Opportunities with polarized beam & target

Yoshiyuki Miyachi
Yamagata University
Contents

- Flavor symmetry violation in the polarized light sea
  - Flavor symmetry violation in the light sea
  - What do we know?
    - Deep Inelastic Scattering
    - W-production at RHIC
- Transverse Momentum Dependent PDFs in polarized Drell-Yan
  - TMDs in SIDIS
  - TMDs in Polarized Drell-Yan
- Summary
Flavor symmetry violation in the polarized light sea?
Flavor symmetry violation in the light sea

Flavor symmetry violation
in the polarized light sea?

Gottfried sum rule violation
Observed by NMC
Confirmed and new surprise
by E866/NeuSea
E906/SeaQuest will solve
“Flavor puzzle”

Origin: pion tornado?

\[ \Delta u(x) \neq \Delta d \]
From SIDIS: HERMES

\[ e \, N \rightarrow e' \, h \, X \]

\[ x \cdot \Delta u \]

\[x \cdot \Delta d\]

\[Q^2 = 2.5 \text{ GeV}^2\]

\[x \cdot \Delta \bar{u}\]

\[x \cdot \Delta \bar{d}\]

\[x \cdot \Delta s\]
$W^\pm$ production at RHIC

\[ p + p \rightarrow W^\pm + X \quad \sqrt{s} = 510 \text{ GeV} \]

\[ A_L^{W^\pm} = \frac{\Delta u(x_1) \bar{d}(x_2) - \Delta \bar{d}(x_1) u(x_2)}{u(x_1) \bar{d}(x_2) + \bar{d}(x_1) u(x_2)} \]

PRL 113, 072301 (2014)
Impact to the helicity distributions

DSSV++

preliminary 2012 STAR data & impact

NNPDF, arXiv:1406.5539

NNPDF: no SIDIS data
DSSV: SIDIS data included
Double polarized Drell-Yan

Drell-Yan

\[ p + p \rightarrow l^+ + l^- + X \]

\[ A_{L,L} \propto \sum e_q^2 \left\{ \Delta q(x_1) \Delta \bar{q}(x_2) + \Delta \bar{q}(x_1) \Delta q(x_2) \right\} \]

\[ \sum e_q^2 \left\{ q(x_1) \bar{q}(x_2) + \bar{q}(x_1) q(x_2) \right\} \]
$A_{LL}$ in DY to probe the flavor symmetry violation

- Drell-Yan with fixed target
  - Sea @ the large $x$
  - E906/SeaQuest: $x \sim 0.3$
- E1027 with L-pol.
  - Additional spin rotator
- E1034 with L-pol.
  - PT magnet + cryostat modification
- Proton and deuteron targets
  - Unpol PDF from E906/SeaQuest
- Important input to the global analysis
Doubly polarized

TMDs in Drell-Yan

(Transverse momentum dependent PDF)
# Leading twist TMDs

<table>
<thead>
<tr>
<th>Unpolarized Nucleon</th>
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<tbody>
<tr>
<td>$f_1$ Parton Density</td>
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<table>
<thead>
<tr>
<th>Longitudinally Polarized Nucleon</th>
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<tbody>
<tr>
<td>$g_{1L}(=\Delta q)$</td>
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<tr>
<th>Transversely Polarized Nucleon</th>
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</thead>
<tbody>
<tr>
<td>$f_{1T} \perp$ Sivers</td>
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<tr>
<td>$g_{1T}$ Worm-gear</td>
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<td>$h_1 \perp$ Boer-Mulders</td>
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<td>$h_{1T}(=\delta q)$ Transversity</td>
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<td>$h_{1T} \perp$ Pretzelosity</td>
</tr>
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</table>
Azimuthal amplitudes in SIDIS

\[ e + N \rightarrow e' + h + X \]

\[
\begin{align*}
\frac{d\sigma}{d\Omega} & \propto \left( 1 + (1-y)^2 \right) F_{UU} + (2 - y) \sqrt{1 - y} \cos \phi_h F_{UU}^{\cos \phi_h} + (1 - y) \cos 2\phi_h F_{UU}^{\cos^2 \phi_h} \\
+ S_L & \left[ (1 - y) \sin 2\phi_h F_{UL}^{\sin 2\phi_h} + (2 - y) \sqrt{1 - y} \sin \phi_h F_{UL}^{\sin \phi_h} \right] \\
+ S_L P_z & \left[ \frac{1 - (1-y)^2}{2} F_{LL} + y \sqrt{1 - y} \cos \phi_h F_{LL}^{\cos \phi_h} \right] \\
+ S_T & \left[ \frac{1 + (1-y)^2}{2} \sin (\phi_h - \phi_s) F_{UT}^{\sin (\phi_h - \phi_s)} \right. \\
& \left. + (1 - y) \left( \sin (\phi_h + \phi_s) F_{UT}^{\sin (\phi_h + \phi_s)} + \sin (3\phi_h - \phi_s) F_{UT}^{\sin (3\phi_h - \phi_s)} \right) + (2 - y) \sqrt{1 - y} \left( \sin \phi_s F_{UT}^{\sin \phi_s} + \sin (2\phi - \phi_s) F_{UT}^{\sin (2\phi - \phi_s)} \right) \right] \\
+ S_T P_z & \left[ \frac{1 - (1-y)^2}{2} \cos (\phi_h - \phi_s) F_{LT}^{\cos (\phi_h - \phi_s)} + y \sqrt{1 - y} \left( \cos \phi_s F_{LT}^{\cos \phi_s} + \cos (2\phi - \phi_s) F_{LT}^{\cos (2\phi - \phi_s)} \right) \right]
\end{align*}
\]
### TMDs in SIDIS

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<td>$f_1$ Parton Density</td>
<td>$g_1$ ($\equiv \Delta q$) Helicity</td>
<td>$f_{1T}$ Sivers</td>
</tr>
<tr>
<td>$h_1^\perp$ Boer-Mulders</td>
<td>$h_{1L}^\perp$ Mulders-Kotzinian</td>
<td>$h_{1T}^\perp$ Transversity</td>
</tr>
<tr>
<td>$\sigma_{UU}$</td>
<td>$h_{1L}^\perp \otimes H_{1L}^\perp \sim \cos 2\phi$</td>
<td>$h_{1T}^\perp \otimes H_{1T}^\perp \sim \sin (\phi + \phi_S)$</td>
</tr>
<tr>
<td>$A_{UL}$</td>
<td>$h_{1L}^\perp \otimes H_{1L}^\perp \sim \sin 2\phi$</td>
<td>$h_{1T}^\perp$ Pretzelosity</td>
</tr>
<tr>
<td>$A_{UT}$</td>
<td>$h_{1T}^\perp$ Transversity</td>
<td>$h_{1T}^\perp \otimes H_{1T}^\perp \sim \sin (3\phi - \phi_S)$</td>
</tr>
<tr>
<td>$A_{LT}$</td>
<td>$h_{1T}^\perp$ Pretzelosity</td>
<td></td>
</tr>
</tbody>
</table>

\[ f_{1T}^\perp \otimes D_1 \sim \sin (\phi - \phi_S) \]
\[ g_{1T}^\perp \otimes D_1 \sim \cos (\phi - \phi_S) \]
Mean asymmetries

\[ h^+ \quad 1 < Q^2 (\text{GeV}/c)^2 < 4 \]
\[ h^- \quad z > 0.2 \quad \langle x \rangle \approx 0.029 \]

**COMPASS preliminary proton 2010 data**

- \( A_{UT}^{\sin(\varphi_h - \varphi_s)} \)
- \( A_{UT}^{\sin(\varphi_h + \varphi_s - \pi)} \)
- \( A_{UT}^{\sin(3\varphi_h - \varphi_s)} \)
- \( A_{UT}^{\sin \varphi_s} \)
- \( A_{UT}^{\sin(2\varphi_h - \varphi_s)} \)
- \( A_{LT}^{\cos(\varphi_h - \varphi_s)} \)
- \( A_{LT}^{\cos \varphi_s} \)
- \( A_{LT}^{\cos(2\varphi_h - \varphi_s)} \)

\[ \propto f_{1T}^{\perp} \otimes D_1 \]
\[ \propto h_{1T}^{\perp} \otimes H_1^{\perp} \]
\[ \propto h_{1T}^{\perp} \otimes H_1^{\perp} \]
\[ \propto Q^{-1}\left(h_{1T}^{\perp} \otimes H_1^{\perp} + f_{1T}^{\perp} \otimes D_1 + \ldots\right) \]
\[ \propto Q^{-1}\left(h_{1T}^{\perp} \otimes H_1^{\perp} + f_{1T}^{\perp} \otimes D_1 + \ldots\right) \]
\[ \propto g_{1T} \otimes D_1 \]
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\[ \propto Q^{-1}\left(g_{1T} \otimes D_1 + \ldots\right) \]
Mean asymmetries
\[ f_{1T}^\perp \otimes D_1 \sim A_{UT} \sin(\phi - \phi_s) \]
\( h_{1T} \otimes H_{1}^{\perp} \sim A \sin(\phi + \phi_S) \)
Boer-Mulders

\[ h_1^\perp \otimes H_1^\perp \sim F_{UU}^{\cos^2 \phi} \]

PRD87(2013)012010

Li\(^6\)D target

NPB 886 (2014) 1046
Pretzelosity

\[ h_{1T} \otimes H_{1} \sim A_{UT} \sin(3\phi - \phi_s) \]

\[ \sum L^q = -\sum h_{1T}^{(1)} q \]

JLab, arXiv:1312.3047
Worm-gear

\[ g_{1T} \otimes D_1 \sim A_{LT}^{\cos(\phi - \phi_S)} \]
$h_{1L} \otimes H_1^{\perp} \sim \sin 2\phi$
SIDIS

\[ e + N \rightarrow e' + h + X \]

Drell-Yan

\[ h + h \rightarrow l^+ + l^- + X \]

\[ d\sigma \propto \sum e_q^2 q(x) D(z) \]

\[ d\sigma \propto \sum e_q^2 \left\{ q(x_1) \bar{q}(x_2) + \bar{q}(x_1) q(x_2) \right\} \]
Azimuthal angles in DY

\[ \phi \]

hadron and lepton planes

\[ \phi_{S_{1,2}} \]

polarization and lepton planes

Collins-Soper Reference Frame
Azimuthal amplitudes and TMDs in DY

\[ h_1 + h_2 \rightarrow l^+ + l^- + X \]

\[ F_{UU}^1 \propto \begin{bmatrix} f_1 \bar{f}_1 \\ \end{bmatrix} \]

\[ F_{UU}^{\cos^2 \phi} \propto \begin{bmatrix} h_1^\perp \bar{h}_1^\perp \end{bmatrix} \]

\[ F_{TT}^\sin (\phi - \phi_{S_1}) \propto \begin{bmatrix} f_1^T \bar{f}_1^T \end{bmatrix} \]

\[ F_{TT}^\sin (\phi + \phi_{S_1}) \propto \begin{bmatrix} h_1^T \bar{h}_1^T \end{bmatrix} \]

\[ F_{TT}^\sin (3\phi - \phi_{S_1}) \propto \begin{bmatrix} h_1^T \bar{h}_1^T \end{bmatrix} \]

E906/SeaQuest

\[ [f \bar{f}] \propto \sum_q e_q^2 \begin{bmatrix} f(x_a) \bar{f}(x_b) + \bar{f}(x_a)f(x_b) \end{bmatrix} \]

E1027

\[ \begin{array}{c|cc}
U & f_1 & \bar{h}_1^\perp \\
L & g_{1L} & h_1^{\perp L} \\
T & f_1^T & g_{1T} \bar{h}_1^{\perp T} \end{array} \]

E1039
Azimuthal amplitudes and TMDs in DY

\[ h_1 + h_2 \rightarrow l^+ + l^- + X \]

E1027 + E1039

\[ F_{TT}^{\cos(\phi_s - \phi)} \propto \left[ f_{1T} \bar{f}_{1T} + g_{1L} \bar{g}_{1T} \right] \]

\[ F_{TT}^{\cos(\phi_s + \phi_s)} \propto \left[ h_{1T} \bar{h}_{1T} \right] \]

\[ F_{TT}^{\cos(2\phi - \phi_s - \phi_s)} \propto \left[ f_{1T} \bar{f}_{1T} - g_{1L} \bar{g}_{1T} \right] \]

\[ F_{TT}^{\cos(2\phi - \phi_s + \phi_s)} \propto \left[ h_{1T} \bar{h}_{1T} \right] \]

\[ F_{TT}^{\cos(2\phi + \phi_s - \phi_s)} \propto \left[ h_{1T} \bar{h}_{1T} \right] \]
Azimuthal amplitudes and TMDs in DY

\[ h_1 + h_2 \rightarrow l^+ + l^- + X \]

L-pol., L.-target

\[ F_{LU}^{\sin 2 \phi} \propto \left[ h_{1L} \bar{h}_1 \right] \]
\[ F_{UL}^{\sin 2 \phi} \propto \left[ h_1 \bar{h}_{1L} \right] \]
\[ F_{LL}^{1} \propto \left[ g_{1L} \bar{g}_{1L} \right] \]
\[ F_{LL}^{\cos 2 \phi} \propto \left[ h_{1L} \bar{h}_{1L} \right] \]

<table>
<thead>
<tr>
<th></th>
<th>( f_1 )</th>
<th>( \bar{h}_1 )</th>
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<tbody>
<tr>
<td>U</td>
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<td>L</td>
<td>( g_{1L} )</td>
<td>( h_{1L} )</td>
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<tr>
<td>T</td>
<td>( f_{1T} )</td>
<td>( g_{1T} )</td>
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Azimuthal amplitudes and TMDs in DY

\[ h_1 + h_2 \rightarrow l^+ + l^- + X \]

\[
F_{LT}^{\cos(\phi - \phi_{S_1})} \propto \left[ g_{1L} \bar{g}_{1T} \right]
\]

\[
F_{LT}^{\cos(\phi + \phi_{S_2})} \propto \left[ h_{1L} \bar{h}_{1T} \right]
\]

\[
F_{LT}^{\cos(3\phi - \phi_{S_2})} \propto \left[ h_{1L} \bar{h}_{1T} \right]
\]

\[
F_{LT}^{\cos(3\phi - \phi_{S_1})} \propto \left[ h_{1L} \bar{h}_{1T} \right]
\]

| U | \( f_1 \) | \( \bar{h}_{1L} \) |
| L | \( g_{1L} \) | \( h_{1L} \) |
| T | \( f_{1T} \) | \( g_{1T} \) | \( h_{1T} \) |

lepton plane (cm)
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam</th>
<th>Target</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>E906/SeaQuest</td>
<td>p</td>
<td>p, d, A</td>
<td></td>
<td>RUNNING</td>
</tr>
<tr>
<td>E1027</td>
<td>p↑</td>
<td>p</td>
<td>16</td>
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<tr>
<td>E1039</td>
<td>p</td>
<td>p↑</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMPASS</td>
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<td>PANDA</td>
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<td>SPAS-CHARM</td>
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<td>AFTER</td>
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<td>p↑, d↑</td>
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<td>RHIC</td>
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<td>250, 510</td>
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</table>
Summary

- Polarized Drell-Yan is a unique tool to study nucleon structure
  - FF does not involved
  - Longitudinal double spin asymmetry, $A_{LL}$, with proton and deuteron targets:
    - Flavor symmetry violation in the polarized sea
    - Important input to the global analysis
- E906, E1027, E1039
  - Boer-Mulder, Sivers, Transversity, Pretzelosity
- E1027 + E1039: Worm-Gear $g_{1T}$
- With L-pol beam, L-pol targets: $h_{1L}$