Recent Progress of Gluon Helicity Measurements at RHIC

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Outline

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Introduction: Spin of the Proton

• Simple picture of proton composed of three valence quarks superseded by complex interaction of quarks, antiquarks, and gluons

• The proton’s spin must arise from combination of intrinsic and orbital angular momenta of these components

\[
\Delta \Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta \bar{u} + \Delta \bar{d} + \Delta \bar{s}) dx
\]

\[
\Delta G = \int \Delta g(x) dx
\]

Helicity Distributions: $\Delta q, \Delta g$
What we learn from DIS and pol-DIS

Polarized DIS data gives $\Delta \Sigma \approx 30\%$

 Scaling violations of structure functions in polarized DIS gives information on gluon polarization but limited kinematic coverage leaves $\Delta G$ poorly constrained

 A primary goal of RHIC Spin program is to map $\Delta g(x)$

$S = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L$
Exploring Gluon Polarization at RHIC

For most RHIC kinematics, gg and qg dominate, making $A_{LL}$ for jets and hadrons sensitive to gluon polarization.

At the parton level, helicity correlations are very large in leading-order QCD.
2009 RHIC Result

- 2009 STAR 200 GeV inclusive jet results and PHENIX $\pi^0$ have much better statistical precision than previous results
- STAR inclusive jet results divided into two pseudorapidity ranges which emphasize different partonic kinematics
- Results sit consistently above the 2008 DSSV curve which was consistent with zero gluon polarization
DSSV Result

\[ \int_0^{1.0} \Delta g(x) \, dx \]

- Integral of \( \Delta g(x) \) in range \( 0.05 < x < 1.0 \) increases from roughly 0.05 to \( 0.20^{+0.06}_{-0.07} \). First indication of non-zero gluon polarization!

- Uncertainty shrinks substantially from DSSV* to new DSSV fit

- The low x behavior and shape of \( \Delta g(x) \) are still poorly constrained.
• Original NNPDF $\Delta g(x,Q^2)$ extraction (DIS data only) in green and new extraction including RHIC data in red

• Integral of $\Delta g(x,Q^2)$ for $x > 0.05$ is $0.23 \pm 0.06$ and is in agreement with new DSSV result of $0.20^{+0.06}_{-0.07}$ over the same $x$ range

Beyond Inclusive Jet: Dijet Measurements

- Correlation measurements such as di-jets capture more information from the hard scattering and provide a more direct link to the initial kinematics than inclusive probes.

- Leading order expressions show how different jet configurations are sensitive to different kinematic values.

- Di-jets may place better constraints on the functional form of $\Delta g(x,Q^2)$.

\[
x_1 = \frac{1}{\sqrt{s}} \left( p_{T_3} e^{n_3} + p_{T_4} e^{n_4} \right)
\]

\[
x_2 = \frac{1}{\sqrt{s}} \left( p_{T_3} e^{-n_3} + p_{T_4} e^{-n_4} \right)
\]

\[M = \sqrt{x_1 x_2 s}\]

\[
\eta_3 + \eta_4 = \ln \frac{x_1}{x_2}
\]

\[
|\cos \theta^*| = \tanh \left| \frac{\eta_3 - \eta_4}{2} \right|
\]
Inclusive jets integrate over a large range of gluon momentum fraction in a given $p_T$ bin.

Advantage of the di-jet final state comes from the better achievable resolution in gluon momentum fraction.

Can also see that same sign topology selects more asymmetric collisions.

Different di-jet mass bins select different gluon momentum fractions.
Mid-Rapidity Di-jet $A_{\text{LL}}$

Emanuele R. Nocera, SPIN2016, arxiv: 1702.05077

Pushing to Lower X: Higher Energy

\[ x_1 = \frac{1}{\sqrt{s}} \left( p_{T3} e^{\eta_3} + p_{T4} e^{\eta_4} \right) \]
\[ x_2 = \frac{1}{\sqrt{s}} \left( p_{T3} e^{-\eta_3} + p_{T4} e^{-\eta_4} \right) \]
\[ M = \sqrt{x_1 x_2 s} \]
\[ \eta_3 + \eta_4 = \ln \frac{x_1}{x_2} \]
\[ |\cos \theta^*| = \tanh \left| \frac{\eta_3 - \eta_4}{2} \right| \]

- RHIC has placed strong constraints on \( \Delta G \) in the range \( x > 0.05 \) but lower \( x \) regions are relatively unexplored.

- There are two knobs to turn which can provide access to lower \( x \): higher energies and forward rapidities.

- Can see that moving to higher center of mass energies will push down to lower \( x \) values.
Inclusive Jets and $\pi^0$s at 510 GeV

- Publication in preparation for STAR run 12 inclusive jet analysis
- The Run 2013 (510 GeV) analysis is also close to finalize.

- PHENIX analyzed $\pi^0$s from Runs 12 and 13
- The combined values from Run 12 and 13 show good agreement with DSSV global fit.
Comparison with 200 GeV

- Both jets and π⁰s show good agreement between the two energies

- See that 510 GeV results push to lower xₜ (lower x)

- 510 GeV results (STAR Run 13, PHENIX Runs 12 & 13) compared with 200 GeV results (STAR Run 9, PHENIX Runs 6 – 9)

- Results plotted vs xₜ = 2pₜ/√s so they are on the same scale; these results show good agreement in x overlap region.
Charged $\pi$ probe at PHENIX

- $A_{LL}$ of charged/neutral pions have different sub-process mixture, thus provide complementary insight into the gluon polarization measurement.
Dijet at 510 GeV from STAR

- Preliminary dijet double spin asymmetry results for 2009, 2012 and 2013 are in agreement in the overlap region
- Publication in preparation for STAR run 12 dijet result

- Di-jet $A_{LL}$ plotted vs $M_{\text{inv}}/\sqrt{s}$ ($\sim \sqrt{x_1 x_2}$ at L.O.) for data taken at $\sqrt{s} = 200$ and 510 GeV
- 510 GeV data extend to lower momentum fractions where $\Delta G$ not as well constrained while 200 GeV data give better precision at mid to high $x$. 
Pushing to Lower X: Higher Rapidity

The second way to push to lower $x$ is to look at jets which go to forward rapidities.

More forward particles are indicative of more asymmetric collisions which will contain lower $x$ partons.

$$x_1 = \frac{1}{\sqrt{s}}(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4})$$

$$x_2 = \frac{1}{\sqrt{s}}(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4})$$

$$M = \sqrt{x_1 x_2 s}$$

$$\eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$

$$|\cos \theta^*| = \tanh \left| \frac{\eta_3 - \eta_4}{2} \right|$$
Forward Inclusive Probes: PHENIX

Recently published J/Ψ A_{LL} measurements in the muon spectrometers (1.2 < |η| < 2.2) offer a new way to access ΔG via heavy-quark production in p+p collisions, and will access gluons down to x values of ~ 0.002.
Intermediate Pseudorapidity $\pi^0$: STAR

- $\pi^0$s in the Endcap are sensitive to the polarized gluon PDF in the range $0.01 < x < 0.05$
- Current results based on low statistics Run 6 data – analysis on higher statistics and larger collision energies at 510 GeV is ongoing.
Intermediate Pseudorapidity Di-jet: STAR

- Adding the Endcap opens up several new di-jet topologies
- Forward jets probe lower values of gluon momentum fraction while selecting more asymmetric collisions
- The large imbalance in momentum fractions, coupled with the unpolarized PDF's, suggests that $x_2$ are dominated by gluons, while $x_1$ are most often valence quarks

Intermediate Pseudorapidity Di-jet: STAR


- Di-jet $A_{LL}$ shown for two Barrel-Endcap topologies
- New results are compared to current DSSV14 and NNPDFpol1.1 expectations
- The dijet data will more tightly constrain predictions for gluon spin at lower momentum fraction
Forward Inclusive Probes: STAR

- Forward Meson Spectrometer (FMS) provides EM calorimetry out to a pseudorapidity of ~4
- $A_{LL}$ of $\pi^0$s in FMS at $\sqrt{s} = 510$ GeV provide access to the lowest $x$ gluons at STAR (~0.001)

arXiv: 1805.09745, submitted to PRD
Forward Inclusive Probes: STAR

- Results are given for transverse momenta in the range $2 < p_T < 10$ GeV/c within two regions of pseudorapidity that span $2.65 < \eta < 3.9$

- These results are sensitive to the polarized gluon parton distribution function, $\Delta g(x)$, down to the region of parton momentum fraction $x \sim 0.001$

- These results will provide the first direct experimental constraints in $x \ll 0.01$
Future Gluon Helicity Measurements

- STAR took a large (52 pb-1) 200 GeV dataset in 2015, jets analyses are ongoing now.

- The STAR experiment is planning to upgrade the forward rapidity region (2.5 < η < 4.5). The forward Di-jets@2.5 < η < 4.0 will provide precession measurement for gluon polarization at x < 10^{-3}.
Conclusion

• 2009 RHIC data have placed the strongest constraints on the gluon helicity and, for the first time, provide evidence for a positive gluon polarization for $x > 0.05$

• Some new results released recently aim to better constrain the shape and low $x$ behavior of the gluon helicity distribution

• Many important analyses currently in progress, with the increased statistics from 2012, 2013 and 2015, new RHIC data will help to further constrain the value and shape of $\Delta g(x)$. 