Transverse Spin Results from PHENIX

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For the PHENIX collaboration
Outline

• Introduction

• PHENIX measured $A_N$
  • mid/forward rapidity $\pi^0$, $\eta$
  • open heavy flavor
  • $J/\psi$

• First PHENIX $p+A$ Transverse Spin results
  • Forward neutron $A_N$ in $p+p$, $p+Au$ and $p+Al$
Transverse Single Spin Asymmetry $A_N$

Transverse Single Spin Asymmetries $A_N$

$$A_N = \frac{\sigma_L^\uparrow - \sigma_R^\uparrow}{\sigma_L^\uparrow + \sigma_R^\uparrow}$$

Theory Expectation:
Small asymmetries at high energies
(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

$A_N \sim O(10^{-4})$

theory

Experiments:
ZGS, AGS, FERMILAB to RHIC

$A_N \sim O(10^{-1})$ observed

$\sqrt{s} = 5 \sim 500$ GeV

Argonne ZGS, $p_{beam} = 12$ GeV/c

W.H. Dragoset et al., PRL36, 929 (1976)
### Mechanisms for $A_N$

<table>
<thead>
<tr>
<th>Transverse Momentum Dependent function approach</th>
<th>Initial State</th>
<th>Final State</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sivers mechanism</strong></td>
<td>$A_N \propto f_T^q(x, k_{\perp}^2) \cdot D^h_q(z)$</td>
<td>$A_N \propto \delta q(x) \cdot H_1(x, k_{\perp}^2)$</td>
</tr>
<tr>
<td>D. Sivers, PR D41 (1990) 83; D43 (1991) 261</td>
<td>Siver’s Effect (PDF)</td>
<td>Transversity (PDF)</td>
</tr>
<tr>
<td><strong>Collins mechanism</strong></td>
<td>John Collins, Nucl Phys B396 (1993) 161</td>
<td></td>
</tr>
</tbody>
</table>

**Collinear Factorization**

- $k_{\perp}$ is integrated
- $\Rightarrow$ represents integrated spin dependence of the parton’s transverse motion

**Twist-3 distribution**

- works at $Q \gg \Lambda_{QCD}$
- Twist-3 quark-gluon correlation function $T_{q,F}$ and two independent tri-gluon correlation functions $T_{G}^{(t)}$, $T_{G}^{(d)}$ are related through

$$T_{q,F}^q(x, x) = - \int d^2 p_\perp \frac{p_\perp^2}{M} f^q_{1T}(x, p_\perp^2) |_{SIDIS}$$

**Twist-3 fragmentation**

- Twist-3 fragmentation function $\hat{H}$ is related to the $k_{\perp}$-moment of the TMD Collins function $H_1^{\perp h/q1}$ as

$$\hat{H}^{h/q}(z) = z^2 \int d^2 \vec{k}_{\perp} \frac{k_{\perp}^2}{2M_h^2} H_1^{\perp h/q}(z, z^2 \vec{k}_{\perp}^2)$$
# PHENIX Transverse Spin Runs

<table>
<thead>
<tr>
<th>Year</th>
<th>√s (GeV)</th>
<th>Recorded Luminosity for longitudinally / transverse polarized p+p STAR</th>
<th>Recorded Luminosity for longitudinally / transverse polarized p+p PHENIX</th>
<th>&lt;p&gt; in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>62.4 200</td>
<td>-- pb(^{-1}) / 0.2 pb(^{-1})</td>
<td>0.08 pb(^{-1}) / 0.02 pb(^{-1})</td>
<td>48</td>
</tr>
<tr>
<td>2008</td>
<td>200</td>
<td>6.8 pb(^{-1}) / 8.5 pb(^{-1})</td>
<td>7.5 pb(^{-1}) / 2.7 pb(^{-1})</td>
<td>57</td>
</tr>
<tr>
<td>2009</td>
<td>200</td>
<td>-- pb(^{-1}) / 7.8 pb(^{-1})</td>
<td>-- pb(^{-1}) / 5.2 pb(^{-1})</td>
<td>45</td>
</tr>
<tr>
<td>2009</td>
<td>500</td>
<td>25 pb(^{-1}) / -- pb(^{-1})</td>
<td>16 pb(^{-1}) / -- pb(^{-1})</td>
<td>55</td>
</tr>
<tr>
<td>2011</td>
<td>500</td>
<td>10 pb(^{-1}) / -- pb(^{-1})</td>
<td>14 pb(^{-1}) / -- pb(^{-1})</td>
<td>39</td>
</tr>
<tr>
<td>2012</td>
<td>200</td>
<td>12 pb(^{-1}) / 25 pb(^{-1})</td>
<td>18 pb(^{-1}) / -- pb(^{-1})</td>
<td>48</td>
</tr>
<tr>
<td>2012</td>
<td>510</td>
<td>-- pb(^{-1}) / 22 pb(^{-1})</td>
<td>-- pb(^{-1}) / 9.7 pb(^{-1})</td>
<td>61/56</td>
</tr>
<tr>
<td>2013</td>
<td>510</td>
<td>82 pb(^{-1}) / -- pb(^{-1})</td>
<td>32 pb(^{-1}) / -- pb(^{-1})</td>
<td>50/53</td>
</tr>
<tr>
<td>2013</td>
<td>510</td>
<td>300 pb(^{-1}) / -- pb(^{-1})</td>
<td>155 pb(^{-1}) / -- pb(^{-1})</td>
<td>51/52</td>
</tr>
<tr>
<td>2015</td>
<td>200</td>
<td>52 pb(^{-1}) / 52 pb(^{-1})</td>
<td>-- pb(^{-1}) / 60 pb(^{-1})</td>
<td>53/57</td>
</tr>
</tbody>
</table>

- **2015 200 p Au** total delivered Luminosity = 1.27 pb\(^{-1}\)  
- **2015 200 p Al** total delivered Luminosity = 3.97 pb\(^{-1}\)

O : Transversely polarized
PHENIX Detectors

• Philosophy
  • high resolution & high-rate
  • trigger for rare events

• Central Arms
  • $|\eta| < 0.35$, $\Delta \phi \sim \pi$
  • Momentum, EM Energy, PID
  • $\pi^0$ and $\eta$

• Muon Arms
  • $1.2 < |\eta| < 2.4$
  • Momentum
  • High $p_T$ muons

• Muon piston calorimeter
  • $3.1 < |\eta| < 3.9$
  • EM Energy
  • $\pi^0$ and $\eta$
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Mid-rapidity $\pi^0$ and $\eta$ $A_N$

The $\pi^0$ and $\eta$ production is sensitive to $qg$ and $gg$ process

Consistent with zero for both $\pi^0$ and $\eta$

A. Adare et al. (PHENIX Collaboration)
PRD 90, 012006 (2014)
Forward-rapidity $\pi^0$ and $\eta$ $A_N$

$A_N$ is independent of collision energy

Similar for $\pi^0$ and $\eta$

No obvious $p_T$ dependence
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Heavy Flavor $A_N$

- Heavy Flavor (especially $D$ meson) production is an ideal tool to investigate gluon distribution.

- $A_N$ in heavy flavor production is sensitive to the tri-gluon correlations by using the twist-3 collinear factorization framework
  - Y. Koike, S. Yoshida PRD84:014026 (2011)

Heavy flavor production is dominated by gluon-gluon fusion at RHIC energies.
Open Heavy Flavor $A_N$

Sources of muon-like tracks

(1) Open Heavy Flavor ($D, B \rightarrow \mu$ signal)

(2) Stopped hadron ($\pi, K$ background)

(3) Decay muon ($\pi, K \rightarrow \mu$ background)

(4) Punch through ($\pi, K$ background)
Open Heavy Flavor $A_N$

Relative contributions of signal and backgrounds

- **Signal**: 1) Open Heavy Flavor ($D, B \rightarrow \mu$ signal)
- **Distinguished Background**: 2) Stopped Hadron ($\pi, K$ background)
- **Non-distinguished background**: 3) Decay Muon ($\pi, K \rightarrow \mu$ background), 4) Punch Through ($\pi, K$ background)
Open Heavy Flavor $A_N$

signal-to-background ratio
Run12 $p+p$ 200 GeV

$A_N^{Phys} = \frac{A_N^{incl} - r \cdot A_N^{BG}}{1 - r}$

$A_N^{incl}$: Inclusive MUID gap4 tracks
$A_N^{BG}$: Background (gap2,3 stopped hadron)

$r = N^{BG}/N^{incl}
= (N^{incl} - N^{signal})/N^{incl}$

$r$: non-distinguished background fraction in gap4 inclusive tracks

Each $A_N$ is calculated by Maximum Likelihood Method
Open Heavy Flavor $A_N$

- Both charges are studied for Run12 $p+p$ 200 GeV, result will be released soon
- Run15 $p+A$ 200 GeV analysis is ongoing

$A_N(D) \neq A_N(\bar{D})$

Calculations for D mesons

Gluon Sivers=Max

Gluon Sivers=0

Y. Koike, S. Yoshida
PRD84:014026 (2011)
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\( J/\psi \, A_N \)

- \( J/\psi \, A_N \) is sensitive to the production mechanisms
  - Assuming a non-zero gluon Sivers function, in pp scattering, \( J/\psi \, A_N \) vanishes if the pair are produced in a color-octet model but survives in the color-singlet model

One color-singlet diagram — no cancellation, asymmetry generated by the initial state interaction, \( A_N \neq 0 \)

Two color-octet diagrams — cancellation between initial and final state interactions, no asymmetry \( A_N = 0 \)
In Muon Arm ($J/\psi \rightarrow \mu^+\mu^-$)

- $A_N^{Incl}$: oppositely-charged muon pairs in the invariant mass range $\pm 2\sigma$ around $J/\psi$ mass.
- $A_N^{BG}$: oppositely-charged muon pairs in the invariant mass range $2.0 < m < 2.5$ along with charged pairs of the same sign in invariant mass range $2.0 < m < 3.6$ in p+p analysis.

$$A_N^{J/\psi} = \frac{A_N^{Incl} - r \cdot A_N^{BG}}{1 - r}$$

In Central Arm ($J/\psi \rightarrow e^+e^-$)

- $A_N^{BG}$: remaining continuum background is small, does not make a significant contribution.
The result is consistent with 0, statistical uncertainty is dominant.

We expect improved result from ongoing Run15 $p+p$ analysis ($>5x$ statistics) as well as $J/\psi A_N$ result in Run15 $p^\uparrow+A$.
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Forward neutron $A_N$

Neutron Detectors at Zero Degree Behind the DX Magnets

Beam Direction

Charge veto counter

Charge veto counter

18 m
Forward Neutron $A_N$

PRD 88, 032006 (2013) PHENIX

- Large asymmetry not expected before the measurements
- Large forward neutron $A_N$ discovered @ RHIC IP12 experiment (2002)
- Large forward neutron $A_N$ measured @ PHENIX with dedicated neutron detectors (2006)
- pQCD is not applicable for $p_T<0.22\,\text{GeV}$ at 200 GeV
- $\pi-a_1$ interference in Reggeon framework explains asymmetry result for $p+p$ data well.

PRD 84, 114012 (2011) Kopeliovich et al.
Origin of Nonzero $A_N$

$$A_N \equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \frac{\Sigma_X |< nX|T| \uparrow>|^2 - \Sigma_X |< nX|T| \downarrow>|^2}{\Sigma_X |< nX|T| \uparrow>|^2 + \Sigma_X |< nX|T| \downarrow>|^2}$$

Using

$$|\uparrow> = \frac{1}{\sqrt{2}} (|+> + i|->) \quad \text{&} \quad |\downarrow> = \frac{1}{\sqrt{2}} (|+> - i|->)$$

$$\Sigma_X |< nX|T| \uparrow>|^2 - \Sigma_X |< nX|T| \downarrow>|^2 = -2\text{Im}\Sigma_X < nX|T|->< +|T^+|nX >$$

$A_N \neq 0$ if
Nonzero term for interference between spin-flip and nonflip interaction with different phase
First Polarized $p + A$ at RHIC

Run15 (2015)

100 GeV

Polarized Proton

100 GeV/nucleon

Au, Al
$A$-dependent $A_N$ (inclusive)

\[ p^+ + A \rightarrow n + X \]

$\sqrt{s} = 200$ GeV

$x_F > 0.5$

$0.3 < \theta < 2.2$ mrad

22% scale uncertainty not shown

<table>
<thead>
<tr>
<th></th>
<th># of proton</th>
<th># of neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Al</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>Au</td>
<td>79</td>
<td>118</td>
</tr>
</tbody>
</table>

Present Framework ($\pi$-$a_1$ interference)

No $A$-dependence?

Stronger gluonic field?
$A$-dependent $A_N$ (inclusive)

- **Surprise** — huge dependence on $A$
- Even sign changes
- Simple $\pi - a_1$ interference predicts small dependence
- Mechanism? Why?

Analysis by Minjung Kim (SNU/RIKEN)
In $pAu$ case

$$Z^2 \cdot \alpha_{EM} \sim \frac{79^2}{137} \sim 45$$

$\alpha_{EM}$
• $\pi^+$ via UPC process is substantially boosted towards the proton beam direction

• Most of $\pi^+$ from $\Delta$ decay go through BBC hole and will be swept away by the dipole magnet (DX).


• UPC (SOPHIA) Monte Carlo includes high N* states though $\Delta$ dominates
BBC Tagging

\[ A_N \sim \text{had} \times \text{had} + \text{had} \times \text{EM} + \text{EM} \times \text{had} + \text{EM} \times \text{EM} \]

- Large \( A_N \) vanished in \( p+Au \)
- No sign flip in \( A_N \)
- \( A_N \) for \( p+p \) and \( p+Al \) are comparable
**BBC Vetoing**

- Even larger $A_N \sim 0.28$ in $p+Au$
- Sign flip occurs between $p+p$ and $p+Al$
- $A_N$ for $p+p$ gets even smaller $\sim 0.02$

---

$A_N \sim \text{had} \times \text{had} + \text{had} \times \text{EM} + \text{EM} \times \text{had} + \text{EM} \times \text{EM}$
BBC Tagging, Vetoing

\[ A_N \sim \text{had} \times \text{had} + \text{had} \times \text{EM} + \text{EM} \times \text{had} + \text{EM} \times \text{EM} \]

**BBC Vetoing**

\[ p^+ + A \rightarrow n + X \]

- ZDC inclusive
- ZDC & BBC p-dir & BBC A-dir
- ZDC & veto BBC p-dir & veto BBC A-dir

**BBC Tagging**

\[ p^+ \rightarrow \gamma^* \rightarrow n^+ \]

- A
- A

\[ A_N > 0 \]

... but why?

\[ A_N < 0 \]
PHENIX observed

- mid/forward rapidity $\pi^0, \eta$ showed similar $A_N$ for $\pi^0$ and $\eta$, no collision energy dependence
- $J/\psi A_N$ is sensitive to production mechanism, expect improved statistics in Run15 data as well as first $p+A$ result
- Open heavy flavor measurement, both charges are studied for Run12 $p+p$ 200 GeV, result will be released soon. $p+A$ analysis is ongoing

Forward Neutron - First $p+A$ result in PHENIX

- strong $A$-dependence large forward neutron $A_N$ observed in forward neutron measurement
- $A_N$ changes sign from $p+p$ to $p+Au$, $A_N$ magnitude increases by factor of $\sim 3$ from $p+p$ to $p+Au$
- $A_N$ behaved quite differently by enhancing/suppressing UPC like events (BBC correlation)
- The $A_N$ result is unexpected from current theory. Theoretical development is ongoing
Thank you!