Measurement of Longitudinal Single-Spin Asymmetry for W Boson Production in p+p collisions at STAR

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Flavor separation of nucleon spin

- Sea quark polarization not well constrained by DIS data yet:

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + < L_{q,g} > \]

- Spin sum rule (longitudinal):

\[ \Delta \Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} \]

Quark spin, (~30%) Poorly known, RHIC

Gluon spin, Poorly known, RHIC

Orbital Angular Momenta Little known

Probing sea quark polarization via W production

• Quark polarimetry with W’s in p+p collision (example of $W^+$):

$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1) \bar{d}(x_2) + \Delta \bar{d}(x_1) u(x_2)}{u(x_1) \bar{d}(x_2) + \bar{d}(x_1) u(x_2)} = \begin{cases} -\frac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\ \frac{\Delta \bar{d}(x_1)}{d(x_1)}, & y_{W^+} << 0 \end{cases}$$

$$A_L^{W^-} = \begin{cases} -\frac{\Delta d(x_1)}{d(x_1)}, & y_{W^-} >> 0 \\ \Delta \bar{u}(x_1) \bar{u}(x_1), & y_{W^-} << 0 \end{cases}$$

• Spin asymmetry measurements:

$\propto \Delta \bar{d}(x) u(x)$

★ W’s naturally separate quark flavors
★ no fragmentation function involved

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RHIC- a polarized proton+proton collider

- Polarization direction changes from bunch to bunch
- Spin rotators provide choice of spin orientation

\[ \sqrt{s} = 200,500 \text{GeV} \]

\[ Pb \sim 60\% \]
RHIC performance with p+p collisions

- STAR data samples for W boson $A_L$ analysis:

<table>
<thead>
<tr>
<th>Year</th>
<th>L (pb$^{-1}$)</th>
<th>P</th>
<th>$P^2L$ (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>12</td>
<td>38%</td>
<td>1.7</td>
</tr>
<tr>
<td>2011</td>
<td>9.4</td>
<td>49%</td>
<td>2.3</td>
</tr>
<tr>
<td>2012</td>
<td>77</td>
<td>56%</td>
<td>24</td>
</tr>
<tr>
<td>2013</td>
<td>246.2</td>
<td>56%</td>
<td>77.2</td>
</tr>
</tbody>
</table>
STAR - Solenoid Tracker At RHIC

Magnet
• 0.5 T Solenoid

Triggering & Luminosity Monitor
• Beam-Beam Counters
  – $3.4 < |\eta| < 5.0$
• Zero Degree Calorimeters
• Vertex Position Detector

Central Tracking
• Large-volume TPC
  – $|\eta| < 1.3$

Calorimetry
• Barrel EMC (Pb/Scintillator)
  – $|\eta| < 1.0$
• Endcap EMC (Pb/Scintillator)
  – $1.0 < \eta < 2.0$
• Forward Meson Spectrometer
  – $2.5 < \eta < 4.0$

(- those marked red are relevant to W analysis)

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$W \rightarrow e^+ \nu$ Candidate Event:

- Isolated track pointing to isolated EM cluster in calorimeter
- Large “missing energy” opposite the electron candidate

QCD Background Event

- Several tracks pointing to energy deposit in several towers
- $p_T$ sum is balanced by di-jet, no large “missing energy”
W selection at STAR: Jacobian peak

Signal of Jacobian peak with $E_T$ distribution after selection:

- STAR 2013 with BEMC ($|\eta|<1$)
**W selection (|\eta|<1) : BG Estimation**

- **Primary Background**
  - Data-driven QCD : BG Events which satisfy e+/− candidate isolation cuts
  - Second EEMC : due to “jet” escape without East EEMC based on real West EEMC

- **Weak decay Background**
  - From Z→ee, and W→τν, determined from MC

-W signal window: [25,50] GeV
STAR mid-rapidity W $A_L$ –2011+2012

• First multiple-eta-bin $A_L$ results from 2011+2012 data:
  
  - $A_L$ of $W^-$ shows indication that data are larger than the DSSV predictions
  
  - $A_L$ of $W^+$ is consistent with theoretical predictions with DSSV pdf.
  
  - Provided new constraints on sea quark polarization at $0.05 < x < 0.25$ for $\Delta \bar{u}, \Delta \bar{d}$.

  \[ \Delta \bar{u}, \Delta \bar{d} \]

**STAR, PRL113(2014)72301**
Global Analysis with STAR W $A_L$ results

- Big impact seen in NNPDFpol1.1 global analysis after including STAR $A_L$ data.


- Polarized sea asymmetry:
**W A\textsubscript{L} results – STAR 2013**

- Most precise W A\textsubscript{L} results from 2013 STAR dataset
- Consistent with published RHIC results; with 40-50% smaller uncertainties than STAR 2011+2012 results
- Confirmed positively polarized anti-up quark first seen in the 2011+2012 data.

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

\[e, \eta_{1-0}, 1-0.5, 0.5-0 \]

**STAR, PRD99, 051102R(2019)**
W $A_L$ results – STAR 2013

- Most precise $W A_L$ results from 2013 STAR dataset
- Consistent with published RHIC results; with 40-50% smaller uncertainties than STAR 2011+2012 results
- Confirmed positively polarized anti-up quark first seen in the 2011+2012 data.
- Combined STAR 2011-2013 results in comparison with theoretical predications

STAR, PRD99, 051102R(2019)
Impact of STAR 2013 $W A_L$ results

- Reweighting based on NNPDF pol1.1 confirmed the polarized sea asymmetry: \( \Delta \bar{u} > \Delta \bar{d} \)

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

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

\[ x(\Delta \bar{u} - \Delta \bar{d}) \]

- The polarized flavor asymmetry is opposite to the unpolarized case!

- Compatible with Pauli suppression by the polarized valence quarks, among different models.

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$Z/\gamma^*$ $A_L$ results from STAR

- $A_L$ from $Z^0$ can provide additional constraints on $\Delta\bar{u}$, $\Delta\bar{d}$, though statistics limited.

- STAR 2013 $A_L$ results from $Z/\gamma^*$

STAR, PRD99, 051102R(2019)
W $A_{LL}$ results from STAR

- Double spin asymmetry of $W$ can also provide access to $\Delta u$, $\Delta d$
  with a different combination:

$$A_{LL}^{W^+} \propto \frac{\Delta u \Delta d}{u \bar{d}}, \quad A_{LL}^{W^-} \propto \frac{\Delta d \Delta \bar{u}}{d \bar{u}} \quad \left( A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \right)$$

- STAR $A_{LL}$ results is consistent with predictions from DSSV

![Graph showing $A_{LL}$ vs. lepton $|\eta|$ with data points and error bars.](image)

$\vec{p} + \vec{p} \rightarrow W^\pm \rightarrow e^\pm + \nu$

$\sqrt{s} = 510$ GeV  $25 < E_T^e < 50$ GeV

**STAR, PRD99, 051102R(2019)**
Summary

- Sea quark polarization plays an important role in understanding the nucleon spin structure.
- Unique clean probe of sea quark polarization via W production at RHIC:
  - $W A_L$ results provide important constraints on $\Delta \bar{u}$, $\Delta \bar{d}$.
- Most precise $W A_L$ results from STAR 2013 data set:
  - 40% uncertainty reduced compared to 2011+2012 data.
  - Clear evidence of flavor asymmetry for polarized sea with opposite sign to the unpolarized case.

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

Unique clean probe of sea quark polarization via $W$ production at RHIC:

- $W A_L$ results provide important constraints on $\Delta \bar{u}, \Delta \bar{d}$.

Most precise $W A_L$ results from STAR 2013 data set:

- 40% uncertainty reduced compared to 2011+2012 data.
- Clear evidence of flavor asymmetry for polarized sea with opposite sign to the unpolarized case.


Thanks!
Backup slides
Flavor symmetry of the polarized sea from SIDIS

- Do we expect a symmetry breaking in the polarized sea?

\[ \int (\Delta \bar{u} - \Delta \bar{d}) \, dx = 0.06 \pm 0.04 \pm 0.02 \quad @ \quad Q^2 = 3 \left( GeV / c \right)^2 \]

\[ \int (\Delta \bar{u} - \Delta \bar{d}) \, dx = 0.048 \pm 0.057 \pm 0.028 \quad @ \quad Q^2 = 2.5 \left( GeV / c \right)^2 \]

\[ \int (\bar{u} - \bar{d}) \, dx = -0.118 \pm 0.012 \quad @ \quad Q^2 = 54 \left( GeV / c \right)^2 \]

- COMPASS, PLB693 (2010) 227
- HERMES, PRD 71 (2005) 012003
- E866, Phys. Rev. D64 (2001) 052002
Expectation of $W A_L$ at RHIC

- Large parity-violating asymmetries expected.
- Simplified interpretation at forward and backward rapidity:

$$A_L^{W^-} \propto -\frac{\Delta d(x_1)\bar{u}(x_2) + \Delta \bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

\[ e^- \quad \bar{u} \quad \text{backward } e^- \quad \Delta \bar{u} \over \bar{u} \quad \text{Parallel to } W^- \]

$$A_L^{W^+} \propto -\frac{\Delta u(x_1)d(x_2) + \Delta \bar{d}(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)}$$

\[ e^+ \quad \bar{d} \quad \text{forward } e^+ \quad \Delta \bar{d} \over \bar{d} \quad \text{Anti-parallel to } W^+ \]
STAR forward detector upgrade

- **STAR forward upgrade:**
  - located at the West side of STAR
  - coverage: $2.5 < h < 4$

- **Key components:**
  - Calorimetry: ECal and HCal
  - Tracking:
    Silicon tracker and
    small-strip Thin Gap Chambers (sTGC)

- **Operation:**
  - pp, pA and AA data taking in FY2021~2025 in parallel with sPHENIX data taking period.

- **Physics:**
  - enables unique opportunities to cold QCD and Heavy ion physics
## Future RHIC Spin in 2021+

<table>
<thead>
<tr>
<th>Year</th>
<th>√s (GeV)</th>
<th>Delivered Luminosity</th>
<th>Scientific Goals</th>
<th>Observable</th>
<th>Required Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021/22</td>
<td>p⁺p @ 510</td>
<td>1.1 fb⁻¹ 10 weeks</td>
<td>TMDs at low and high x</td>
<td>$A_{UT}$ for Collins observables, i.e. hadron in jet modulations at $\eta &gt; 1$</td>
<td>Ecal + HCal +Tracking</td>
</tr>
<tr>
<td>2021/22</td>
<td>p⁻p @ 510</td>
<td>1.1 fb⁻¹ 10 weeks</td>
<td>$\Delta g(x)$ at small x</td>
<td>$A_{LL}$ for jets, di-jets, h/γ-jets at $\eta &gt; 1$</td>
<td>Ecal + HCal</td>
</tr>
<tr>
<td>2024</td>
<td>p⁺p @ 200</td>
<td>300 pb⁻¹ 8 weeks</td>
<td>Subprocess driving the large $A_{N}$ at high $x_F$ and $\eta$</td>
<td>$A_N$ for charged hadrons and flavor enhanced jets</td>
<td>Ecal + HCal +Tracking</td>
</tr>
<tr>
<td>2024</td>
<td>p⁺Au @ 200</td>
<td>1.8 pb⁻¹ 8 weeks</td>
<td>Nature of the initial state and hadronization in nuclear collisions</td>
<td>$R_{pAu}$ direct photons and DY Dihadrons, γ-jet, h-jet, diffraction</td>
<td>Ecal + HCal +Tracking</td>
</tr>
<tr>
<td></td>
<td>p⁺Al @ 200</td>
<td>12.6 pb⁻¹ 8 weeks</td>
<td>A-dependence of nPDF, A-dependence for Saturation</td>
<td>$R_{pAl}$: direct photons and DY Dihadrons, γ-jet, h-jet, diffraction</td>
<td>Ecal + HCal +Tracking</td>
</tr>
</tbody>
</table>

• RHIC is the world’s only polarized hadron hadron collider
• Unique physics opportunities in pp and pA