How to Unravel the Nucleon Helicity Structure at an EIC

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Piecing Together the Proton Spin

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

- Simple picture of proton composed of three valence quarks superseded by complex interaction of quarks, antiquarks, and gluons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
- This talk will deal only with the intrinsic contributions, \( \Delta G \) and \( \Delta \Sigma \)

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

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

Helicity Distributions: \( \Delta q \), \( \Delta g \)
Intrinsic Gluon Contribution: $\Delta G$

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

- Current fits to polarized DIS data give $\Delta \Sigma = 0.366^{+0.042}_{-0.062}$ for $10^{-3} < x < 1$
- Scaling violations of structure functions in polarized DIS gives information on gluon polarization but limited kinematic coverage leaves $\Delta G$ poorly constrained
- Want leading order access to gluons – polarized pp collisions at RHIC

Kinematic reach of polarized DIS measurements
RHIC: First Polarized pp Collider
Accessing $\Delta G$ at RHIC: $A_{LL}$

In polarized pp collisions, access $\Delta G$ via the longitudinal double helicity asymmetry $A_{LL}$ which is sensitive to the polarized gluon distribution at leading order.

- STAR and PHENIX measure $A_{LL}$ using inclusive jet and $\pi^0$ final states, respectively.

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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.

- Uncertainty on integral over low x region is still sizable (only $\sqrt{s} = 200$ GeV RHIC data).

Di-jet $A_{LL}$

- Coincidence measurements capture more information about hard scatter and better constrain initial kinematics.
Where to from Here?

- Inclusive jet and $\pi^0$ data from RHIC have placed meaningful constraints on $\Delta G$ for $0.05 < x < 0.2$

- Future results at $\sqrt{s} = 500$ GeV and forward rapidity will extend constraints to somewhat lower $x$ and di-jet measurements will provide better constraints on the shape of $\Delta G$

- Despite this, RHIC data will not be able to completely constrain the full integral of $\Delta G$

- What is needed to pin down the gluon contribution to the proton spin?
EIC: Polarized ep Collider

- **Hera**
  - DIS: Kinematic precision
  - Colliders: Large kinematic coverage

- **RHIC**
  - Compass & HERMES

- **EIC!**
  - Polarization: Spin observables
EIC: Accessing $\Delta G$ Via $g_1$

Several observables are sensitive to $\Delta G$ in DIS but golden measurement at an EIC would be scaling violation of $g_1(x,Q^2)$

$$\frac{dg_1(x, Q^2)}{d\ln(Q^2)} \approx -\Delta g(x, Q^2)$$

Current DIS constraints on $\Delta G$ hampered by limited $x$ & $Q^2$ coverage

EIC would greatly expand kinematic reach and precision of $g_1(x,Q^2)$ measurements!
$\Delta \Sigma = \int \left( \Delta u + \Delta d + \Delta s + \Delta \bar{u} + \Delta \bar{d} + \Delta \bar{s} + \cdots \right) dx$

- $g_1$ is sensitive to the sum of all quark and anti-quark polarized PDFs meaning an EIC will place strong constraints on $\Delta \Sigma$

- An EIC will also be able to constrain the individual quark and anti-quark polarized PDFs via semi-inclusive DIS (SIDIS) measurements

- The polarized anti-quark distributions are of particular interest as they provide information on non-perturbative aspects of proton structure

- The above plots show the expected reduction in uncertainty for the polarized anti-quark distributions from EIC SIDIS data

- Individual quark and anti-quark distributions can also be measured at an EIC via charged current DIS which access different combinations of PDFs
1/2 - Gluon - Quarks = orbital angular momentum

• Above plot shows the running integral of \( \Delta g(x,Q^2) \) from \( x_{\text{min}} \) to 1 as a function of \( x_{\text{min}} \)

• Large reduction in uncertainty on \( \Delta G \) from EIC can be seen

• EIC will also reduce the uncertainty on the quark contribution to the proton spin

• No assumptions about hyperon beta decay in EIC uncertainty

Constraints on gluon and quark contributions will provide information on the orbital angular momentum component of proton spin
Gluons can be also be probed in DIS via the higher-order photon gluon fusion process.
$X_\gamma$: Reconstructed Vs True

- Will use virtual photon momentum fraction to discriminate between resolved and direct processes
- See good agreement between reconstructed and true $X_\gamma$ for all $Q^2$ ranges
- Di-jets found in Breit frame and required one jet with $p_T \geq 5$ GeV and the other with $p_T \geq 4$ GeV

$$X_\gamma = \frac{1}{2E e y} \left( p_{T1} e^{-\eta_1} + p_{T2} e^{-\eta_2} \right)$$
Direct Vs Resolved Processes

- Plot reconstructed $X_{\gamma}$ for direct and resolved processes
- Direct processes should concentrate toward 1 while resolved processes are at lower values
- Direct processes dominate at higher $Q^2$ while resolved are more prevalent at low $Q^2$
- Cut of $X_{\gamma} > 0.7$ enhances the direct fraction at all $Q^2$
See that the cut on $X_\gamma > 0.7$ significantly reduces the resolved contribution while maintaining the direct events.

Separation between resolved and direct is most prominent at high $Q^2$ and low di-jet invariant mass.
Proton Partonic Kinematics

\[ X_P = x_B \left( 1 + \frac{M^2}{Q^2} \right) \]

\[ Q^2 = s y x_B \]

\[ X_P = x_B + \frac{M^2}{s y} \]

\[ \approx \frac{100}{(20000 \times 0.95)} \approx 0.005 \]

- To measure \( \Delta G \), need to probe the parton coming from the proton
- Momentum fraction of the parton from proton is well reconstructed
**X_p For Different Q^2**

- For Different Q^2:
  - Q^2 = 10-100
    - \[ \int L = 0.002 \, fb^{-1} \]
  - Q^2 = 1-10
    - \[ \int L = 0.01 \, fb^{-1} \]
  - Q^2 = 0.01-0.1
    - \[ \int L = 0.25 \, fb^{-1} \]

- Experimentally possible to extend these measurements to Q^2 < 1

- At lower Q^2, contribution from resolved process increases while QCD Compton contribution decreases.

- For a given di-jet mass range, same X_p can be probed over large range of Q^2.

- Can test evolution of \( \Delta G \).

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Summary

- Early fixed target data showed that the proton’s spin cannot be carried by quark helicity alone but could not constrain the gluon contribution.

- Jet and Pion asymmetries from polarized pp collisions at RHIC have placed strong constraints on $\Delta G$ for $Bjorken-x > 0.05$, but will not have the kinematic reach to fully determine the gluon contribution to the proton spin.

- A high energy/luminosity polarized ep collider will have the kinematic reach and precision to pin down the gluon polarization via scaling violations of the $g_1$ structure function.

- An EIC will also constrain both the total quark helicity contribution $\Delta \Sigma$ and the individual polarized quark and anti-quark PDFs.

- NLO access to $\Delta G$ will be possible via the photon-gluon fusion process and will provide a systematic check on the $g_1$ results while allowing the study of the evolution of $\Delta G$ over a wide $Q^2$ range.
Backup
RHIC: First Polarized pp Collider

Time Projection Chamber (TPC)  Charged Particle Tracking $|\eta|<1.3$

Barrel Electromagnetic Calorimeter (BEMC): $|\eta|<1$
EIC: eRHIC or JLEIC
Accessing $\Delta G$ at RHIC: $A_{LL}$

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \rightarrow f_c X} \cdot \hat{a}_{LL}^{f_a f_b \rightarrow f_c X} \otimes D^h_{f_c}}{\sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \rightarrow f_c X} \otimes D^h_{f_c}}$$

Partonic fractions in jet production at 200 GeV

For most RHIC kinematics, $g g$ and $q g$ dominate, making $A_{LL}$ for jets and hadrons sensitive to gluon polarization.
2009 results have factor of 3 to 4 better statistical precision than 2006 results

Result divided into two pseudorapidity ranges which emphasize different partonic kinematics

Result lies consistently above the 2008 DSSV fit and is consistent with the LSS10p fit
New NNPDF Results

- 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 $0.05 < x < 0.2$ increases from $0.05 \pm 0.15$ to $0.17 \pm 0.06$
- 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: Di-jet Measurements

• Coincidence measurements capture more information about the partonic 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

\[
x_1 = \frac{1}{\sqrt{s}} \left( p_{T3} e^{\eta_3} + p_{T4} e^{\eta_4} \right)
\]

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

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

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

\[
|\cos \theta^*| = \tanh \left| \frac{\eta_3 - \eta_4}{2} \right|
\]
Importance of Systematic Control

- The excellent statistical precision achievable with an EIC means control of systematics will be critical.

- Above plot shows how the constraint on $\Delta G$ is affected by systematic uncertainty.
EIC: Probing the Sea

- DIS largely 1-photon exchange, but can also proceed via charged current (CC) interaction mediated by W boson
- CC interactions in polarized DIS give access to quark / antiquark helicity distributions as well as unique structure functions
- Because W is virtual, can access lower values of $Q^2$ to overlap with and provide cross check to SIDIS measurements

arXiv:1409.1633
• See that the cut on $X_\gamma$ significantly reduces the resolved contribution while maintaining the direct events

• Separation between resolved and direct is most prominent at high $Q^2$ and low di-jet invariant mass
As shown on the previous slide, accessible $X_P$ range is determined largely by beam energy.

Different di-jet mass ranges select different process fractions with lower masses containing less resolved contribution.

Selection of high mass events also cut out low $X_P$ contribution.