0.188</td>
<td>123566.4</td>
<td>0.018</td>
</tr>
<tr>
<td>0.21-0.5</td>
<td>0.258</td>
<td>119508</td>
<td>0.019</td>
</tr>
</tbody>
</table>

Exp + Beam availability from E906 = .6  
efficiency due to pol target = .8

\[ \Delta A = \frac{1}{f} \frac{1}{P} \frac{1}{\sqrt{N_{Total}}} \]

measuring time for given $\Delta A$  
\[ t^{-1} \propto \rho \left( f \cdot P \right)^2 \]

\[ \cdot f = .6 \]
\[ \cdot P = .88 \]
Changes under study

Add third magnet SM0 ~500cm upstream
- Improves Dump-Target separation
- Moves \( <x_2> \) from 0.21 to 0.176
- Reduces overall acceptance
- Adds shielding problems
Projected Statistical Precision with a Polarized Target at SeaQuest

Statistics shown for one calendar year of running: 
\[ \mathcal{L} = 1.9 \times 10^{42} \text{/cm}^2 \quad \Leftrightarrow \quad \text{POT} = 2.8 \times 10^{18} \]

Running will be two calendar years of beam time

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

- First Sea Quark Sivers Measurement
- Determine sign and value of u\bar{u} Sivers distribution
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

• If \( A_N \neq 0 \), major discovery: “Smoking Gun” evidence for \( L_{ubar} \neq 0 \)
• If \( A_N = 0 \): \( L_{ubar} = 0 \), spin puzzle more dramatic?

• Approved experiment E1039
• 2 calendar years of beam time
• Start of a spin program at FNAL
Backup
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?

Left-right bias generated through fragmentation process?

\[ \bar{p} (\bar{u} \bar{u} \bar{d}) \]

\[ K^- (\bar{u} s) \]
# Planned Polarized Drell-Yan Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Particles</th>
<th>Energy (GeV)</th>
<th>$x_b$ or $x_t$</th>
<th>Luminosity ($cm^{-2} s^{-1}$)</th>
<th>$A_{\sin A_S \phi}^y$</th>
<th>$P_b$ or $P_t (f)$</th>
<th>rFOM&quot;</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPASS (CERN)</td>
<td>$\pi^\pm + p^\uparrow$</td>
<td>160 GeV $\sqrt{s} = 17$</td>
<td>$x_t = 0.2 - 0.3$</td>
<td>$2 \times 10^{33}$</td>
<td>0.14</td>
<td>$P_t = 90%$ $f = 0.22$</td>
<td>$1.1 \times 10^{-3}$</td>
<td>2014, 2018</td>
</tr>
<tr>
<td>PANDA (GSI)</td>
<td>$\bar{p} + p^\uparrow$</td>
<td>15 GeV $\sqrt{s} = 5.5$</td>
<td>$x_t = 0.2 - 0.4$</td>
<td>$2 \times 10^{32}$</td>
<td>0.07</td>
<td>$P_t = 90%$ $f = 0.22$</td>
<td>$1.1 \times 10^{-4}$</td>
<td>&gt;2018</td>
</tr>
<tr>
<td>PAX (GSI)</td>
<td>$p^\uparrow + \bar{p}$</td>
<td>collider $\sqrt{s} = 14$</td>
<td>$x_b = 0.1 - 0.9$</td>
<td>$2 \times 10^{30}$</td>
<td>0.06</td>
<td>$P_b = 90%$</td>
<td>$2.3 \times 10^{-5}$</td>
<td>&gt;2020?</td>
</tr>
<tr>
<td>NICA (JINR)</td>
<td>$p^\uparrow + p$</td>
<td>collider $\sqrt{s} = 26$</td>
<td>$x_b = 0.1 - 0.8$</td>
<td>$1 \times 10^{31}$</td>
<td>0.04</td>
<td>$P_b = 70%$</td>
<td>$6.8 \times 10^{-5}$</td>
<td>&gt;2018</td>
</tr>
<tr>
<td>PHENIX (RHIC)</td>
<td>$p^\uparrow + p$</td>
<td>collider $\sqrt{s} = 500$</td>
<td>$x_b = 0.05 - 0.1$</td>
<td>$2 \times 10^{32}$</td>
<td>0.06</td>
<td>$P_b = 60%$</td>
<td>$3.6 \times 10^{-4}$</td>
<td>&gt;2018</td>
</tr>
<tr>
<td>SeaQuest (FNAL: E-906)</td>
<td>$p + p$</td>
<td>120 GeV $\sqrt{s} = 15$</td>
<td>$x_b = 0.35 - 0.9$ $x_t = 0.1 - 0.45$</td>
<td>$3.4 \times 10^{35}$</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>2012 - 2015</td>
</tr>
<tr>
<td>Pol tgt DY‡ (FNAL: E-1039)</td>
<td>$p + p^\uparrow$</td>
<td>120 GeV $\sqrt{s} = 15$</td>
<td>$x_t = 0.1 - 0.45$</td>
<td>$4.4 \times 10^{35}$</td>
<td>0 - 0.2*</td>
<td>$P_t = 80%$ $f = 0.176$</td>
<td>0.13</td>
<td>2016</td>
</tr>
<tr>
<td>Pol beam DY§ (FNAL: E-1027)</td>
<td>$p^\uparrow + p$</td>
<td>120 GeV $\sqrt{s} = 15$</td>
<td>$x_b = 0.35 - 0.9$</td>
<td>$2 \times 10^{35}$</td>
<td>0.04</td>
<td>$P_b = 60%$</td>
<td>1</td>
<td>2018</td>
</tr>
</tbody>
</table>

* ‡ 8 cm NH$_3$ target  
* § $L = 1 \times 10^{36} cm^{-2} s^{-1} (LH_2 tgt limited)$  
* *not constrained by SIDIS data  
* # rFOM = relative lumi * $P^2 * f^2$ wrt E-1027 ($f=1$ for pol p beams)  

W. Lorenzon (U-Michigan)
### COMPASS, E-1027, E-1039 (and Beyond)

<table>
<thead>
<tr>
<th></th>
<th>Beam Pol.</th>
<th>Target Pol.</th>
<th>Favored Quarks</th>
<th>Physics Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physics Goals</strong></td>
<td></td>
<td></td>
<td></td>
<td>(Sivers Function)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>sign change</td>
</tr>
<tr>
<td><strong>COMPASS</strong></td>
<td>✓</td>
<td>✓</td>
<td>valence</td>
<td>✓</td>
</tr>
<tr>
<td>$\pi^- p^\uparrow \to \mu^+ \mu^- X$</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>E-1027</strong></td>
<td>✓</td>
<td>✗</td>
<td>valence</td>
<td>✓</td>
</tr>
<tr>
<td>$p^\uparrow p \to \mu^+ \mu^- X$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>E-1039</strong></td>
<td>✓</td>
<td>✓</td>
<td>sea</td>
<td>✗</td>
</tr>
<tr>
<td>$p p^\uparrow \to \mu^+ \mu^- X$</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>E-10XX</strong></td>
<td>✓</td>
<td>✓</td>
<td>sea &amp; valence</td>
<td>Transversity, Helicity, Other TMDs ...</td>
</tr>
</tbody>
</table>
Observables and Kinematics

SIDIS

Drell Yan
Target Frame

Collins Soper frame: rest frame of virtual photon