Results from PHENIX from Polarized \( pp \) Collisions at RHIC

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on behalf of the PHENIX Collaboration
Motivation for Spin Physics with $W$s at RHIC

- Goal of this work: measurement of flavor separated, polarized PDFs $\Delta \bar{u}(x)$ and $\Delta \bar{d}(x)$
- Recall $\Delta q(x, \mu^2) = q_+(x, \mu^2) - q_-(x, \mu^2)$, helicity-dependent PDFs
- Currently $\Delta \bar{u}(x)$ and $\Delta \bar{d}(x)$ poorly known

- Why is this important?
  - NA51, E866 observed large differences in unpolarized sea quarks $\bar{u}(x) - \bar{d}(x) \neq 0$
  - Natural to ask whether $\Delta \bar{u}(x) - \Delta \bar{d}(x) \neq 0$?
  - Such differences related to fundamentals like Pauli principle: predicts $\Delta \bar{u} > 0$, $\Delta \bar{d} < 0$

- Measured in semi-inclusive polarized DIS experiments (SMC, HERMES, COMPASS) - detect scattered lepton and hadron $h$
  - $\sigma \propto \sum_{q=u,d,s} \left[ \Delta q(x) D^h_q(z) + \Delta \bar{q}(x) D^h_{\bar{q}}(z) \right]$
- Results limited by knowledge of fragmentation functions $D^h_q$
- Low scale $\Rightarrow$ active work on NLO, target fragmentation, higher twist corrections
Motivation for Spin Physics with $W$'s at RHIC

- Polarized PDF results from recent global analysis
- Fractional uncertainties large on $\Delta \bar{u}(x)$ and $\Delta \bar{d}(x)$
- Q. How else can we reduce these uncertainties?
- A. STAR and PHENIX by exploiting maximal parity violation in $W$ production in polarized $pp$ collisions
  - No uncertainty from fragmentation (couplings of $W$ well known)
  - Measurements made at high scale ($Q^2 \approx M_W^2 \approx 6400$ GeV$^2$)
  - NLO and resummation effectively handle QCD effects

- Results determined primarily by semi-inclusive DIS
- Data already suggest symmetry breaking of polarized u and d sea quarks
- $\Delta \bar{u} > 0$, $\Delta \bar{d} < 0$, comparable to unpolarized case (red line)
- Many models: large-$N_c$, chiral quark solitons models, Pauli-blocking, ...
Measuring polarized sea quarks through $W^+ \rightarrow l^+ + \nu_l$ and $W^- \rightarrow l^- + \bar{\nu}_l$

- At leading order: $u_L + \bar{d}_R \rightarrow W^+$, $d_L + \bar{u}_R \rightarrow W^-$
- Construct parity-violating asymmetry:

$$A_{W^+}^L \equiv \frac{1}{P} \frac{N^+(W) - N^-(W)}{N^+(W) + N^-(W)} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta \bar{d}(x_1)u(x_2)}{u(x_1)d(x_2) + \bar{d}(x_1)u(x_2)}$$

$\Rightarrow W^+$ production sensitive to $\Delta u(x)$, $\Delta \bar{d}(x)$; $W^-$ sensitive to $\Delta d(x)$, $\Delta \bar{u}(x)$;

- Can extract ratios $[\Delta d(x)/\Delta u(x)]$ and $[d(x)/u(x)]$
- Central arm measurement $pp \rightarrow W^\pm \rightarrow e^\pm \nu$ probes PDFs at:

$$\langle x_{1,2} \rangle \approx \frac{M_w}{\sqrt{s}} \exp(\pm y_W) \approx 0.16$$

- N.B. We detect the decay lepton, not the $W$, interpretation more complicated
Motivation for Spin Physics with $W$s at RHIC

Plots from RHIC Spin Plan 2008. For \textit{lepton} asymmetry from $W$ decay

$$A_L(W^+) \propto -\Delta u(x_1)\bar{d}(x_2)(1 - \cos \hat{\theta})^2 + \Delta \bar{d}(x_1)u(x_2)(1 + \cos \hat{\theta})^2$$

$$A_L(W^-) \propto +\Delta \bar{u}(x_1)d(x_2)(1 - \cos \hat{\theta})^2 - \Delta d(x_1)\bar{d}(x_2)(1 + \cos \hat{\theta})^2$$

- At positive $Y_{W^+}$ ($x_1 \gg x_2$) sensitive to $-\Delta u(x)/u(x)$, at negative $Y_{W^+}$ to $\Delta \bar{d}(x)/d(x)$
- $y_W$ can not be determined unambiguously from $y^{lab}_e$ at mid-rapidity:
  $$y^{lab}_e = \hat{y}_e + y_W$$, where $\hat{y}_e = \frac{1}{2} \ln \left[ \frac{1 + \cos \hat{\theta}}{1 - \cos \hat{\theta}} \right]$,
  $$p_T^e \approx \frac{M_W}{2} \sin \hat{\theta} = \frac{M_W}{2} \sin(\pi - \hat{\theta})$$
- Irreducible uncertainty in sign, $P_T^W \neq 0$ either, extraction of $\Delta \bar{u}(x)$, $\Delta \bar{d}(x)$ not trivial
- NLO+resummation description complete (Nadalosky, Yuan, Vogelsang, de Florian)
RHIC : The World’s only Polarized Proton Collider

- Peak luminosity $\approx 2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ at $\sqrt{s} = 500$ GeV/c, $P \approx 50\%$, longitudinal or transverse
- Up to 120 bunches in each ring, crossing every 106 ns, helicity of pairs $++, +-, -+, - -$ alternates rapidly
- Rapid reversals reduce most systematics; $\exists$ crossing-by-crossing differences in $\mathcal{L}$ and vertex distribution
For $W^\pm \rightarrow e^\pm + \nu_e$ at $|\eta| < 0.35$

- Each arm $\Delta \phi = \pi/2$, $|\eta| < 0.35$ ($70^\circ < \theta < 110^\circ$)
- $\int \vec{B} \cdot d\vec{l} \approx 0.8 \text{ T} \cdot \text{m}$
- Vertex cut : $|z| < 30 \text{ cm}$

- EM calorimeter finely segmented : $\Delta \phi \times \Delta \eta \approx 0.01 \times 0.01$
- Tracking : Drift Chamber (DC) and Pad Chamber (PC1)
- Charge sign determination in DC
- SiVTX commissioned in 2011
- FVTX commissioned in 2012
- DAQ : Handles trigger rates 7-9 kHz
Backgrounds : Reducible and Irreducible

- Look for $e^\pm$, limited acceptance means can’t see missing $E_T$ from $\nu$, can’t identify $W \Rightarrow e + \nu_e$ definitively on event-by-event basis : rely on excess of events over background

Reducible Backgrounds : Collision-independent

- Cosmic rays
- Beam related backgrounds (fragments, halo, scattering upstream)
- Timing cuts reduce by more than factor of 5

Reducible Backgrounds : Collision-dependent

- $\pi^0$, $\eta \Rightarrow \gamma\gamma$, or direct-$\gamma$: conversion $\gamma \rightarrow e^+e^-$ yields cluster + matching track
- $h^\pm$ + hadronic shower in EMCal: cluster + matching track
- $\pi^0$ or direct-$\gamma$ with accidentally matching track from other fragments

Irreducible Backgrounds

- Irreducible in the sense they pass our cuts (high energy cluster+matching track)
- Leptonic charm, bottom decay : $\Rightarrow e^\pm+$anything
- Other $W$ decays : $W \Rightarrow \tau + \nu_\tau \Rightarrow e\nu_e\nu_\tau\bar{\nu}_\tau$, detect $e$
- $Z/\gamma^* \Rightarrow e^+ + e^-$, detect one $e$, other outside acceptance
- $Z \Rightarrow e^+ + e^-$ rate significant compared to $W^- \Rightarrow e^- + \bar{\nu}_e$
- $Z$ production comes with a small parity-violating asymmetry
Find the $W$s: Analysis Strategy

- Trigger on high E cluster in EMCal, threshold 10 GeV, timing cut reduces cosmics
- Match cluster with track in DC and PC1,
- Determine momentum from bend angle in DC, $E/p$ cut reduces hadronic background and mismatches; fiducial cuts on DC reduce ghost tracks
- Determine charge sign from bend angle in DC, 40 GeV track $\approx 2.3$ mrad
- Resolution $\approx 1.5$ mrad, remove region $|\alpha| < 1$ mrad, charge mid-ID few %
- Relative isolation cut: Energy in $R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \leq 0.4$ less than 10% of candidate cluster energy
  - Signal region 30-50 GeV unchanged
  - Background region 10-20 GeV reduced factor 10
• Identify $W^+ \rightarrow e^+ + \nu_e$ from Jacobian peak of signal events over falling background

- After cuts, background in $W^+ \rightarrow e^+$ signal region 30-50 GeV $\approx 18\%$
Identify $W^- \rightarrow e^- + \bar{\nu}_e$ from Jacobian peak of signal events over falling background

After cuts, background in $W^- \rightarrow e^-$ signal region 30-50 GeV $\approx 14\%$

$\chi^2$ for combined results $\approx 50$ for 35 DoF
Need more events to discriminate between different models of polarized PDFs
$W$ production cross section measurement from 2009

\begin{align*}
\text{Theory curves: FEWZ and MSTW08 NLO PDF's} \\
\text{\bullet $\sigma(pp \to W^+X) \times \text{BR}(W^+ \to e^+\nu_e) = 144.1 \pm 21.2(\text{stat})^{+3.4}_{-10.3}(\text{syst}) \pm 21.5(\text{norm}) \text{ pb}$} \\
\text{\bullet $\sigma(pp \to W^-X) \times \text{BR}(W^- \to e^-\bar{\nu}_e) = 31.7 \pm 12.1(\text{stat})^{+10.1}_{-8.2}(\text{syst}) \pm 4.8(\text{norm}) \text{ pb}$} \\
\text{\bullet Theory curves from FEWZ; K. Melnikov and F. Petriello, Phys. Rev. D 70, 114017 (2006).}
\end{align*}
Measuring Sea Quark Polarizations with the Muon Arms: $W^\pm \rightarrow \mu^\pm$

- South Muon Arm $-2.2 < \eta < -1.2$; North Muon Arm $1.2 < \eta < 2.4$, $\Delta\phi = 2\pi$
- Signal is isolated high $p_T$ muon, detected with MuTr, MuID, RPC
- Trigger on small sagitta in magnetic field + muon ID + timing cut from BBC,RPC
- Reduced collision rate of several MHz to trigger rate of few kHz dedicated to muon arms
- Absorber between vertex and MuTr, and interspersed in MuID, reduces low energy and decay background
Measuring Sea Quark Polarizations with the Muon Arms: Preliminary Results

- Preliminary results from 2011 data set

- $\sqrt{s} = 500$ GeV, Pol.$\approx 50\%$, $\int \mathcal{L}dt \approx 25$ pb$^{-1}$

- First results in this channel

- Anticipated for many years

$\Rightarrow$ Cover different $x$ than central arms
Further Improvements: Data from 2012 and 2013

<table>
<thead>
<tr>
<th>Year</th>
<th>√s (GeV)</th>
<th>$\int \mathcal{L} dt$ (pb$^{-1}$)</th>
<th>Pol. (%)</th>
<th>$P^2L$ (pb$^{-1}$)</th>
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<tbody>
<tr>
<td>2009</td>
<td>500</td>
<td>8.6</td>
<td>39</td>
<td>1.3</td>
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<tr>
<td>2011</td>
<td>500</td>
<td>16</td>
<td>48</td>
<td>3.7</td>
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<tr>
<td>2012</td>
<td>510</td>
<td>≈ 30</td>
<td>52</td>
<td>8.1</td>
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<tr>
<td>2013 (TBD)</td>
<td>510</td>
<td>≈ 200</td>
<td>55</td>
<td>60</td>
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</tbody>
</table>

- $\int \mathcal{L} dt$ recorded luminosity within vertex cut $|z| < 30$ cm (more for $\mu$ analysis)
- Analysis of 2011 data sets being finalized
- Data from 2012 being analyzed: substantial compared to 2009 and 2011
- For $\mu$ analysis 2012 includes improved trigger, VTX/FVTX detectors to reduce background
- For $e$ analysis, commissioning of VTX detector might improve isolation cut
- Very large data set anticipated in 2013
Anticipated $W^\pm$ results in central and muon arms should discriminate between some models.
Projections for Central Arms: 250 pb$^{-1}$ and P=55%

• Anticipated $W^{\pm}$ results in central and muon arms should discriminate between some models
• RHIC spin program to measure polarized sea quark distributions well underway
• Published results for central arms available:
• Substantial data sets under analysis (2011 at $\sqrt{s} = 500$ GeV, 2012 at $\sqrt{s} = 510$)
• More than 200 $pb^{-1}$ anticipated in 2013 - combined results should discriminate between some models
• Data should allow a measurement of $\Delta \bar{d}(x) / \Delta \bar{u}(x)$ between $0.08 \lesssim x \lesssim 0.4$