Measuring the gluon Sivers function at a future Electron-Ion Collider

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Outline

• Nucleon structure and gluon Sivers effect
• Model calculations
• Experimental considerations
• Summary
Exploring nucleon structure

• Nucleon is a dynamical system of quarks and gluons
  – How are the partons distributed in space and momentum inside the nucleon?
  – How are these quark and gluon distributions correlated with the overall nucleon properties, such as spin direction?
  – What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin.

• EIC: the ultimate machine to understand the nature of the nucleon partonic structure.
TMDs and Sivers function

- Transverse Momentum Dependent (TMD) parton distributions provide useful tools to image the nucleon 3D structure in momentum space.

- Sivers function describes the correlation of $k_T$ and $S_T$.

\[ \hat{f}_{a/p}(x, k_{\perp}) = f_{a/p}(x, k_{\perp}) - f_{1T}^{aL}(x, k_{\perp}) \frac{g \cdot (\hat{P} \times \vec{k}_{\perp})}{M_p} \]

Leading Twist TMDs

- Similar for gluons
Current knowledge to quark Sivers

\[ \frac{d\sigma}{dx
dy
d\phi_S
dz
d\phi_T
d\nu_T} \propto F_{UU,T} + |S| \sin(\phi_H - \phi_S) F_{UT,T}^{S_H - \phi_S} + \ldots \]


- Accessed with SIDIS measurements.
- Sizable Sivers effect.
- u, d quark Sivers with opposite sign.
- Subject to large uncertainty.

\[ \Delta N f_{a/P}(x, k_{\perp}) = -\frac{2k_{\perp}}{M_p} f_{1T}(x, k_{\perp}) \]

PRL 103, 152002 (2009) HERMES data
PLB 717, 383 (2012) COMPASS data
Current constraints on gluon Sivers

Extraction based on $A_N$ data at RHIC

- Effective gluon Sivers from $A_N$ may differ from the actual gluon Sivers in TMD.
- Limited $x$ and $Q^2$ range explored in SIDIS. Still allow for gluon Sivers contributions of $1/N_c$.
- No hard constraints at this moment.

Extraction on COMPASS data

$A_{PGF}^{\sin(\phi_{2h} - \phi_S)} = -0.14 \pm 0.15\text{(stat.)}$

$\langle x_G \rangle = 0.126$

- Effective gluon Sivers from $A_N$ may differ from the actual gluon Sivers in TMD.
- Limited $x$ and $Q^2$ range explored in SIDIS. Still allow for gluon Sivers contributions of $1/N_c$. 
Studying Sivers in the EIC era

- Disentangle Sivers and Collins asymmetries.
- Extend the current Sivers data to smaller $x$.
- Large $Q^2$, $x$, coverage to pin down TMD evolution.

Quark Sivers before and after EIC
Accessing gluon Sivers at an EIC

\[
\frac{d\sigma_{\text{tot}}^{\gamma^*+p^\uparrow \rightarrow h_1 + h_2 + X}}{dz_{h_1}dz_{h_2}d^2p_{h_1\perp}d^2p_{h_2\perp}} = C \int_{z_{h_1}}^{1-z_{h_2}} dq \: \frac{z_q(1-z_q)}{z_{h_2}^2 z_{h_1}^2} d^2p_{1\perp} d^2p_{2\perp} \hat{f}_{g/p}(x_g, k_{\perp}) \times H_{\text{tot}}^{\gamma^* g \rightarrow q\bar{q}}(z_q, k_{1\perp}, k_{2\perp}) e_q^2 D_{h_1/q}(\frac{z_{h_1}}{z_q}, p_{1\perp}) D_{h_2/\bar{q}}(\frac{z_{h_2}}{1-z_q}, p_{2\perp})
\]

Back-to-back limit:

\[
P_T' = \frac{|P_T^{h_1} - P_T^{h_2}|}{2}
\]

\[
k_T' = \frac{|P_T^{h_1} + P_T^{h_2}|}{2}
\]

\[k_T' \ll P_T'
\]

Treatable single spin asymmetry (SSA) dependent on gluon Sivers

\[A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \frac{\Delta_N f_{g/p}(x, k_{\perp})}{f_1^g(x_g, k_{\perp})}
\]
Inputs to the model calculation

\[ \Delta^N f_{a/p^+}(x, k_\perp) = 2N_a(x) f_{a/p}(x, k_\perp) h(k_\perp) \]

\[ N_a(x) = N_a x^{\alpha_a (1 - x)} \beta_a \frac{(\alpha_a + \beta_a) (\alpha_a + \beta_a)}{\alpha_a \beta_a} \]

\[ h(k_\perp) = \sqrt{2e} \frac{k_\perp}{M} e^{-k_\perp^2/M^2} \]


u and d quarks only

\[ N_u = 0.40, \quad \alpha_u = 0.35, \quad \beta_u = 2.6 \]
\[ N_d = -0.97, \quad \alpha_d = 0.44, \quad \beta_d = 0.90 \]
\[ M_1^2 = 0.19 \text{ GeV}^2 \]


u, d + Kretzer FF (SIDIS1)

u, d + sea + DSS FF (SIDIS2)

\[ N_g = 0.05, \alpha_g = 0.8, \beta_g = 1.4, M_g^2 = 0.34 \text{ GeV}^2 \quad \text{(SIDIS1)} \]

Positivity bound ansatz:

\[ f_{1T}^g = -\frac{2\sigma M_p}{k_\perp^2 + \sigma^2} f_g(x, k_\perp), \quad \sigma = 0.8 \]

Model-I: Positivity bound

Model-II: Positivity bound x 5%

Model-III: SIDIS1 gluon Sivers fit
EIC setup for gluon SSA study

Kinematics:
ep↑ 20x250 GeV
√s=141 GeV
0.01<y<0.95
1<Q²<20 GeV²

Final state observables
1. D⁰ pair
2. K⁺K⁻ pair
3. Charged hadron pair

Scattered electron

<\eta>=1.24E-3
\langle Q^2 \rangle = 2.5 \, \text{GeV}^2

<W>=54.6 \, \text{GeV}
D meson pair selection

Branching ratio: 3.9%

$D^0(c\bar{u}) \to \pi^+(u\bar{d})K^-(s\bar{u})$

$\bar{D}^0(\bar{c}u) \to \pi^-(\bar{u}d)K^+(u\bar{s})$

- Acceptance for PID is assumed to be $|\eta|<3.5$
- Decay products from D mesons are mostly less than 10 GeV in mid-rapidity.
- Decay products $p_T>0.2$ GeV.
Projections for the SSA with D meson pairs

\[ \text{ep} \uparrow 20 \times 250 \text{ GeV} \]

D\(^0\) cut:

\[ \text{D} \rightarrow \text{K} + \text{pi} \quad (3.9\%) \]

Acceptance \( |\eta|^{\pi/K} < 3.5 \)

\[ p_T^{\pi/K} > 0.2 \text{ GeV}, \quad z^{\pi/K} > 0.1, \]

Correlation limit: \( k_T' < 0.7 P_T' \)

\[ <x_g> = 0.033 \]

\[ \sigma_{\text{DDbar pair}} = 2.2 \times 10^{-3} \text{ nb} \]

PGF fraction: 99.4\%

- Gluon Sivers best identified with positivity bound: Model I.
- Dominated by Gluon Sivers effect
- Integrated Luminosity: 20 fb\(^{-1}\)
  delivers \( \delta A_{UT} \approx 2.1 \times 10^{-2} \)

Difference between black and red shows the effect of gluon Sivers

The statistical uncertainty obtained with \( P = 70\% \) polarization

\[ (\delta A_{UT})^2 = \frac{1}{P^2 \sigma_L} \]

\[ A(\phi_{Sk}) = R^{SIG} A^{SIG}(\phi_{Sk}) + R^{BG} A^{BG}(\phi_{Sk}) \]

\[ \phi_{Sk'} = \phi_S - \phi_{k_T'} \]
Dihadron pair selection

\[ p_T > 1.7 \text{ GeV} \] effectively enhances the gluon initiated process.
Projections on the SSA with $K^+K^-$ pairs

Kinematic cuts:
- $p_T > 1.7$ GeV, $z_h > 0.1$, $|\eta| < 3.5$
- $0.01 < y < 0.95$
- $1 < Q^2 < 20$ GeV$^2$
- $p_T > 1.7$ GeV, $z_h > 0.1$, $|\eta| < 3.5$
- Back-to-back limit: $k_T' < 0.7P_T'$
- $\sigma_{K^+K^-} = 3.4 \times 10^{-2}$ nb
- $\langle x_g \rangle = 0.05$

- Hard to resolve 5% level of positivity bound: Model-II.
- PGF events accounting for 93%.
- Integrated Luminosity: 20 fb$^{-1}$ delivers $\delta A_{UT}$ $\approx 5.5 \times 10^{-3}$

The statistical uncertainty obtained with P=70% polarization ($\delta A_{UT})^2 = \frac{1}{P^2 \sigma_L}$

$$A(\phi_{Sk}) = R^{SIG} A^{SIG}(\phi_{Sk}) + R^{BG} A^{BG}(\phi_{Sk})$$

Difference between black and red shows the effect of gluon Sivers
Projections on the SSA with charged dihadron pairs

Kinematic cuts:
ep 20x250 GeV
0.01<y<0.95
1<Q<20 GeV
pT>1.7 GeV, z_h>0.1, |η|<4.5
Back-to-back limit: kT’ < 0.7pT’
σ_dihadron=0.5 nb
<x_g>=0.063

- Model II well identified but hard to resolve Model III.
- PGF events accounting for 80%.
- Integrated Luminosity: 20 fb^{-1} delivers δA_{UT} ≈ 1.4x10^{-3}

Together with well understood quark Sivers function, gluon Sivers sign and behavior can be constrained with an EIC.

\[ A(φ_{Sk}) = R^{SIG} A_{SIG}(φ_{Sk}) + R^{BG} A_{BG}(φ_{Sk}) \]

\[ (δA_{UT})^2 = \frac{1}{P^2 σ_L} \]

The statistical uncertainty obtained with P=70% polarization.
Comparison of all the probes

- Gluon Sivers effect is a luminosity hungry measurement.
- Vertical line represents the statistical uncertainty.
- Charged dihadron probe is the most statistically favored.
- D meson probe is mostly dominated by gluon dynamics.

**D meson**

**Charged dihadron**

\[ K^+ K^- \]
Summary

• Gluon Sivers function is an important ingredient of the complete 3D imaging of the nucleon.

• The single spin asymmetry arising from gluon Sivers is treatable in an effective TMD framework.

• D meson and $K^+K^-$ are better to tag gluon dynamics than charged dihadron, but will be more luminosity challenged.

• Gluon Sivers can be constrained via PGF coupling within EIC machine and detector reach.