Recent spin results from PHENIX

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for the PHENIX Collaboration

UCLA
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June 8, 2022
Outline

1. Experimental setup

2. Longitudinal double spin asymmetry $A_{LL}$
   - Direct photon
   - Jet
   - Charged pion

3. Transverse single spin asymmetry $A_N$
   - Direct photon
   - $\pi^0$ and $\eta$
   - Charged pion
   - Open heavy flavor
   - Forward neutron

4. Summary
PHENIX detector

- $|\eta| < 0.35$ and $\pi$ coverage for $\phi$.
- EMCal: primary detector for photons.
- EMCal trigger: select high energy particles.
- DC: measure charged particles.
- PC3: track matching.
- RICH: PID from Čerenkov light.
Probing the gluon spin inside the proton

- The proton spin can be decomposed as

\[
\frac{1}{2} = \frac{1}{2} \sum_q \Delta q + \Delta g + L_q + L_g
\]

- Gluon spin \(\Delta g\) is important for the proton spin puzzle.

\[A_{LL}^{pp \to \gamma X} \sim \frac{\Delta q(x_q)}{q(x_q)} \cdot \frac{\Delta g(x_g)}{g(x_g)} \cdot a_{LL}^{qg \to \gamma q}\]

\[A_{LL} = \frac{\Delta \sigma}{\sigma} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}\]

- Little fragmentation contributions to direct photon production.

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Jet and charged pion production

- Larger statistics: not suppressed by small QED coupling.
- RHIC 200 GeV data probe $0.05 < x < 0.2$.
- RHIC 510 GeV data probe $0.02 < x < 0.08$.

Figure 2: Relative contributions of different partonic subprocesses contributing to inclusive $\pi^\pm$ (left panel) and jet production (right panel) as a function of $x_T$. Only minor differences can be seen when going from $\sqrt{s} = 200$ GeV to 500 GeV. At low $x_T$, gluon-gluon scattering dominates, followed by quark-gluon scattering at higher $x_T$. At very high $x_T$, quark-quark scattering eventually becomes the dominant production channel.

Table 2-1: Current nuclear physics performance milestones related to the RHIC $p+p$ physics program. In the following sections we will describe how these questions have been and will be addressed by the RHIC spin physics program in the next years.

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestone</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>HP8</td>
<td>Measure flavor-identified and contributions to the spin of the proton via the longitudinal-spin asymmetries of W production.</td>
</tr>
<tr>
<td>2013</td>
<td>HP12</td>
<td>Utilize polarized proton collisions at center of mass energies of 200 and 500 GeV, in combination with global QCD analyses, to determine if gluons have appreciable polarization over any range of momentum fraction between 1 and 30% of the momentum of a polarized proton.</td>
</tr>
<tr>
<td>2015</td>
<td>HP13</td>
<td>Test unique QCD predictions for relations between single-transverse spin phenomena in $p-p$ scattering and those observed in deep–inelastic lepton scattering.</td>
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</table>

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From $A_{LL}$ to $\Delta g$

- Existing RHIC data mainly probe $0.05 < x_g < 0.2$.
- PHENIX $\pi^0 A_{LL}$ at 510 GeV confirms a nonzero $\Delta g$ and extend $x_g$ to 0.01.
- STAR jet data clearly imply a polarization of gluons in this range.
- Results from $\gamma$, jet and $\pi^\pm$ will add additional independent constraints on the $\Delta g$.

\[
\int dx \, \Delta g(x) \\
0.001 \quad 0.05 \\
\int dx \, \Delta g(x) \\
1 \\
0.05
\]

\[
Q^2 = 10 \text{ GeV}^2
\]

PRL 113, 012001 (2014)

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Identifying direct photon through isolation

\[ r_{\text{cone}} = \sqrt{(\delta \eta)^2 + (\delta \phi)^2} = 0.5 \]

Isolation cut requirement:
\[ \sum E_{\text{in cone}} < 0.1 E_\gamma \]

Quark-gluon Compton scattering: Easy to pass isolation cut

Fragmentation: Hard to pass isolation cut

Bremsstrahlung: Hard to pass isolation cut
Direct photon cross section

- Consistent with NLO pQCD.
- MPI and parton shower are important for inclusive direct photon production.
- Constrain unpolarized gluon PDF.
Direct photon $A_{LL}$

- Consistent with NLO DSSV14.
- Will be the first published direct photon $A_{LL}$.
- Constrain polarized gluon PDF $\Delta g$.

![Graph showing $A_{LL}$ as a function of $p_T$ with data points and error bars plotted against a theoretical curve.](arXiv:2202.08158)
Jet cross section

- Calculation from NLO + ln(R) resummation overestimates data.
- The calculation is at partonic level: MPI and parton shower are important.
- Similar observation from CMS, for small \( R \) anti-\( k_T \).
Jet $A_{LL}$

- Consistent with DSSV14 at NLO + ln(R) resummation.
- Independent constraint on polarized gluon PDF $\Delta g$.
- Uncertainty are correlated due to unfolding.
Charged pion $A_{LL}$

PRD 102, 032001 (2020)
Consistent with DSSV14.

510 GeV data probe low $x$ range.
Not enough statistics to decide $\pi^\pm$ order.
Transverse Single Spin Asymmetry (TSSA)

\[ A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \]
Origin of TSSA: TMD

When $Q \gg k_T \gtrsim \Lambda_{QCD}$:

Quark correlation matrix $\Phi^\alpha{}_{\beta}(x, k_T) \sim$

$$\langle P, S | \bar{q}_\beta(\xi_-, \xi_T) W^- (\xi_-, \infty) W^T (\xi_T, \infty) \times W^T (\infty, 0) W^- (-\infty, 0) q^\alpha (0_-, 0_T) | P, S \rangle$$

$Tr[\Gamma \gamma^+ \Phi(x, k_T)] \rightarrow$ TMD functions

[Progress in Particle and Nuclear Physics 65, 267]

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Nucleon Spin  
Quark Spin

$\Gamma : 1 \quad \gamma^5 \quad \gamma' \gamma^5$
Origin of TSSA: Collinear twist-3

\[ \Phi^{(3)}(x_1, x_2, S_T) \sim q g q : \langle P, S_T | \bar{q}(x_2 P) \gamma^+ \epsilon_{ij} G^i_{T} q(x_1 P) | P, S_T \rangle \]

\[ g g g : C_{abc} G^+_a \epsilon_{ij} G^i_{T} g^j_{S_T} G^c_{T} , \quad C_{abc} = if_{abc} \text{ or } d_{abc} \]

\[ \Delta \sigma_{CO}(S_T) \approx \Phi^{(3)}(x_1, x_2, S_T) \otimes \Phi^{(2)}(x') \otimes \hat{\sigma} \otimes D^{(2)}(z) \rightarrow \text{Sivers type} \]

\[ \Delta \sigma_{CO}(S_T) = \Delta \sigma_{TMD}(S_T) \text{ at leading } k_T/Q. \]

\[ \Phi^{(3)}(x, x, S_T) \sim \int d^2k_T(k_T^2/M_P)f^{1\perp}_T(x, k_T), \]

\[ \Delta \sigma_{CO}(S_T) = \Delta \sigma_{TMD}(S_T) \text{ at leading } k_T/Q. \]
Direct photon $A_N$

- First direct photon $A_N$.
- Measured $A_N$ consistent with zero.
- Small contribution from qgq correlation.
- Clean extraction of ggg correlation.
- ggg models have different gluon PDFs.
- Constrain gluon spin-momentum correlations.

![Graph showing $A_N$ vs. $p_T$](image-url)

PHENIX

$|\eta| < 0.35$, $s = 200$ GeV, $|\eta| < 0.35$
\[ \pi^0 \text{ and } \eta \, A_N \]

**PHENIX** $p^+ \! + \! p, \sqrt{s} = 200 \text{ GeV, } |\eta| < 0.35$

- $p^+ + p \rightarrow \pi^0 + X$
- $p^+ + p \rightarrow \eta + X$

**PHENIX** $p^+ + p \rightarrow \pi^0 + X, \sqrt{s} = 200 \text{ GeV, } |\eta| < 0.35$

- Small qgq and constrain ggg.
- Sivers TMD PDF: GPM and CGI-GPM.
- CPI-GPM include initial- and final-interactions to reproduce Sivers sign change.
- Scenario 1 (2) maximize (minimize) open heavy flavor TSSA.

- PRD 103, 052009 (2021)
- Improved stat. uncertainty.
- Consistent with previous measurement and with zero.
- $A^\pi_N$ vs $A^\eta_N$: strangeness, isospin and mass.
Charged pion $A_N$

- Low statistics due to few $\pi^\pm$ fire triggers.
- $\chi^2 \approx 9$ (ndf = 5) between $\pi^\pm$.
- Indicate differences between $\pi^\pm$.

![Graph showing $A_N$ vs. $p_T$]
Open heavy flavor $e^{\pm}$ $A_N$ in p+p

- Signal: OHF decay $e^{\pm}$.
- Backgrounds:
  - $e^{\pm}$ from $\pi^0$, $\eta$, $\gamma^{\text{dir}}$, $J/\psi$, $K^0_S$, $K^{\pm}$.
  - Misidentified $e^{\pm}$ (primary $\pi^{\pm}$).
- Mainly from gg hard interactions.
  → Sensitive to ggg correlators $T_G^{(f,d)}$.

$$A_N(p^+p \rightarrow \text{HF}(e^{+/−}) + X)$$

$\sqrt{s} = 200$ GeV

$|\eta| < 0.35$

**PHENIX**

Theory: PRD78, 114013

$A_N^{D^0/D^0} \rightarrow e^{ε^+}(\lambda_f, \lambda_d)$

$$T_G^{(f,d)}(x, x) = \lambda_{f,d} G(x)$$

**arXiv:2204.12899**

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Forward neutron $A_N$ in $p+p$

- Mainly from $\pi$-R interference in hadronic interactions.
- Negative $A_N$ with linear $p_T$ dependence.

\[
\sum \pi \rightarrow p\rightarrow Rp
\]

$\pi$-R interference

PRD 84, 114012 (2011)
Forward neutron $A_N$ in p+A

- UPC: Positive $A_N$ with $Z^2$ dependence.
- $A_N^{UPC+HAD} = \frac{\sigma_{UPC}A_N^{UPC} + \sigma_{HAD}A_N^{HAD}}{\sigma_{UPC} + \sigma_{HAD}}$
- PRC 95, 044908 (2017)

- ZDC⊗BBC-tag($N \cap S$): Select hadronic interactions.
- ZDC⊗BBC-veto($\bar{N} \cap \bar{S}$): Select UPC interactions.
- Strong A dependence in inclusive and BBC-veto.
- PRL 120, 022001 (2018)
Forward neutron $A_N$ vs $p_T$ and $x_F$
Gluon spin is important for proton spin decomposition and the proton spin puzzle.
Direct photon production have little fragmentation contributions.
Jet and $\pi^\pm$ production have larger statistics.
Contribute to future global analyses together with forward cluster and forward/central $\eta$ $A_{LL}$.
TSSA measurements from $\gamma$, $\pi^0$, $\eta$, $\pi^\pm$, OHF $e^\pm$ are important to understand the qgq and ggg correlations in collinear twist-3 formalism as well as the TMD functions.
Forward neutron $A_N$ in p+A results from both hadronic and EM interactions.
Backup
## Processes

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Dom. partonic process</th>
<th>probes</th>
<th>LO Feynman diagram</th>
</tr>
</thead>
</table>
| $\overline{p}p \rightarrow \pi + X$ | $\overline{g} \overline{g} \rightarrow gg$  
  $\overline{q} \overline{g} \rightarrow qg$ | $\Delta g$ | ![Feynman Diagram](image1.png) |
| $\overline{p}p \rightarrow \text{jet(s)} + X$ | $\overline{g} \overline{g} \rightarrow gg$  
  $\overline{q} \overline{g} \rightarrow qg$ | $\Delta g$ | ![Feynman Diagram](image2.png) (as above) |
| $\overline{p}p \rightarrow \gamma + X$  
  $\overline{p}p \rightarrow \gamma + \text{jet} + X$  
  $\overline{p}p \rightarrow \gamma \gamma + X$ | $\overline{q} \overline{g} \rightarrow \gamma q$  
  $\overline{q} \overline{g} \rightarrow \gamma q$  
  $\overline{q} \overline{q} \rightarrow \gamma \gamma$ | $\Delta g$  
  $\Delta g$  
  $\Delta q, \Delta \overline{q}$ | ![Feynman Diagram](image3.png)  
  ![Feynman Diagram](image4.png)  
  ![Feynman Diagram](image5.png) |
| $\overline{p}p \rightarrow DX, BX$ | $\overline{g} \overline{g} \rightarrow c\overline{c}, b\overline{b}$ | $\Delta g$ | ![Feynman Diagram](image6.png) |