PHENIX Cold QCD Highlights

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Polarized DIS discovered the proton spin crisis: quarks only carry small fraction of spin

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g
\]

Gluons poorly constrained by DIS (indirect access via scaling violation)

\(p+p\) provides direct access to gluons
RHIC Spin Program

- What is the gluon contribution to the proton spin?
- What do transverse spin phenomena teach us about proton structure?

arXiv: 1501.01220
PHENIX Experiment

- Central Arms ($|\eta| < 0.35$)
  - Tracking: DC and PC
  - EM Calorimeter

- Forward Arms
  - Muon arms ($1.2 < |\eta| < 2.4$)
  - Zero Degree Calorimeter (ZDC)
Access to Gluons

At RHIC kinematics, the qq and qg LO processes dominate.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Dom. partonic process</th>
<th>probes</th>
<th>LO Feynman diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\bar{p} \rightarrow \pi + X$</td>
<td>$\bar{g}g \rightarrow gg$</td>
<td>$\Delta g$</td>
<td></td>
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<tr>
<td></td>
<td>$\bar{q}\bar{q} \rightarrow gg$</td>
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<tr>
<td>$p\bar{p} \rightarrow \text{jet(s)} + X$</td>
<td>$\bar{g}g \rightarrow gg$</td>
<td>$\Delta g$</td>
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<tr>
<td></td>
<td>$\bar{q}\bar{q} \rightarrow gg$</td>
<td>(as above)</td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \gamma + X$</td>
<td>$\bar{q}g \rightarrow \gamma q$</td>
<td>$\Delta g$</td>
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<td>$p\bar{p} \rightarrow \gamma + \text{jet} + X$</td>
<td>$\bar{q}g \rightarrow \gamma q$</td>
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<td>$p\bar{p} \rightarrow \gamma\gamma + X$</td>
<td>$\bar{q}\bar{q} \rightarrow \gamma\gamma$</td>
<td>$\Delta q, \Delta\bar{q}$</td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow D X, B X$</td>
<td>$\bar{g}g \rightarrow c\bar{c}, b\bar{b}$</td>
<td>$\Delta g$</td>
<td></td>
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</tbody>
</table>
Gluon Spin

- Gluon helicity distribution function $\Delta g(x)$ is measured to find $\Delta G$, the gluon spin contribution.

$$\Delta G \equiv \int_0^1 \Delta g(x) \, dx$$

- The $\Delta g(x)$ is found via the longitudinal double spin asymmetry, $A_{LL}$

$$A_{LL} \equiv \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

Polarized PDFs

Parton-level hard scattering cross section calculable in pQCD

Unpolarized PDFs

Fragmentation functions from e+e- scattering
Gluon Spin

\[ \int_{0.05}^{1} dx \Delta g(x) = 0.2^{+0.06}_{-0.07} (Q^2 = 10 \text{GeV}^2) \]
Gluon Spin III

- 510 GeV data confirmed non-zero gluon spin
- Extended x down to $\sim 10^{-2}$
Charged Pion $A_{LL}$ at 510 GeV

- First PHENIX measurement at 510 GeV
- Consistent with DSSV global fits within statistical uncertainty

Charged pions potential indicator for sign of $\Delta g$ via 
pton $A_{LL}$ ordering

Phys. Rev. D 102, 032001 (2020)
Direct Photon $A_{LL}$ at 510 GeV

- First PHENIX direct photon cross section and $A_{LL}$ at 510 GeV
- “Golden” channel to access gluon polarization since hard interaction is mostly q-g

![Graph showing isolated direct photon $A_{LL}$ at 510 GeV, $|\eta| < 0.25$ with data and theory curves, along with a graph depicting the isolation cut condition and a comparison between NLO pQCD (by JETPHOX) and CT14 PDF & BFGII predictions.]
Jet $A_{LL}$ at 510 GeV

- Jets present a challenge in PHENIX due to limited acceptance
- Jes reconstructed with anti-$k_T$ $R(\Delta \eta, \Delta \phi) = 0.3$
- Unfolded to correct for underlying event and detector effects
  - Use Pythia simulations to generate response matrix which correlates true and reconstructed jets
Jet $A_{LL}$ at 510 GeV II

- First jet $A_{LL}$ at PHENIX
- Cross section below NLO prediction
  - Similar to LHC finding for small $R$
Transverse Spin

- Prediction of small asymmetry (PRL 41 1689 (1978))
- Found surprisingly large TSSA observed (FNAL E704)
- Asymmetry survive at higher energy at various collision energies

Transverse single spin asymmetry (TSSA)

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

- Transverse momentum dependent (TMD) distributions and fragmentations
  - Sivers effect (initial state): correlation between nucleon spin and parton momentum
  - Collins effect (final state): correlation between fragmenting parton and hadron transverse momentum
- Multi-parton correlation in collinear framework
  - Initial state or in fragmentation process
  - SSA appears as twist-3 observable
η and π⁰ A_N at 200 GeV

- Sensitive to both initial and final state effects
- Mid-rapidity sensitive to gluon spin-momentum correlations
- New data significantly improves precision
- Asymmetries consistent with zero
Direct Photon $A_N$ at 200 GeV

- Sensitive to initial state effects
- Production dominated by $q+g \rightarrow q+\gamma$
- First measurement at PHENIX
  - Help constrain theory models
Neutron $A_N$ at 200 GeV

- Forward measurement using ZDC
- Unfolded using different functional forms
- Improve understanding of forward neutron SSA
Summary

- PHENIX spin program continues to elucidate our understanding of QCD

- Results:
  - Longitudinal spin analyses:
    - Jet, direct photon, charged pion $A_{LL}$
  - Transverse spin analyses:
    - Direct photon, $\pi^0$ and $\eta$, and neutron $A_N$

- Still more to come in the future!
Future Spin Program

- sPHENIX cold QCD program: arXiv: 1602.03922
  - Improved acceptance and detectors
  - Precision measurement of jets, DY, and more!

- Electron Ion Collider (EIC)
- Polarized eN, eA collider
  - Many complementary processes
- Wide kinematic range ($x, Q^2$)