The Gluon Contribution to the Nucleon Spin

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• Introduction

• $\Delta G$ from scaling violations of $g_1(x,Q^2)$

• The Bjorken Sum Rule

• $\Delta G$ from charm production
Where is the nucleon spin?

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

\[ \frac{1}{2} \int_0^1 dx \left[ \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} \right] \]

\[ \int_0^1 dx \Delta g(x) \]

\[ \sim 0.25 \]
World Data on $F_2^p$ Structure Function

Next-to-Leading-Order (NLO) perturbative QCD (DGLAP) fits
World Data on $F_2^p$

4 orders of magnitude in $x$ and $Q^2$

World Data on $g_1^p$

< 2 orders of magnitude, precision much worse!
The gluon spin distribution $\Delta g$

Not much information until recently:

$$\frac{d g_1}{d \log(Q^2)} \propto \frac{\alpha_s}{2\pi} P_{qq} \otimes \Delta g(x, Q^2) + \text{quark contrib.}$$

Bag model Chen, Ji $\Delta G \approx 0.3$

$\Delta G \approx 1.8 \text{ (@ 1 GeV}^2)$

"axial anomaly" Altarelli et al.

$\Delta G \approx 0.4$

$\Delta G \approx -1.7$
World Data on $F_{2}^{p}$

An EIC makes it possible!

Region of existing $g_{1}^{p}$ data
$\Delta G$ from scaling violations of $g_1$
• Bjorken's sum rule

\[
\int_0^1 \, dx \, g_1^{ep-en}(x, Q^2) = \frac{1}{6} \frac{g_A}{g_V} \left\{ 1 - \frac{\alpha_s(Q^2)}{\pi} - \frac{43}{12} \frac{\alpha_s^2(Q^2)}{\pi^2} - 20.215 \frac{\alpha_s^3(Q^2)}{\pi^3} \right\}
\]

high-order perturbation theory

\[
+ \frac{M^2}{Q^2} \int_0^1 \, x^2 \, dx \left\{ \frac{2}{9} g_1^{ep-en}(x, Q^2) + \frac{1}{6} g_2^{ep-en}(x, Q^2) \right\}
\]

target-mass corrections

\[
- \frac{1}{Q^2} \frac{4}{27} \mathcal{F}^{u-d}(Q^2) \quad \text{Twist-4 matrix elements} \sim \langle \bar{q} \Gamma q \rangle
\]

• Precision QCD. Currently tested at \(\sim 10\%\).
Can it be tested at \(\sim 1\) or \(2\%\)?
Bjorken Sum Rule: \[ _1^p - _1^n = \frac{1}{6} g_A [1 + \alpha_s(Q^2)] \]

- Sub-1% statistical precision at ELIC (averaged over all \(Q^2\))
- 7% (?) in unmeasured region, in future constrained by data and lattice QCD
- 3-4% precision at various values of \(Q^2\)

Holy Grail: excellent determination of \(\alpha_s(Q^2)\)

Needs: \(O(1\%)\) Ion Polarimetry!!!
Polarized gluon distribution via charm production

very clean process!

LO QCD: asymmetry in D production directly proportional to $\Delta \frac{G}{G}$
Polarized gluon distribution via charm production

problems: luminosity, charm cross section, background!
starting assumptions for EIC:

- vertex separation of 100µm
- full angular coverage (3<Θ<177 degrees)
- perfect particle identification for pions and kaons (over full momentum range)
- detection of low momenta particles (p>0.5 GeV)
- measurement of scattered electron (even at very small scattering angles)
- 100% efficiency

very demanding detector requirements!
Polarized gluon distribution via charm production

Background suppression:
Separation of primary and secondary vertex absolutely essential!
Pion/kaon separation very helpful!

invariant mass of $K\pi$ system
Polarized gluon distribution via charm production

Momenta of decay kaon and pion:
$1.5 < p < 10 \ (15) \ \text{GeV}$

Angles of decay kaon and pion:
$160^0 < \Theta < 177^0$
Polarized gluon distribution via charm production

Precise determination of $\Delta G/G$ for $0.003 < x_g < 0.4$

at common $Q^2$ of 10 GeV$^2$ however...
Polarized gluon distribution via charm production

Precise determination of $\Delta G/G$ for $0.003 < x_g < 0.4$

at common $Q^2$ of 10 GeV$^2$

**If:**
- We can measure the scattered electron even at angles close to $0^\circ$ (determination of photon kinematics)
- We can separate the primary and secondary vertex down to about 100 $\mu$m
- We understand the fragmentation of charm quarks (✔)
- We can control the contributions of resolved photons
- We can calculate higher order QCD corrections (✔)
• Need to measure the scattered electron at angles close to $0^0$ ➔ how?
• Need to separate the primary and secondary vertex down to about 100 $\mu$m ➔ how to determine the primary vertex?
• For charm decay products need to instrument only $\pm$ 15-20$^0$ around proton direction
• Simple set of silicon disks might be sufficient for vertex detection
• Momenta of decay products between 1.5 and 10(15) GeV
charm production: influence of fragmentation

\[ x_g^{\text{rec}} = x(s_{\text{hat}}/Q^2+1) \]
\[ s_{\text{hat}} = 4 \ M_{\text{inv}}^2 \]

correction presently by simple parametrisation of \( x_g - x_g^{\text{rec}} \) vs \( x_g \)
Future: Polarized gluon distribution from RHIC

\[ p + p \rightarrow \gamma + \text{jet} + X \text{ with STAR + EEMC at } \sqrt{s} = 200 \text{ GeV (320 pb}^{-1}) + \sqrt{s} = 500 \text{ GeV (800 pb}^{-1}) \]

\[ x_G \times \Delta G(x) \]

- **GS-A**: \( x^2 = 1.24 \), \( \eta = 1.63 \pm 0.62 \), \( a = 0.58 \pm 0.31 \), \( \rho = -2.89 \pm 0.57 \)
- **GS-B**: \( x^2 = 2.32 \), \( \eta = 0.21 \pm 0.07 \), \( a = 1.52 \pm 0.76 \), \( \rho = -5.11 \pm 0.06 \)
Future: Polarized gluon distribution from RHIC

N. Saito
Future: Polarized gluon distribution from RHIC
Future: $x \Delta g(x,Q^2)$ from RHIC and EIC

EIC

$0.003 < x < 0.5$

uncertainty in $x\Delta g$ typically $< 0.01$
Polarized gluon distribution vs $Q^2$

\[ \int_{x_{\text{min}}}^{1} dx \frac{\Delta g(x, Q^2)}{\Delta G(Q^2)} \]

- black GS–A
- red GS–C
- dashed lines $Q^2 = 200$ GeV$^2$
- full lines $Q^2 = 9$ GeV$^2$
- dotted lines $Q^2 = 1$ GeV$^2$

$Q^2 = 10$ GeV$^2$

GRSV NLO std. gluon
Next Steps

- determine sensitivity of $g_1$ to different “realistic” models for $\Delta G$ (including different functional forms !)

- generate pseudo EIC data and include in full QCD fit procedure (including estimates of systematic uncertainties !)

- determine precision of Bjorken Sum measurement as function of $Q^2$ (including extrapolations)

- study fragmentation in charm production

- include other charm decay channels (including D* tagging)

- get first estimates of systematic uncertainties

- specify more clearly detector requirements for different processes
Summary

EIC is the ideal machine to finally determine the contribution of the gluons to the nucleon spin!

• measurements of $g_1$ will allow
  ➢ a determination of $\Delta G/G$ from its scaling violation
  ➢ a statistically very precise determination of the Bjorken Sum
    (systematics due to uncertainty in proton beam polarization ???)

• measurements of charm cross section asymmetries will provide a precise determination of $\Delta G/G$ for $0.003 < x < 0.5$ at a fixed value of $Q^2$ of $\sim 10 \text{ GeV}^2$

……… provided we can
  • measure the scattered electron at extremely small angles
  • separate the primary and secondary vertex with sufficient precision
  • control the contribution of resolved photons
• more work needed to define the necessary detector requirements!