Why He-3?

- The ability to optically-pump Helium-3 provides the opportunity to create a convenient approximation of a polarized neutron target since to a high degree, the polarization $^3$He arises solely due to the neutron. (Quote from the polarized $^3$He Target Lab of W&M)

- U-quark and D-quark has different sign describing transverse spin asymmetry

- Under isospin symmetry, U and D interchange between proton and neutron

- With both polarized proton and neutron in hand, one could in principle uniquely determine the sign of both U and D quarks

- Polarized $^3$He (neutron) will certainly help the verification of sign change
Outline

- Introduction: two approaches to SSAs
- TMD approach: sign change
  - SSAs of DY from polarized neutron
  - SSAs of W bosons (lepton decayed from W)
- Collinear approach:
  - SSAs of inclusive pion from polarized neutron
- Connection: indirect check of sign change?
- Summary
Experiment: Single Spin Asymmetries

- Fermilab E704, STAR, PHENIX, BRAHMS, COMPASS, HERMES, JLAB:

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

SSAs are observed in various experiments at different \( \sqrt{s} \)
Two mechanisms to generate SSA in QCD

- **SSA is related to parton’s transverse motion**

- **Collinear factorization approach:**
  - Twist-3 three-parton correlation functions: Qiu-Sterman matrix element, ...
  - Twist-3 three-parton fragmentation functions:

- **TMD approach:** Transverse Momentum Dependent distributions probe the parton’s intrinsic transverse momentum
  - Sivers function: in Parton Distribution Function (PDF)
    - Sivers 90
  - Collins function: in Fragmentation Function (FF)
    - Collins 93
Relation between twist-3 and TMD approaches

- They apply in different kinematic domain:
  - TMD approach: need TMD factorization, applies for the process with two observed momentum scales: DY at small $Q_T$
    \[ Q_1 \gg Q_2 \]
    - necessary for pQCD factorization to have a chance
    - sensitive to parton's transverse momentum
  - Collinear factorization approach: more relevant for single scale hard process: inclusive pion production at pp collision

- They generate same results in the overlap region when they both apply:
  - Twist-3 three-parton correlation in distribution \(\rightarrow\) Sivers function
    Ji, Qiu, Vogelsang, Yuan, 2006, ...
  - Twist-3 three-parton correlation in fragmentation \(\rightarrow\) Collins function
    Zhou, Yuan, 2009, Kang, Yuan, Zhou, 2010
TMD approach: SIDIS and Drell-Yan

- Initial-state vs final-state interactions

\[ Sivers_{\text{DY}} \mid \neq -Sivers_{\text{DIS}} \]

- Modified universality (sign change): fundamental QCD prediction
Sivers function from SIDIS: Current Global Analysis

- Includes HERMES Proton data and COMPASS Deuteron data

These are Sivers functions in proton

\[ \sin (\phi_h - \phi_S) \]

\[ A_{UT} \]

- \( \pi^0 \)
- \( \pi^+ \)
- \( \pi^- \)

\[ Q^2 = 2.4 \text{ GeV}^2 \]

\[ x \Delta N_{f_u}^{(1)}(x) \]

\[ x \Delta N_{f_d}^{(1)}(x) \]

Anselmino, et.al., 2009

May 15, 2010
Zhongbo Kang, RBRC
Reverse the sign to make predictions for Drell-Yan

- Reverse the sign to obtain the Sivers function in Drell-Yan process:

<table>
<thead>
<tr>
<th>SIDIS</th>
<th>QCD</th>
<th>DY</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Sivers}_{u-\text{quark}} &gt; 0$</td>
<td>$\text{Sivers}_{u-\text{quark}} &lt; 0$</td>
<td>$\text{Sivers}_{d-\text{quark}} &gt; 0$</td>
</tr>
<tr>
<td>$\text{Sivers}_{d-\text{quark}} &lt; 0$</td>
<td>$\text{Sivers}_{d-\text{quark}} &lt; 0$</td>
<td>$\text{Sivers}_{u-\text{quark}} &gt; 0$</td>
</tr>
</tbody>
</table>

- $u$ and $d$ almost equal size, different sign
- $u$-Sivers is slightly smaller than $d$-Sivers
Sivers effect in Drell-Yan process: \( A^\uparrow + B \rightarrow [\gamma^* \rightarrow \ell^+ \ell^-] + X \)

- Formula in TMD approach: weighted sum of u and d-Sivers

\[
A_N = \frac{\sum_q e_q^2 \int \Delta^N f_{q/A^\uparrow} (x_1, k_{\perp 1}) f_{\bar{q}/B} (x_2, k_{\perp 2})}{2 \sum_q e_q^2 \int f_{q/A} (x_1, k_{\perp 1}) f_{\bar{q}/B} (x_2, k_{\perp 2})} \propto \frac{4}{9} \Delta^N u_{\text{proton}} + \frac{1}{9} \Delta^N d_{\text{proton}}
\]

\( \Rightarrow \ A_N < 0 \)

- Because d-Sivers is larger, thus u and d are partially cancel each other, \( A_N \) is not very large
Use polarized neutron: advantage

- Sign will be opposite to the proton case

\[ A_N = \frac{\sum q e_q^2 \int \Delta^N f_{q/A}(x_1, k_{\perp 1}) f_{\bar{q}/B}(x_2, k_{\perp 2})}{2 \sum q e_q^2 \int f_{q/A}(x_1, k_{\perp 1}) f_{\bar{q}/B}(x_2, k_{\perp 2})} \propto \frac{4}{9} \Delta^N u_{\text{neutron}} + \frac{1}{9} \Delta^N d_{\text{neutron}} \]

- d-Sivers is positive, \( A_N > 0 \)

- d-Sivers is slightly larger, at the same time, it gets enhanced more by \( 4/9 \) compared with u-Sivers, thus the size of the asymmetry will be much bigger than the proton case
Rapidity-dependence of the asymmetry

- Positive and much larger asymmetry for He-3

![Graphs showing asymmetry for proton and neutron](image)
Some predictions for SSA of W bosons: pp@500 GeV

- W+ and W- could probe different flavor of u and d Sivers function

- SSA of leptons decayed from W: similar feature but diluted
SSA of $W$ for polarized He-3

- SSA of $W^-$:

- SSA of $W^+$:

May 15, 2010
Zhongbo Kang, RBRC
Collinear approach: twist-3 correlation functions

- $A_N$: twist-3 effect

$\sigma(Q, s) \propto p^\uparrow p \rightarrow h + X$

\[ \Delta(s_T) \propto T^{(3)}(x, x) \otimes \hat{\sigma}_T \otimes D_f(z) + \delta q_f(x) \otimes \hat{\sigma}_D \otimes D^{(3)}(z, z) \]

$T^{(3)}(x, x) \propto \text{Qiu, Sterman, 1991}$

$D^{(3)}(z, z) \propto \text{Kang, Yuan, Zhou, 2010}$

- So far only global fitting to extract $T^{(3)}(x, x)$
Asymmetries from the $T_F(x, x)$

- Global fitting both E704 and RHIC data

Kouvaris, Qiu, Vogelsang, Yuan, 2006
$T_F(x, x)$ extracted from experiments

- U-valence is positive, and D-valence is negative, thus
  - $\pi^+$ has positive asymmetry
  - $\pi^-$ has negative asymmetry
Asymmetry of pion for polarized neutron

- Under isospin symmetry, U and D correlation functions interchange
  - proton: \( u \rightarrow \pi^+ \) while \( T_{u,F}^{\text{proton}} > 0 \), thus SSA of \( \pi^+ \) is positive
  - neutron: \( u \rightarrow \pi^+ \) while \( T_{u,F}^{\text{neutron}} = T_{d,F}^{\text{proton}} < 0 \), thus SSA of \( \pi^+ \) is negative
  - Similar for \( \pi^- \) case

- Current parametrization gives a huge asymmetry for \( \pi^- \) in polarized He-3
Compare side by side

- **pi0** has similar size and sign

- **pi+, pi-** have different sign, also the magnitude is different
Impose a question: indirect check the sign change

- $T_F(x, x)$ is the first moment of the quark Sivers function

$$g T_{q,F}(x, x) = \frac{1}{M} \int d^2\vec{k}_\perp |\vec{k}_\perp|^2 f_{1T}^{q}(x, k_{\perp}^2)$$

- where Sivers function in above equation is defined via the Drell-Yan process
- If $f_{1T}^{q}(x, k_{\perp}^2)$ has the same sign in the whole $k_\perp$ region, then $T_{q,F}(x, x)$ will have the same sign as $f_{1T}^{q}(x, k_{\perp}^2)$

- Now $T_F(x, x)$ has been measured in single inclusive hadron production in pp collisions
- At the same time, quark Sivers function in SIDIS has been extracted

- One may compare them to see if everything works out nicely ...
Summary

- In terms of measuring the SSAs of Drell-Yan production to verify the sign change, polarized neutron (He-3) seems better than the proton.

- If we could measure both $W^+$ and $W^-$ (or leptons from $W^+$ and $W^-$), He-3 doesn’t seem to cause dramatic change.

- The single inclusive hadron production doesn’t have dramatic changes when changing from proton to He-3.

- Using the connection between the quark-gluon correlation and Sivers functions, it seems we could check sign between DY and SIDIS indirectly.
Summary

- In terms of measuring the SSAs of Drell-Yan production to verify the sign change, polarized neutron (He-3) seems better than the proton.

- If we could measure both $W^+$ and $W^-$ (or leptons from $W^+$ and $W^-$), He-3 doesn’t seem to cause dramatic change.

- The single inclusive hadron production doesn’t have dramatic changes when changing from proton to He-3.

- Using the connection between the quark-gluon correlation and Sivers functions, it seems we could check sign between DY and SIDIS indirectly.

Thank you