W Boson Production in Polarized p+p Collisions at RHIC

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Moriond QCD and High Energy Interactions
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Proton Spin Puzzle

The observed spin of the proton can be decomposed into contributions from the intrinsic quark and gluon spin and orbital angular momentum:

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

Integral of quark polarization is well measured in DIS to be only \(~30\%\), but decomposition (especially sea) is not well understood:

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

Being measured at RHIC (Jets, hadrons, etc.)

Polarized PDFs:

\[ \Delta f(x) = f^+(x) - f^-(x) \]
Flavor Asymmetry of the Sea

- Quantitative calculation of Pauli blocking does not explain $\bar{d}/\bar{u}$ ratio
- Non-perturbative processes may be needed in generating the sea
- E866 results are qualitatively consistent with pion cloud models, chiral quark soliton models, instanton models, etc.

Polarized PDFs from recent global fits:
- Valence $u$ and $d$ distributions are well determined
- Polarized flavor asymmetry $x(\Delta \bar{u} - \Delta \bar{d})$ could help differentiate models

PRL 101, 072001 (2008)
Probing the Sea Through W Production

$$u + d \rightarrow W^+ \rightarrow e^+ + \nu$$
$$\bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}$$

• Detect Ws through e^+/e^- decay channels
• V-A coupling leads to perfect spin separation
  • LH quarks and RH anti-quarks
• Neutrino helicity gives preferred direction in decay

Measure parity-violating single-spin asymmetry:

$$A_L^W = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

(Helicity flip in one beam while averaging over the other)

$$A_{L^-}^W \propto -\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)$$
$$A_{L^+}^W \propto -\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)$$
RHIC: Polarized p+p Collider

• First collisions at $\sqrt{s}=500$ GeV in 2009
• Beam polarization $\sim 40\%$
Barrel EM Calorimeter ($|\eta|<1$):
Lepton Energy Veto jets

Endcap EM Calorimeter ($1<\eta<2$):
Veto jets

Time Projection Chamber ($|\eta|<1.3$):
Vertex, Charge Separation Veto jets

Pythia+Geant $p+p\rightarrow W\rightarrow e+\nu$ event @ 500 GeV
500 GeV Data Set from Run 9

**W Trigger:**
High Tower Hardware L0 Trigger (E_T > 7.3 GeV)
High E_T 2x2 Cluster Software L2 (E_T > 13 GeV)

Integrated Luminosity @ 500 GeV:
• **Vernier Scan** technique used to measure cross section for high tower trigger
  \[ \sigma_{BHT3} = 481 \text{ nb} \pm 10 \text{ (stat.)} \pm 110 \text{ (syst.)} \]
• Scaling the number of background-subtracted high tower triggers by \(1/\sigma_{BHT3}\) yields the integrated luminosity of \(L=13.7 \text{ pb}^{-1}\)
W Algorithm: Lepton Isolation

Lepton Isolation Cuts:
- Require TPC track with $p_T > 10$ GeV
- Extrapolate track to Barrel Calorimeter
- Require highest $2x2$ cluster around pointed tower sum $E_T > 15$ GeV
- Require excess $E_T$ in $4x4$ cluster < 5%
- Match track to $2x2$ cluster position
W Algorithm: Suppress QCD Background

Suppress jets with leading hadron
- Near side jet-cone veto

Suppress di-jets and multi-jet events
- Away side $p_T$ sum veto
- Require an imbalance in $p_T$ of the lepton cluster and any jets reconstructed outside the near side jet cone

Signal region

EMC Cluster $E_T / 0.7$ Cone $E_T$

Away side $p_T$ sum (GeV)

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e\(^+\)/e\(^-\) Charge Separation at High \(P_T\)

[Diagram showing TPC and BEMC with vertex at 200 cm of tracking.]

- Positron \(P_T = 5\) GeV
- Electron \(P_T = 5\) GeV

+/- distance \(D \sim 1/P_T\)

- \(P_T = 5\) GeV : \(D \sim 15\) cm
- \(P_T = 40\) GeV : \(D \sim 2\) cm
### Background Subtraction

#### Background Events ($E_T > 25$ GeV)

<table>
<thead>
<tr>
<th>Process</th>
<th>W⁻ → $e^- + \bar{\nu}_e$</th>
<th>W⁺ → $e^+ + \nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow \tau + \nu_\tau$</td>
<td>2.7 ± 0.7</td>
<td>8.4 ± 2.2</td>
</tr>
<tr>
<td>Missing Endcap</td>
<td>14 ± 4</td>
<td>13 ± 4</td>
</tr>
<tr>
<td>Normalized QCD</td>
<td>8.0$^{+20}_{-4}$</td>
<td>25$^{+36}_{-9}$</td>
</tr>
<tr>
<td>Total</td>
<td>25$^{+21}_{-7}$</td>
<td>46$^{+36}_{-11}$</td>
</tr>
</tbody>
</table>

#### Background Systematic

- Calculate different data driven QCD background shapes by varying $p_T$ Balance and away side $p_T$ cuts
- Vary normalization region ($E_T < 17$ and $E_T < 21$ GeV)
- The largest deviation in each bin gives an estimate of the systematic uncertainty
STAR Ws from Run 9

Run 9 STAR Preliminary $\sqrt{s} = 500$ GeV

$p+p \rightarrow W^- \rightarrow e^- + \bar{\nu}_e$

- electron $|n| < 1$
- $W^-$ candidates
- Backg. est.
- Backg. subtr. $W^-$

Counts vs. EMC cluster $E_T$ (GeV)

Run 9 STAR Preliminary $\sqrt{s} = 500$ GeV

$p+p \rightarrow W^+ \rightarrow e^+ + \nu_e$

- positron $|n| < 1$
- $W^+$ candidates
- Backg. est.
- Backg. subtr. $W^+$

Counts vs. EMC cluster $E_T$ (GeV)
Monte-Carlo is full PYTHIA+GEANT simulation of $W \rightarrow e+\nu$ events at 500 GeV
W Production Cross Section at STAR

Run 9 STAR Preliminary $p+p \sqrt{s} = 500$ GeV
Kinematic acceptance: $|\eta| < 1$ and $E_T > 25$ GeV

$$\sigma(W^\pm \rightarrow e^\pm + \nu_e)$$

<table>
<thead>
<tr>
<th>$W^- \rightarrow e^- + \bar{\nu}_e$</th>
<th>$W^+ \rightarrow e^+ + \nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{W}^{\text{obs}}$</td>
<td>156</td>
</tr>
<tr>
<td>$N_{W}^{\text{back}}$</td>
<td>$25 \pm 21_{-7}^{+19}$</td>
</tr>
<tr>
<td>$\epsilon_{\text{total}}$</td>
<td>0.56 $\pm 0.11_{-0.09}^{+0.12}$</td>
</tr>
<tr>
<td>$\int L dt (\text{pb}^{-1})$</td>
<td>$13.7 \pm 3.2$</td>
</tr>
</tbody>
</table>

Run 9 STAR Preliminary ($p+p$ 500 GeV)

$$\sigma_{W^+\rightarrow e^+ + \nu} = 61 \pm 3 \text{ (stat.)} \pm 10 \text{ (syst.)} \pm 14 \text{ (lumi.)} \text{ pb}$$

$$\sigma_{W^-\rightarrow e^- + \bar{\nu}} = 17 \pm 2 \text{ (stat.)} \pm 3 \text{ (syst.)} \pm 4 \text{ (lumi.)} \text{ pb}$$
**$A_L$ for Ws at STAR**

After spin sorting the yields, calculate longitudinal parity-violating spin asymmetry $A_L$:

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

**STAR Preliminary Run 9**

$A_L(W^+) = -0.33 \pm 0.10\,(\text{stat.}) \pm 0.04\,(\text{syst.})$

$A_L(W^-) = 0.18 \pm 0.19\,(\text{stat.}) \pm 0.04\,(\text{syst.})$
Conclusions

• W boson production in polarized p+p collisions provides a new means of studying the spin-flavor asymmetries of the proton sea quark distributions

• The cross sections for $W^+$ and $W^-$ measured at STAR are consistent with theoretical expectations

• The parity-violating asymmetries, $A_L$, were also observed and agree with theoretical predictions

• Future planned STAR measurements at mid-rapidity and forward rapidity with increased luminosity and beam polarization will provide significant constraints on the polarized sea
Backup
Example Lego Plots

BEMC $E_T$ Distribution (GeV)  

TPC $p_T$ Distribution (GeV/c)

W event

Dijet event
Example Event Display
Data Driven Background

**Iterative Normalization**
- Small W signal is expected in normalization region (ET<19 GeV)
- Use linear fit to low ET side of Jacobian peak to estimate signal in normalization region

**Systematic Uncertainty**
- Calculate 1200 different QCD background shapes by varying awayside pT cut, ptBalance cut, and normalization region
- Take maximum extent for each bin as uncertainty
Event Rejection

Run 9 Data

- Electron candidate, cut = max 2x2
- Entries 152197
- Track $p_T > 10$ GeV
- Lepton Isolation Cut
- Near Side $p_T$ Veto
- Away Side $p_T$ & $p_T$ Balance Veto

Pythia+Geant $W^+$ MC

- Electron candidate, cut = max 2x2
- Entries 5107

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Cross Section

\[ \sigma_w = \int dE_T^e \int d\eta^e \frac{d^2\sigma_{W \rightarrow ev}}{d\eta^e dE_T^e} = \frac{1}{L} \frac{1}{\varepsilon_{\text{trig}}} \frac{1}{\varepsilon_{\text{vertex}}} \frac{1}{\varepsilon_{\text{reco}}} (N_{W_{\text{obs}}} - N_{\text{back}}) \]

Kinematic acceptance: \( |\eta_e| < 1 \) and \( E_T^e > 25 \text{GeV} \)

Efficiencies Calculated from full PYTHIA + GEANT simulations

<table>
<thead>
<tr>
<th>Efficiency Component</th>
<th>( W^- \rightarrow e^- + \bar{\nu}_e )</th>
<th>( W^+ \rightarrow e^+ + \nu_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger: ( \varepsilon_{\text{trig}} )</td>
<td>0.86 ( \pm ) 0.04</td>
<td>0.88 ( \pm ) 0.04</td>
</tr>
<tr>
<td>Vertex: ( \varepsilon_{\text{vertex}} )</td>
<td>0.91 ( \pm ) 0.03</td>
<td>0.91 ( \pm ) 0.03</td>
</tr>
<tr>
<td>Reconstruction: ( \varepsilon_{\text{reco}} )</td>
<td>( +0.13 ) ( \pm 0.11 )</td>
<td>( +0.14 ) ( \pm 0.11 )</td>
</tr>
<tr>
<td>Total: ( \varepsilon_{\text{total}} )</td>
<td>0.56 ( \pm 0.11 ) ( \pm 0.09 )</td>
<td>0.56 ( \pm 0.12 ) ( \pm 0.09 )</td>
</tr>
</tbody>
</table>
Cross Section Uncertainties

• W Reconstruction Systematic
  – Track Reconstruction: 15-20%
  – Vertex Reconstruction: 4%
  – Energy Scale: < 1%

• Normalization/Luminosity Systematic
  – Vernier scan absolute cross section: 23%

• Background Systematic
  – Vary data driven QCD background shape and normalization region
Anti-quark Distribution Functions

\[ \bar{d}(x)/\bar{u}(x) \text{ at } Q^2 = 36 \text{ GeV}^2 \]
Spin dependent x-section for longitudinal polarization

\[
\begin{align*}
\frac{N_{++}}{L_{++}} &= \sigma_0 \left[ 1 + A_L(P_1 + P_2) \right] + A_N(Q_1 - Q_2)\delta + A_{LL}P_1P_2 \\
\frac{N_{+-}}{L_{+-}} &= \sigma_0 \left[ 1 + A_L(P_1 - P_2) \right] + A_N(Q_1 + Q_2)\delta - A_{LL}P_1P_2 \\
\frac{N_{-+}}{L_{-+}} &= \sigma_0 \left[ 1 - A_L(P_1 - P_2) \right] - A_N(Q_1 + Q_2)\delta - A_{LL}P_1P_2 \\
\frac{N_{--}}{L_{--}} &= \sigma_0 \left[ 1 - A_L(P_1 + P_2) \right] - A_N(Q_1 - Q_2)\delta + A_{LL}P_1P_2
\end{align*}
\]

\( N = \# \) events and \( L = \) luminosity for each spin state

\( \delta \approx \int_{2\pi} d\phi_e \ \text{Effi}(\phi_e) \sin(\phi_e) \approx 0.02 \)

Yields integrated over \( |\eta| < 1 \)

\( \frac{N_{++}}{L_{++}} = \sigma_{++} \), etc.
Longitudinal spin asymmetries for Ws

- Four independent yields were measured. Six asymmetries were computed, of which three are independent, and one of these is a null test.

<table>
<thead>
<tr>
<th>Leading physics asymmetry</th>
<th>cross section dependence</th>
<th>raw asymmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_L$ (blue)</td>
<td>$(\sigma_{++} + \sigma_{+-} - \sigma_{-+} - \sigma_{--})/\text{sum4}$</td>
<td>$A_L P_1$</td>
</tr>
<tr>
<td>$A_L$ (yellow)</td>
<td>$(\sigma_{++} + \sigma_{-+} - \sigma_{--} - \sigma_{+-})/\text{sum4}$</td>
<td>$A_L P_2$</td>
</tr>
<tr>
<td>$A_L$ (average)</td>
<td>$(\sigma_{++} - \sigma_{--})/\text{sum4}$</td>
<td>$A_L \frac{P_1 + P_2}{2}$</td>
</tr>
<tr>
<td>$A_{LL}$</td>
<td>$(\sigma_{++} + \sigma_{-+} - \sigma_{--} - \sigma_{+-})/\text{sum4}$</td>
<td>$A_{LL} P_1 P_2$</td>
</tr>
<tr>
<td>$A_L(P_1 - P_2)$</td>
<td>$(\sigma_{+-} - \sigma_{--})/(\sigma_{++} + \sigma_{+-})$</td>
<td>$A_L \frac{P_1 - P_2}{1 - A_{LL} P_1 P_2}$</td>
</tr>
<tr>
<td>$A_L^* \approx A_L$</td>
<td>$(\sigma_{++} - \sigma_{--})/(\sigma_{++} + \sigma_{--})$</td>
<td>$A_L \frac{P_1 + P_2}{1 + A_{LL} P_1 P_2}$</td>
</tr>
</tbody>
</table>

Null test

Yields integrated over $|\eta|<1$

where $\text{sum4} = \sigma_{++} + \sigma_{+-} + \sigma_{-+} + \sigma_{--}$
The QCD background was estimated as described for the cross section determination. This background is assumed to be unpolarized. However, it can impact the extraction of the physics asymmetry, $A_L$.

$$N_{\pm} = \sigma_0 \mathcal{L}_0 \varepsilon_0 \left[ 1 + \beta \pm A \right]$$

where $\beta$ is background contamination

$$\beta = \frac{\text{signal + backg}}{\text{signal}}$$

$$\epsilon_{\text{s}} = \frac{N_{+} - N_{-}}{N_{+} + N_{-}}$$

$$A = \frac{\beta \epsilon_{\text{s}}}{P} \quad \text{physics asy corrected for background}$$

- Uncorrected event by event background is equivalent to beam depolarization.
- High/low limits on the background translate to an $A_L$ scale uncertainty.
Systematic Errors for $A_L$

- The table below lists the systematic uncertainties for $A_L$.
  - No contribution assumed from wrong sign $W$ contamination, due to $Q/p_T$ cut.
  - No other spin observables assumed to contribute.

<table>
<thead>
<tr>
<th></th>
<th>$W^+$</th>
<th></th>
<th>$W^-$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>high</td>
<td>0.092</td>
<td>low</td>
<td>0.092</td>
<td>CNI average polarization of both beams $(P1+P2)$</td>
</tr>
<tr>
<td>0.070</td>
<td>0.020</td>
<td>0.130</td>
<td>0.030</td>
<td>QCD unpolarized background</td>
</tr>
<tr>
<td>0.065</td>
<td>0.065</td>
<td>0.135</td>
<td>0.135</td>
<td>QCD pol. bckg. ~0: use 1/2 stat error of this test</td>
</tr>
<tr>
<td>0.004</td>
<td>0.000</td>
<td>0.004</td>
<td>0.000</td>
<td>decay of pol. within fill</td>
</tr>
<tr>
<td>0.13</td>
<td>0.11</td>
<td>0.21</td>
<td>0.17</td>
<td>total syst. in fraction of measured AL</td>
</tr>
</tbody>
</table>
W Kinematics

\[ x_1 = \frac{M_W}{\sqrt{s}} e^{y_w} \]
\[ x_2 = \frac{M_W}{\sqrt{s}} e^{-y_w} \]
\[ y_{lep}^{lab} = y_{lep}^* + y_W \]

If \( W q_T \) is small

\[ y_{lep}^* = \frac{1}{2} \ln \frac{1 + \cos \theta^*}{1 - \cos \theta^*} \]
\[ p_{T,l}' = \frac{M_W}{2} \sin \theta^* \]

If \(|\text{rapidity}|\gg 0\)

\[ A_L^+ (y_W >> 0) \approx \frac{\Delta u(x)}{u(x)} \]
\[ A_L^- (y_W >> 0) \approx \frac{\Delta d(x)}{d(x)} \]

\[ A_L^+ (y_W << 0) \approx -\frac{\Delta d(x)}{d(x)} \]
\[ A_L^- (y_W << 0) \approx -\frac{\Delta u(x)}{u(x)} \]

|\( y_{lep}^{lab} - y_{lep}^* - y_W \)|

- **mid-rapidity**
- **for./back. rapidity**