Recent Highlights from the STAR Cold-QCD Physics Program

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Introduction

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The RHIC Cold QCD Plan for 2017 to 2023: A Portal to the EIC

Polarized protons

Integrated polarized proton luminosity [pb⁻²]

Time [weeks in physics]

2012 P = 52%
2013 P = 53%
2015 P = 55%
2009 P = 34%
2012 P = 59%
2006 P = 55%
2011 P = 48%
2009 P = 56%
2005 P = 47%
2003 P = 34%
Longitudinally polarized beam: Gluon polarization
**Gluon helicity**

**Proton spin (Jaffe-Manohar sum rule)**

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

**Gluon helicity distribution:** \( \Delta g(x, Q^2) \)

\[ \Delta G = \int_0^1 \Delta g(x, Q^2) dx \]

**Measurements**

\[ A_{LL} = \frac{\frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}}{\frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} \hat{a}_{LL}}{\Sigma f_a \otimes f_b \otimes \hat{\sigma}}} \]

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**How to access \( \Delta G \) at RHIC?**

- Midrapidity jet production at RHIC is dominated by \( qg \) and \( gg \) scatterings at low \( x_T \)
- The \( qg \) and \( gg \) scattering cross sections are sensitive to the helicities of the gluon
Evidence of positive $\Delta G$

- Evidence of positive gluon polarization at 0.05 < x < 0.2
- These data are included in NNPDF and DSSV fits: help constrain gluon polarization at intermediate x

\[
\int_{0.05}^{0.2} \Delta g(x, Q^2) \, dx = 0.17 \pm 0.6
\]

at $Q^2=10$ GeV$^2$
Impact of di-jet data

- STAR 2009 pp 200 GeV di-jet data included in global fit:
  - Central value of $\Delta g$ is slightly revised and uncertainty is reduced by including STAR di-jet data
• Largest 200 GeV longitudinally polarized pp dataset; improved both statistical and systematic uncertainties
• This result can reduce the uncertainty of gluon polarization for $x_T > 0.05$ if included in global fits
Di-jet $A_{LL}$ at 200 GeV

Newly published results!

STAR, PRD 103 (2021) L091103

Two different $\eta$ topology bins

STAR, PRD 95 (2017) 071103

Di-jets: Much narrower ranges of initial state partonic momentum fraction tested; different topologies enhance sensitivity of the data to selected $x$;
Inclusive jets and di-jets $A_{LL}$ at 510 GeV

Measurement of jet and di-jet $A_{LL}$ at 510 GeV with 2012 data:

- Higher $\sqrt{s}$ pushes sensitivity to lower $x$ (down to 0.02)
- Consistent results from both energies
- Constrain the shape of $\Delta g$

$$|\cos \theta^*| = \tanh (|\eta_1 - \eta_2|)/2$$

We have concluded the collection of longitudinally polarized data (Run 2013 $A_{LL}$ publication in preparation)
Transversely polarized Beam: Proton 3D Structure
Transverse structure of the proton

- Transverse momentum dependent PDFs (TMDs, \( f(x, k_T) \)) → 3D structure of the proton
- Access to two types of TMDs
  - Initial state effect from PDFs → **Sivers function**
  - Final state effect from fragmentation → **Collins function**
- Measurement: Transverse single spin asymmetry (TSSA)

\[
A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}
\]
$A_N$ for Z and W boson

- Sivers effect: the correlation between the transverse momentum of a parton ($k_T$) and the transverse spin ($S_p$) of the proton
- TSSA of weak bosons sensitive to Sivers sign-change and TMD evolution effects
- Improved uncertainties using STAR 2017 data

Diagram: Correlation between proton spin and transverse motion of parton

Graph: $A_N$ vs $y^{Z^0}$

- STAR p+p 500 GeV
- $0.5 < P_T^{Z^0} < 10$ GeV/c
- STAR Preliminary

Data points:
- STAR run 11 (L = 25 pb$^{-1}$)
- STAR prel. run 17 (L = 340 pb$^{-1}$)
- arXiv:2103.03270

beam pol. uncertainty not shown

3.4% (run 11)
1.4% (run 17)
$A_N$ for Z and W boson

- Sivers effect: the correlation between the transverse momentum of a parton ($k_T$) and the transverse spin ($S_p$) of the proton
- TSSA of weak bosons sensitive to Sivers sign-change and TMD evolution effects
- Improved uncertainties using STAR 2017 data
A dependence of $\pi^0 A_N$

TSSA for forward ($2.7 < \eta < 3.8$) $\pi^0$ in pp, pAl and pAu collisions using 2015 data

- Ratios of average $A_N$ values as a function of $\log A$ in each $x_F$ bin are measured
- Suppression of $A_N$ in pA to $A_N$ in pp collisions is observed
Collins asymmetry indicates the azimuthal asymmetry of a hadron originating from the fragmentation of a transversely polarized quark.

\[ \langle S_q \cdot (p \times k_{T,\pi}) \rangle \neq 0 \]

Collins asymmetry is sensitive to transversity and TMD fragmentation.

\[ A_{UT}^{\sin(\phi)} \sin(\phi) = \frac{\sigma^\uparrow(\phi) - \sigma^\downarrow(\phi)}{\sigma^\uparrow(\phi) + \sigma^\downarrow(\phi)} \]

\[ \phi = \phi^s - \phi^H \]

Collins asymmetry indicates the azimuthal asymmetry of a hadron originating from the fragmentation of a transversely polarized quark.
Collins asymmetry for $\pi^\pm$ in jets

- Collins asymmetries of $\pi^\pm$ are measured
- Consistent results from 2012 and 2015 data; improved uncertainties using 2015 data
Collins asymmetry for $\pi^\pm$ in jets

- Collins asymmetries of $\pi^\pm$ are measured
- Combined results will help constrain theoretical calculations
Collins asymmetry for $\pi^0$ in jets

**Newly published results!**

Forward $\pi^0$: $2.7 < \eta < 4.0$

$$Z_{em} = \frac{E_{\pi^0}}{E_{jet}}$$, EM-jet reconstructed only by photons and electrons

$j_T$ is $E_{\pi^0}$ projection perpendicular to jet axis

Cancellation of the Collins effect of the u/d quark; weak $j_T$ dependence is observed
Summary

STAR longitudinal program is completed (Run 2013 $A_{LL}$ publication in preparation)

- Di-jet $A_{LL}$: test the sensitivity of $\Delta g$ in selected $x$ region
- Higher $\sqrt{s}$ and more forward rapidity: access to smaller $x$ region

Measurements of TSSA using transversely polarized data probe the transverse spin structure of the proton

- $A_N$ for $W$ and $Z$ boson → precise measurement to investigate Sivers effect
- Collins asymmetry for $\pi^\pm$ and $\pi^0$ → transversity of the proton and TMD fragmentation

New released results: $A_N$ of $W$ and $Z$

Results below, not covered by this talk, will be presented by T. Lin:

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<th>Dataset</th>
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<td>Di-jet Sivers effect</td>
<td>Intrinsic $k_T$ of parton</td>
<td>Transversely polarized pp</td>
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<td>Non-linear gluon dynamics in nuclei</td>
<td>Forward di-hadron correlation</td>
<td>Unpolarized pp and pA</td>
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<td>Sea quark distributions</td>
<td>$W^+ / W^-$ cross-section ratio</td>
<td>Unpolarized pp</td>
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(see T. Lin’s talk in the next session)