Direct photon cross section and double-helicity asymmetry measurement at PHENIX

Sanghwa Park (Jefferson Lab) for the PHENIX collaboration
• How do gluons contribute to the proton spin?
• What is the landscape of the polarized sea in the nucleon?
• What do transverse spin phenomena teach us about proton structure?
Proton spin decomposition

• (Quark + antiquark) spin contribution

$$\frac{1}{2} \int dx (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s})$$

~30%. Well constrained by polarized DIS

• Gluon spin contribution

$$\Delta G = \int dx \Delta g(x)$$

Start to understand better with RHIC p+p data

• Quark and gluon orbital angular momentum

Very little known, need to know 3D structure
Exploring gluon polarization at RHIC

- Access gluons at LO
- gg and qg dominant at RHIC kinematics

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Dom. partonic process</th>
<th>probes</th>
<th>LO Feynman diagram</th>
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</thead>
<tbody>
<tr>
<td>$\bar{p}p \to \pi + X$</td>
<td>$\bar{g}g \to gg$</td>
<td>$\Delta g$</td>
<td>![Feynman diagram for $\bar{g}g \to gg$]</td>
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Exploring gluon polarization at RHIC

- Double-helicity asymmetry:

\[ A_{LL} = \frac{\sum \Delta f_a \otimes \Delta f_b \otimes d\sigma_{f_a f_b \rightarrow f_c X} \otimes D_{f_c}^{\pi^0}}{\sum \sigma_{++} + \sigma_{+-}} \]

- Experimentally:

\[ A_{LL} = \frac{1}{P_B P_Y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}} \]

- Fragmentation functions from e+e- scattering

- Polarized PDFs

- Unpolarized PDFs

- Parton-level hard scattering cross section calculable in pQCD

Longitudinally polarized protons
Exploring gluon polarization at RHIC

- Two workhorse measurements: $\pi^0$ and jets
- First experimental evidence of non-zero gluon contribution to the proton spin at $x > 0.05$:

$$\int_{0.05}^{1} dx \Delta g(x) = 0.2^{+0.06}_{-0.07} \left( Q^2 = 10 \text{GeV}^2 \right)$$

(included 2009 200 GeV data only)

- Confirmed non-zero gluon polarization at 510 GeV
- Mixed gg and qg contributions: Recent analysis by JAM collaboration showed that existing data cannot rule out negative $\Delta g$ scenario

[JAM, Phys. Rev. D 105, 074022 (2022)]
Direct photon measurements in $\vec{p} + \vec{p}$

- Theoretically clean interpretation: only sensitive to initial partonic hard process and doesn’t involve strong interaction

- Direct photons are produced dominantly by quark-gluon Compton scattering at RHIC
  - linearly sensitive to gluon helicity distribution

- Proposed as a golden channel to study the gluon spin (RHIC Spin Proposal, 1992)

- Also:
  - Unpolarized cross section: test NLO pQCD applicability, constraint unpolarized gluon distribution

[PHENIX, Phys. Rev. Lett. 127, 162001 (2021)]
PHENIX Detector

- Central arms: $\Delta \phi = (\pi/2) \times 2$, $|\eta| < 0.35$
  - electrons, photons, $\pi^0$, $\eta$, charged hadrons

- Electromagnetic calorimeter (EMCal): fine granularity PbSc and PbGl detectors

- Drift chamber (DC): charged particle tracking

- Beam-beam counter (BBC): luminosity monitor, minimum bias trigger
Analysis overview

- Photons detected by EMCal
- Effectively reduced BGs by $\pi^0$ decay tagging

Isolation cut: reduced the BG contributions from patron fragmentation and hadron decays

\[ p_T: 6.0-6.5 \text{ GeV} \]

Yield of direct photon:

\[ N_{dir} = N_{total} - (1 + A)(1 + R)N_{\pi^0} \]

- R: $\pi^0$ one photon missing ratio.
- A: Other hadrons’ to $\pi^0$’s photon ratio.

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

\[ E_{cone} < E_\gamma \cdot 10\% \]
Cross section results

- NLO pQCD calculation underestimates the inclusive cross section data at low pT
- Multiparton interaction and parton shower are important to consider for better describing the data
- With isolation criteria, the calculation consistent with the data.
Cross section results

Phys. Rev. Lett. 130, 251901 (2023)

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Direct photon $A_{LL}$

- First published measurement of direct photon $A_{LL}$
- Compared with two scenarios for gluon spin
- Data consistent with the positive gluon spin contributions and disfavor the negative $\Delta g$ scenario
Summary

• PHENIX has measured the first direct photon cross section and double-helicity asymmetry at 510 GeV
• Direct photon result provides an important input to improve our understanding of the polarized gluon distribution
  • Theoretically clean interpretation
  • Directly sensitive to the sign of the gluon spin
  • Data consistent with the positive gluon spin contribution