The PHENIX W Program

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ISSP2013 (Erice)
Polarized PDFs

PDF = parton distribution function

Number distribution of partons inside the proton (or other hadron)

\[
\begin{align*}
\text{Momentum contribution} & \quad f(x) = f^+(x) + f^-(x) \\
\text{Spin contribution} & \quad \Delta f(x) = f^+(x) - f^-(x)
\end{align*}
\]

Unpolarized

Don’t care about the helicity of the parton

Polarized

Care about the helicity of the parton in polarized proton
The Spin Puzzle

The proton is viewed as being a “bag” of bound quarks and gluons interacting via QCD.

Spins + orbital angular momentum need to give the observed spin 1/2 of proton.

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + L^z_q + \Delta G + L^z_g
\]

Fairly well measured only ~30% of spin.

Being measured at RHIC.

Its decomposition is not well understood, especially the sea (low-x)... needs data.

\[
\Delta \Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta \bar{u} + \Delta \bar{d} + \Delta \bar{s} + \cdots)dx
\]
Flavor Asymmetry in Parton Sea

- E866 results are qualitatively consistent with pion cloud models, instanton models, chiral quark soliton models, etc.

- Pauli blocking should contribute to the observed signal, but how much is currently debated
- Non-perturbative processes may be needed in generating the sea

$Q^2 = 54 \text{ GeV}^2$
Probing the Sea through Ws

- Detect Ws through $e^+$ and $e^-$ (and $u^+$ and $u^-$) decay channels
- V-A coupling leads to perfect spin separation
- Neutrino helicity gives preferred direction in decay

Measure parity violating single helicity asymmetry $A_L$
(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

The world’s first polarized proton collider
Central Arms:
- $\gamma/\pi^0/\eta$ detection
  - Electromagnetic Calorimeter (-0.35 < $\eta$ < 0.35)
  - PC3 - Charge Veto

Muon Arms: (1.2<|$\eta$|<2.4 + 2$\pi$)
- Large absorber in front
- Separate magnet (radial field)
- Tracking and high-p triggering

MPC
- Electromagnetic Calorimeter (3.1<|$\eta$|<3.9 + 2$\pi$)

Global Detectors:
- Relative Luminosity
  - Beam-Beam Counter (BBC) (+- 3.1 < $\eta$ < 4.0)
  - Zero-Degree Calorimeter (ZDC) (+- 6.9 < $\eta$ < infinity)
- Local Polarimetry - ZDC
The Mid-Rapidity Analysis Idea

Expect a Jacobian peak in the $E_T$ distribution

$W$ Signal

$E_T$ ~ $M_W/2$

QCD Background

Expect a steeply falling, but large background

We expect to see a bump in the $E_T$ spectrum at $M_W/2$
Jacobian Peaks + Cross Section
At forward rapidity there is either NO Jacobian peak or our p resolution isn’t good enough, so we can’t use shape to separate signal and background.
Currently we rely heavily on simulation for the estimation of the background size and shape.

There are ideas to extract background shapes from $\sqrt{s}=200\text{GeV}$ data where there should be less $W$ signal (less simulation dependent).
A Spin Experiment

\[ A_L = \frac{\tilde{\sigma} - \bar{\sigma}}{\tilde{\sigma} + \bar{\sigma}} = \frac{1}{P} \frac{N^+ - RN^-}{N^+ + RN^-} \]

- \( P \) - polarization of beam
- \( R \) - relative luminosity
- \( N \) - physics process
PHENIX Run12 $A_L$ Results
Future Projections

\[ W^+ \rightarrow e^+, \mu^+ \]

\[ W^- \rightarrow e^-, \mu^- \]
Conclusions

• RHIC has a vibrant program measuring W production in polarized p+p collisions to get the flavor separated pdfs (polarized and unpolarized)
• The first proof of principle measurements have been done and the analysis of larger datasets is ongoing
• We have just recorded a large sqrt(s)=510 p+p dataset (run13, 150pb⁻¹) and are in the process of analyzing it.
• Stay tuned for more results!
Backup Slides
Expectations for $W A_L$

\[ A_{L}^{W^-} = \frac{\Delta \bar{u}}{u} \]

\[ A_{L}^{W^+} = \frac{1}{2} \left( \frac{\Delta \bar{u}}{\bar{u}} - \frac{\Delta d}{d} \right) \]

\[ A_{L} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \]

\[ A_{L}^{W^+} = \frac{\Delta d}{d} \]

\[ A_{L}^{W^-} = -\frac{\Delta \bar{u}}{\bar{u}} \]
W Cross Sections

Theory: FEWZ and MSTW08 NLO PDFs

$\sigma_{W}^{\text{tot}} \cdot \text{BR}(W \rightarrow l \nu)$ (pb)

$\sigma_{Z/\gamma^{*}}^{\text{tot}} \cdot \text{BR}(Z/\gamma^{*} \rightarrow l l)$ (pb)

$p\bar{p} \rightarrow W$

$pp \rightarrow W^+$

$pp \rightarrow W^-$

$p\bar{p} \rightarrow Z/\gamma^{*}$

$pp \rightarrow Z/\gamma^{*}$

$\sqrt{s}$ (GeV)

Experiments:
- STAR
- UA1
- UA2
- Phenix
- ATLAS
- CDF
- CMS
- D0

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Polarized Protons at RHIC

\[ L_{\text{max}} = 2 \times 10^{32} \text{s}^{-1} \text{cm}^{-2} \]

70% Polarization

\[ \sqrt{s} = 50 \ldots 500 \text{ GeV} \]

- **Absolute Polarimeter (H jet)**
- **RHIC pC Polarimeters**
- **BRAHMS & PP2PP (p)**
- **PHENIX (p)**
- **STAR (p)**
- **Siberian Snakes**
- **Pol. H\(^-\) Source**
  - 500 \(\mu\)A, 300 \(\mu\)s
- **200 MeV Polarimeter**
- **Rf Dipoles**
- **AGS Internal Polarimeter**
- **AGS pC Polarimeters**
- **Partial Siberian Snake**
- **Strong AGS Snake**
- **2 \times 10^{11} \text{Pol. Protons / Bunch}**
- **\(\varepsilon = 20 \pi \text{ mm mrad}\)**
Control of Helicity of Beams

Experiment

Yellow beam helicity:
+ - + -

Blue beam helicity:
- - + +

spin rotator

transverse pol

(mostly) longitudinal polarization

transverse pol

Both experiments sees 4 helicity configurations
Future Projections

STAR Run 12 + Run 13 Projections $\sqrt{s} = 500$ GeV

$\bar{p} + p \rightarrow W^{\pm} + X \rightarrow e^{\pm} + X$

$25 < E_T^e < 50$ GeV

$|\eta| < 1.5$ $L = 250$ pb$^{-1}$

$1.5 < |\eta| < 2.0$ $L = 165$ pb$^{-1}$

$P = 55\%$

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STAR Run12 $A_L$ Results

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

$W^+$ and $W^-$ distributions with different theoretical predictions.
Jacobian Peaks

Positive Charge $p_T$ spectrum for p+p (195 GeV) Run 2012 (y < 0.36)
EMCal cluster associated with track
Jacobian peak (PYTHIA+GEANT) with background fit
Background uncertainty estimation

STAR 2012 Data
\[ W \rightarrow e^+ e^- \text{ MC} \]
Data-driven QCD

Events / 4 GeV

Negative Charge $p_T$ spectrum for p+p (195 GeV) Run 2012 (y < 0.36)
EMCal cluster associated with track
Jacobian peak (PYTHIA+GEANT) with background fit
Background uncertainty estimation

Second EEMC
\[ W \rightarrow \tau^+ \tau^- \text{ MC} \]
\[ Z \rightarrow ee \text{ MC} \]
RHIC Performance

Polarized proton runs

Integrated polarized proton luminosity [pb⁻¹]

Time [weeks in physics]

2003 \(P = 34\%\)

2005 \(P = 47\%\)

2006 \(P = 55\%\)

2008 \(P = 44\%\)

2009 \(P = 34\%\)

2011 \(P = 48\%\)

2012 \(P = 59\%\)

2013 \(P = 52\%\)

250/255 GeV

100 GeV
STAR

- BEMC + EEMC: EM Calorimetry (-1 < h < 2 + 2π)
- TPC: Tracking and particle ID (-1 < h < 1)
- FMS: Forward EM Calorimetry (2.3 < h < 4)
- ZDC: Relative luminosity and local polarimetry
- BBC: Relative luminosity and Minimum bias trigger

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Motivation

What we want to accept

Look for the electron-type events with no energy/momentum on the away side

What we want to reject
PHENIX Run9 $A_L$ Results

![Graphs showing $A_L$ results for $W^+Z^0$ and $W^+Z^0$]

- **$W^+Z^0$**
  - PHENIX Run 2009 (500 GeV) + Run 2011 (500 GeV) + Run 2012 (510 GeV)
  - $p_T > 30$ GeV/c, $|y| < 0.35$

- **$W^+Z^0$**
  - PHENIX preliminary

**Polarization scale uncertainty:** 5.9%

*RHIC-PS (W+Z): $\sigma_{BR}=43$ pb assumed for background*

*Sampled cross-section: 25 pb$^{-1}$ per arm*

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Sea Quark Pol. PDFs
DSSV Polarized PDFs
PHENIX Forward Likelihoods

S-

N-

S+

N+
Run12 Muon Trigger Hardware

FVTX Upgrade
+ Adds tracking
RPC1
+ Adds acceptance
+ Adds trigger rejection
Additional Absorber
+ Shields detector from in-time backgrounds

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**W Algo: Motivation**

What we want to accept

What we want to reject

Look for the electron-type events with no energy/momentum on the away side
W Algo: 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
• Get charge sign of lepton

TPC track extrapolated to BTOW tower grid

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W Algo: 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
The Raw Signal

STAR recorded 13.7 pb⁻¹ in the run9 500 GeV running period
Extracting the W Signal

PYTHIA+GEANT MC

1. Run analysis with EEMC in veto cuts
2. Run analysis without EEMC in veto cuts
3. Subtract two raw signals

\( W \rightarrow \tau + \nu_{\tau} \)
\( \tau \rightarrow e + \nu_{\tau} + \nu_e \)
MC Normalized to \( L=13.7 \text{ pb}^{-1} \)

Run 9 Data
Missing Endcap
Vetoed QCD Background

Total Background

Normalized at \( E_T < 19 \text{ GeV} \)
Data Driven QCD Bkgd.
**Data/MC Shape Comparison**

Monte-Carlo is full PYTHIA+GEANT simulation of $W \rightarrow e^+ \nu$ events at 500 GeV
2009 500 GeV Data Set

STAR recorded 13.7 pb⁻¹ in the 500 GeV running period

Required a high tower trigger ($E_T > 7.3$ GeV) and a high $E_T 2 \times 2$ clusters ($E_T > 13$ GeV)
Predictions for $A_L$

\[ \hat{p} + p \rightarrow W^\pm \rightarrow e^\pm + \nu \]

$E_T^e > 25$ GeV

$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$

**STAR Barrel EMC**

\[ \int \frac{dE_T^e}{25} \int d\eta_e \frac{d^2 \sigma^{W^\pm}}{d\eta_e dE_T^e} \approx \left( \frac{0.75}{0.50} \right) \sigma_{tot}^{W^\pm} \]

$A_L^{W^-} = \frac{1}{2} \left( \frac{\Delta \bar{u}}{\bar{u}} - \frac{\Delta d}{d} \right)$

$A_L^{W^+} = \frac{1}{2} \left( \frac{\Delta \bar{d}}{\bar{d}} - \frac{\Delta u}{u} \right)$

**LO interpretation for** $x1=x2$
Charge Separation at High $p_T$

shown
electron & positron

$PT = 5 \text{ GeV/c}$

$PT = 40 \text{ GeV/c}$

$\pm$ distance $D \sim 1/PT$

$PT = 5 \text{ GeV/c}$ : $D \sim 15 \text{ cm}$

$PT = 40 \text{ GeV/c}$ : $D \sim 2 \text{ cm}$

vertex

200 cm of tracking

infinite $PT$
Event Rejection

Run 9 Data

- Track $p_T > 10$ GeV
- Lepton Isolation Cut
- Near Side $p_T$ Veto
- Away Side $p_T$ & ptBalance Veto

Pythia+Geant $W^+$ MC

- Electron candidate, cut=max 2x2
- Entries 5167

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Example Lego Plots

W event

Dijet event
Cross Section Formula

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

Kinematic Acceptance: \(|\eta_e| < 1 \) and \( E_T^e > 25 \) 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 ± 0.04</td>
<td>0.88 ± 0.04</td>
</tr>
<tr>
<td>Vertex: ( \varepsilon_{\text{vertex}} )</td>
<td>0.91 ± 0.03</td>
<td>0.91 ± 0.03</td>
</tr>
<tr>
<td>Reconstruction: ( \varepsilon_{\text{reco}} )</td>
<td>0.72 ±0.13 -0.11</td>
<td>0.71 +0.14 -0.11</td>
</tr>
<tr>
<td>Total: ( \varepsilon_{\text{total}} )</td>
<td>0.56 ±0.11 -0.09</td>
<td>0.56 +0.12 -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
Helicity of beams at STAR

STAR sees 4 helicity states
STAR runs 4 parallel measurements

RHIC measured polarization
Run 9 @ 2x250 GeV
Pol yellow 0.40
Pol blue 0.38
syst. pol (blue+yellow)=9.2%
Monitor spin dependent luminosity

Relative luminosities of 4 states monitored to ~1%

TPC track extrapolated to BTOW tower grid

Counts vs. cluster $2x2_{ET}$ / $4x4_{ET}$

Relative luminosity monitor

$\pi^0$'s jets

Counts vs. Ws

Helicities of beams colliding at STAR
Up quark pol. seen by “naked eye”

\[ A_L^{W^+} = \frac{1}{2} \left( \frac{\Delta \bar{d}}{\bar{d}} - \frac{\Delta u}{u} \right) \]

\[ W^+ \text{ yield integrated over } |\eta|<1 \]

\[ N_{++} \simeq \sigma_0 L_{++} \left[ 1 + A_LP_1 + A_LP_2 \right] \]

\[ N_{--} \simeq \sigma_0 L_{--} \left[ 1 - A_LP_1 - A_LP_2 \right] \]

\[ \epsilon = \frac{N_{++} - N_{--}}{N_{++} + N_{--}} \]

\[ \sim A_L \cdot (P_1 + P_2) \simeq -0.3 \cdot 0.8 = -0.24 \]

Counts

- \( B^- \cdot Y^- \)
- \( B^- \cdot Y^+ \)
- \( B^+ \cdot Y^- \)
- \( B^+ \cdot Y^+ \)

\[ \epsilon = \frac{82 - 130}{212} = -0.23 \]

\[ \sigma(\epsilon) \simeq \frac{1}{\sqrt{212}} = 0.07 \]

\[ \frac{\epsilon}{\sigma(\epsilon)} = 3.3 \]
Spin dependent xsec for long. Pol.

\[ \frac{N_{++}}{L_{++}} = \sigma_0 \left[ 1 + A_L(P_1 + P_2) \right] \]
\[ \frac{N_{+-}}{L_{+-}} = \sigma_0 \left[ 1 + A_L(P_1 - P_2) \right] \]
\[ \frac{N_{--}}{L_{--}} = \sigma_0 \left[ 1 - A_L(P_1 + P_2) \right] \]
\[ \frac{N_{-+}}{L_{-+}} = \sigma_0 \left[ 1 - A_L(P_1 - P_2) \right] \]

\[ P-V A_L \] (the goal) \hspace{2cm} A_N \times \text{residual transverse pol } Q \hspace{2cm} A_{LL} \]

\[ \delta \sim \int_{2\pi} d\phi_e \text{ Effi}(\phi_e) \sin(\phi_e) \approx 0.02 \]
Long. spin asymmetries for Ws

STAR has measured 4 independent yields for the physics process selected 3 asymmetries are independent (6 were investigated)

<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>$(\sigma_{++} + \sigma_{+-} - \sigma_{--} - \sigma_{-+}) / sum4$</td>
<td>$A_LP_1$</td>
</tr>
<tr>
<td>$A_L$ (yellow)</td>
<td>$(\sigma_{++} + \sigma_{-+} - \sigma_{--} - \sigma_{+-}) / sum4$</td>
<td>$A_LP_2$</td>
</tr>
<tr>
<td>$A_L$ (average)</td>
<td>$(\sigma_{++} - \sigma_{--}) / sum4$</td>
<td>$A_L \frac{P_1 + P_2}{2}$</td>
</tr>
<tr>
<td>$A_{LL}$</td>
<td>$(\sigma_{++} + \sigma_{-+} - \sigma_{--} - \sigma_{+-}) / sum4$</td>
<td>$A_{LL}P_1P_2$</td>
</tr>
</tbody>
</table>

Null test

$A_L(P_1 - P_2)$

$(\sigma_{+-} - \sigma_{++}) / (\sigma_{++} + \sigma_{+-})$

$A^* \approx A_L$

$(\sigma_{++} - \sigma_{--}) / (\sigma_{++} + \sigma_{--})$

where $sum4 = \sigma_{++} + \sigma_{+-} + \sigma_{--} + \sigma_{-+}$
6 measured spin asymmetries for Ws

Physics asymmetries corrected for unpolarized background

Positve charge, unpol yield=392

Negative charge, unpol yield=118
Systematic errors for AL

Full list of accounted systematic errors in Run 9

Following effects were considered and their contribution set to zero

* dilution of $A_L$ due to swap of $W^+/W^-$ charge - the Q/PT cut prevents it

* $A_{LL}P_1P_2$ term cancels out

* $A_N \delta(P_1^T - P_2^T) < 1/1000$ since: $\delta \approx \int_{2\pi} d\phi_e \text{Eff}(\phi_e) sin(\phi_e) \approx 0.02$ and $P_1^T \sim P_2^T < 0.1$

$W^+$ $W^-$

<table>
<thead>
<tr>
<th>high</th>
<th>low</th>
<th>high</th>
<th>low</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.092</td>
<td>0.092</td>
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<tr>
<td>0.070</td>
<td>0.020</td>
<td>0.130</td>
<td>0.030</td>
</tr>
<tr>
<td>0.065</td>
<td>0.065</td>
<td>0.135</td>
<td>0.135</td>
</tr>
<tr>
<td>0.004</td>
<td>0.000</td>
<td>0.004</td>
<td>0.000</td>
</tr>
</tbody>
</table>

CNI average polarization of both beams ($P1+P2$)

QCD unpolarized background

QCD pol. bckg. ~0: use 1/2 stat error of this test

decay of pol. within fill

0.13 0.11 0.21 0.17 total syst. in fraction of measured AL