Measurement of the Longitudinal Single Spin Asymmetries for W Boson Production in Polarized Proton-Proton Collisions at STAR

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Jaffe and Monahar showed in 1990 that the proton spin can be written as a sum of contributions from quark and gluon spin and orbital angular momentum.

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

\[ \Delta \Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta \bar{u} + \Delta \bar{d} + \Delta \bar{s}) dx \]

\[ \Delta G = \int \Delta g(x) dx \]

**\( \Delta f(x) \) Helicity Distribution:** Probability density for finding a parton in a longitudinally polarized nucleon with flavor \( f \) and momentum fraction \( x \) in a nucleon.
• DSSV08 global analysis.

• The total contribution of up and down quarks spin has been well constrained.

• The flavor separated contributions of the sea quarks, still have quite large uncertainties.

• The gluon polarization also shows a large uncertainty band.
Weak Boson Production

The production of W boson in polarized proton-proton collisions is an independent method of probing the polarization of the light quarks and antiquarks.

• W production provides direct sensitivity to the u and d quark and antiquark helicity distributions.
• Large-scale defined by $W$ mass ($\sim 80$ GeV).
• Simple final state of charged lepton: no dependency on fragmentation functions.
• V-A coupling of the weak interaction leads to perfect spin separation.
Single Spin Asymmetry of W

\[ p^+ + p \rightarrow W^\pm + X \rightarrow e^\pm + X \]

STAR \( \sqrt{s} = 500 \text{ GeV} \)

25 < \( E^e_T < 50 \text{ GeV} \)

\[
A_L^- \approx \frac{\int_{\otimes(x_1,x_2)} \left[ \Delta \bar{u}(x_1)d(x_2)(1 - \cos \theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1 + \cos \theta)^2 \right]}{\int_{\otimes(x_1,x_2)} \left[ \bar{u}(x_1)d(x_2)(1 - \cos \theta)^2 + d(x_1)\bar{u}(x_2)(1 + \cos \theta)^2 \right]}
\]

\[
A_L^+ \approx \frac{\int_{\otimes(x_1,x_2)} \left[ \Delta \bar{d}(x_1)u(x_2)(1 + \cos \theta)^2 - \Delta u(x_1)\bar{d}(x_2)(1 - \cos \theta)^2 \right]}{\int_{\otimes(x_1,x_2)} \left[ \bar{d}(x_1)u(x_2)(1 + \cos \theta)^2 + u(x_1)\bar{d}(x_2)(1 - \cos \theta)^2 \right]}
\]

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Relativistic Heavy-Ion Collider (RHIC)

RHIC is the world’s first polarized proton collider

Absolute Polarimeter (H↑ jet) → RHIC pC Polarimeters

Spin Rotators (longitudinal polarization)

Siberian Snakes

Pol. H⁻ Source → Solenoid Partial Siberian Snake

RHIC pC Polarimeters → Spin flipper

Siberian Snakes

Spin Rotators (longitudinal polarization)

1.5 GeV BOOSTER

AGS

Alternating Gradient Synchrotron 24 GeV

AGS pC Polarimeters

Strong Helical AGS Snake

AGS Internal Polarimeter

200 MeV Polarimeter

Rf Dipole

PHOBOS

BRAHMS

PHENIX

STAR

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STAR Detector

\[ \eta = -\ln \tan \frac{\theta}{2} \]

- Calorimetry system with 2π coverage:
  - BEMC (-1 < η < 1)
  - EEMC (1 < η < 2)
- TPC: Tracking and particle ID
  - (|η|<1.3)

Approximate kinematic range at RHIC
-2 < η < 2  
0.06 < x < 0.4
Run 2013 Dataset

Production runs at $\sqrt{s}=500/510$GeV (long. polarization) in 2009, 2011, 2012 and 2013:

- W production (Quark polarization)
- Jet and Hadron production (Gluon polarization)

<table>
<thead>
<tr>
<th>Run</th>
<th>L (pb$^{-1}$)</th>
<th>P (%)</th>
<th>FOM ($P^2L$) (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 9</td>
<td>12</td>
<td>0.38</td>
<td>1.7</td>
</tr>
<tr>
<td>Run 11</td>
<td>9.4</td>
<td>0.49</td>
<td>2.3</td>
</tr>
<tr>
<td>Run 12</td>
<td>72</td>
<td>0.56</td>
<td>24</td>
</tr>
<tr>
<td>Run 13</td>
<td>200</td>
<td>0.56</td>
<td>63</td>
</tr>
</tbody>
</table>

Polarized protons

- 2009 $P = 34\%$
- 2006 $P = 55\%$
- 2005 $P = 47\%$
- 2003 $P = 34\%$
- 2012 $P = 52\%$
- 2015 $P = 55\%$
- 2017 $P = 53\%$
- 2013 $P = 53\%$

(L peak limited by STAR)
W Selection at STAR

The W selection algorithm is built based on the topological and kinematic differences between W events and QCD events.

\[ p + p \rightarrow W \rightarrow e + \nu \]

- Isolated track pointing to isolated cluster in the calorimeter.
- Missing energy in the opposite azimuthal direction.

\[ p + p \rightarrow QCD \rightarrow \text{jets} \]

- Several tracks pointing to several towers.
- Vector \( p_T \) sum is balanced by opposite jet.
Jacobian Peak

- $E_T^{2x2}/E_T^{4x4} > 0.95$
- $E_T^{2x2}/E_T^{\Delta R<0.7} > 0.88$
- Signed $p_T$ balance $> 14$ GeV/c
- Away $E_T < 11$ GeV

Signal of Jacobian Peak with $E_T$ distribution after selection cuts
Background Estimation

**Electroweak Background:**
This background arises from well-understood electroweak processes:
- $Z \rightarrow e^-e^+$
- $W \rightarrow \tau+\nu$

**QCD Background:**
- **Second EEMC:**
  Background (di-jets) which counts as a $W$ event by escaping detection through non-existing calorimeter coverage ($-2 < \eta < -1$).
- **Data-driven QCD:**
  Background which passes $e^\pm$ isolation cuts.
**W A_L from Run 2011+2012**

- \( A_L \) of \( W^- \) shows indication that data are larger than the DSSV predictions.

- \( A_L \) of \( W^+ \) is consistent with theoretical predictions with DSSV pdf.

- Indication of symmetry breaking of polarized sea.

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The flavor asymmetry of polarized antiquarks in the nucleon is positive.

It has almost the same absolute size as the flavor asymmetry of unpolarized antiquarks.
**WA_L from Run 2013**

- Most precise WA_L results from 2013 dataset.
- Consistent with 2011+2012 published results, with 40% uncertainty reduced.
- Further confirmed the polarized sea asymmetry.

\[ \vec{p} + p \rightarrow W^\pm + X \rightarrow e^\pm + X \]
\[ \sqrt{s} = 510 \text{ GeV} \]
\[ 25 < E_T < 50 \text{ GeV} \]
• The data confirm the existence of a sizable, positive $u$-bar polarization in the range $0.05 < x < 0.2$.

• The data confirm the existence of a flavor asymmetry in the polarized quark sea.
Double spin asymmetry of W can also provide access to u-bar, d-bar polarization

\[
A_{LL}^{W^+} \propto \frac{\Delta u \Delta \bar{d}}{u \bar{d}} \\
A_{LL}^{W^-} \propto \frac{\Delta d \Delta \bar{u}}{d \bar{u}}
\]

$$\vec{p} + \vec{p} \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$$
\(\sqrt{s}=510 \text{ GeV} \quad 25 < E_T^{\ell} < 50 \text{ GeV} \)

6.5% beam pol scale uncertainty not shown

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Summary

- Sea quark polarization plays an important role in understanding the nucleon spin structure.

- STAR W $A_L$ place unique and significant constraints on the polarized quark and antiquark distributions.

- Significant shift of the central value of $\Delta \bar{u}$ by including the new STAR 2013 W $A_L$ results.

- First clear evidence of the flavor-asymmetry in the polarized quark sea.

\[ \vec{p} + p \rightarrow W^\pm + X \rightarrow e^\pm + X \]  
$\sqrt{s} = 510$ GeV  
$25 < E_T^e < 50$ GeV