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

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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?
  – Spin as fundamental intrinsic property and also as a mechanism to do tomography of many body system of quarks and gluons

• EIC: polarized collider to have full access to the nucleon dynamics.
2+1 D partonic image of the nucleon

Transverse Momentum Dependent parton distributions (TMDs)
- Spin dependent 3D momentum space image
- Semi-inclusive DIS
- \( f(x,k_T) \)

Generalized Parton Distributions (GPDs)
- Spin dependent 2D coordinate space (transverse) + 1D momentum space (longitudinal) image
- exclusive DIS
- \( f(x,b_T) \)
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 $S_T$.
- Non-trivial QCD color gauge invariance.

\[
\hat{f}_{a/p}(x, k_\perp) = f_{a/p}(x, k_\perp) + \frac{1}{2}\Delta^N f_{a/p}(x, k_\perp) \vec{S} \cdot (\hat{\vec{P}} \times \hat{\vec{k}}_\perp)
\]

Similar for gluons
Current knowledge to quark Sivers

\[ \frac{d\sigma}{dx \, dy \, d\phi_s \, dz \, d\phi_h \, dP_{hT}^2} \propto F_{UU,T} + |S_1| \sin(\phi_h - \phi_s) F_{UT,T}^{\sin(\phi_h - \phi_s)} + \ldots \]

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


PRL 103, 152002 (2009) HERMES data
PLB 717, 383 (2012) COMPASS data

JHEP 04(2017) Anselmino et. al.
Current constraints on gluon Sivers

Extraction based on $A_N$ data at RHIC


Extraction on COMPASS data


$A_{PGF}^{\sin(\phi_{2h}-\phi_S)} = -0.14 \pm 0.15$ (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 $1/N_c$.
- No hard constraints at this moment.
EIC Physics vs Luminosity and Energy

- JLEIC high lumi detector
- Ultimate eRHIC ERL
- HERA
- Ultimate eRHIC ERL no cooling
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 EIC

$s$: center-of-mass energy squared

$Q^2$: resolution power

$x_B$: the fraction of the nucleon’s momentum carried by the struck quark (0<$x$<1)

$y$: inelasticity

Treatable single spin asymmetry (SSA) sensitive to gluon Sivers

$$A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \frac{\Delta^N f_{g/p}(x, k_\perp)}{f^g_1(x_g, k_\perp)}$$
Inputs to the model calculation

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

\[ w = \frac{\Delta^N f_{a/p}^\dagger(x, k_\perp, Q^2)}{2f_{a/p}(x, k_\perp, Q^2)} \]

\[ A_{UT} = R_g \frac{\sum_{i=1}^{N_g} w_i}{N_g} + R_q \frac{\sum_{i=1}^{N_q} w_i}{N_q} \]

**Quark Sivers:** JHEP 04(2017) Anselmino et. al.

u and d quarks

**Gluon Sivers:** JHEP 09 (2015) 119 D’ Alesio et. al.

u, d + Kretzer FF (SIDIS1)

Positivity bound ansatz:

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

Comparing with charged hadron density measurements from HERA

Kinematics:
ep 27.6 GeV x 920 GeV
5<Q^2<10, 0.0005<x_{Bj}<0.002
p_T^*, \eta^* defined in gamma-hadron center of mass frame

Data from EPJC 73, 2406 (2013)

H1 charged particle density data reasonably described by simulations.
EIC setup for gluon SSA study

Kinematics:
ep↑ 20x250 GeV
\(\sqrt{s}=141\text{ GeV}\)
0.01<y<0.95
1<\(Q^2\)<20 GeV²

Final state observables
1. D⁰ pair
2. Charged hadron pair
3. Dijet pair

\(<x_{Bj}>=1.24\times10^{-3}\)
\(<Q^2>=2.5\text{ GeV}^2\)
\(<W>=54.6\text{ GeV}\)

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D meson pair selection

Branching ratio: 3.9%

\[ D^0(c\bar{u}) \rightarrow \pi^+(u\bar{d})K^-(s\bar{u}) \]
\[ \bar{D}^0(\bar{c}u) \rightarrow \pi^-(\bar{u}d)K^+(u\bar{s}) \]

- 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 open charm probe

$e^+ p \uparrow 20 \times 250 \text{ GeV}$

$D^0$ cut:

$D \rightarrow K + \pi$ (3.9%)

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

$p_T^{\pi/K} > 0.2 \text{ GeV}, p_T^{D} > 0.7 \text{ GeV}, z^D > 0.1$

$\int L \, dt = 10 \text{ fb}^{-1}$

- Gluon initiated events account for 90% of $D$ meson production
- $D$ can be regarded as a good parton kinematics proxy
- Statistics not enough to resolve the gluon Sivers level even on 10% positivity bound
Projections on the SSA with charged dihadron probe

Kinematic cuts:
ep 20x250 GeV
0.01<y<0.95
1<Q^2<20 GeV^2
p_T>1.7 GeV, z_h>0.1, |η|<4.5
Back-to-back limit: k_T' < 0.7P_T'
∫Ldt = 10 fb^{-1}

• Gluon initiated process account for a large fraction of events at small x_B
• Smear to parton level asymmetry becomes stronger
• Statistically more favored than open charm, resolve 5% positivity bound gluon Sivers size
Projections on the SSA with charged dihadron probe

Single out the asymmetry amplitude

\[ A_{UT}^{\sin(\phi_{ks})} = \frac{\int d\phi_{ks}(d\sigma^\uparrow - d\sigma^\downarrow) \sin(\phi_{ks})}{\int d\phi_{ks}(d\sigma^\uparrow + d\sigma^\downarrow)} \]

- Asymmetry size dependence on xB, Q2 can be identified with 5% positivity bound
- Clearer sense of direction to distinguish model discrepancy in xB behavior
- No significant Q^2 trend as missing TMD evolution.
Projections on the SSA with dijet probe

Kinematic cuts:
- ep 20x250 GeV
- 0.01<y<0.95
- 1<Q^2<20 GeV^2

Anti-\kT, R=1, jet constituent:
- pT>250 MeV, π/K/p/γ, |\eta|<4.5
- pT^{jet1}>4.5 GeV, pT^{jet2}>4 GeV
- \int L dt = 10 fb^{-1}

- Gluon initiated process still dominant at small x_B
- Stronger final state observable to parton kinematics correlation
- Resolution down to 5% positivity bound gluon Sivers size
Projections on the SSA with dijet probe

- SSA amplitude can be analyzed in multiple dimensions.
- Direct handle on parton kinematics put stronger constraint such as $x_{\text{parton}}$.
Summary

• Gluon Sivers function is an ingredient of complete 3D imaging of nucleon.
• It can be uniquely accessible and constrained in a wide kinematic range at EIC.
• Charged dihadron and dijet methods are more statistically favored compared to the open charm production.
• Different probes can be complementary to each other at EIC.
BACKUP
Explored $x_g$ in different probes
Nucleon structure and Sivers function

- Collisions on the hadronic objects as incoherent superposition off partonic constituents.
- TMD framework provides a useful tool to image the nucleon structure in 2+1D momentum space.
Accessing Sivers in SIDIS

\[
\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_T^2} \propto F_{UU,T} + |S_\perp| \sin(\phi_h - \phi_S) F_{UT,T}^{\sin(\phi_h - \phi_S)} + ...
\]


PRL 103, 152002 (2009) HERMES data
PLB 717, 383 (2012) COMPASS data
Accessing gluon Sivers at EIC

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

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

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

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

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

Treatable single spin asymmetry (SSA) sensitive to gluon Sivers

\[
A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \frac{\Delta^N f_{g/p}(x, k_\perp)}{f_1^g(x, k_\perp)}
\]

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Accessing gluon Sivers at an EIC

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

Treatable single spin asymmetry (SSA) sensitive to gluon Sivers

\[
A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \frac{\Delta^N f_g/p^\uparrow(x, k_{\perp})}{f_1^g(x, k_{\perp})}
\]
PYTHIA confronted with HERA data

Data taken from: EPJC 72, 1995 (2012)

Comparing with D* measurements from HERA
ep 27.6 GeV x 920 GeV
$Q^2<2$ GeV$^2$, $100<W<285$ GeV, $|\eta|<1.5$
$p_T$, $\eta$ defined in gamma-hadron center of mass frame

Simulation describes the data trend reasonably.
Accessing gluon dynamics DIS collisions

1. Tag photon-gluon fusion events.
2. Find back-to-back hadron pairs from the quark-antiquark jet.
3. Reconstruct the gluon dynamics with the hadron pair information.

Gluon information can be extracted with the hadron pairs from the quark-antiquark jet.

Back-to-back limit:
\[ P_T' = \frac{|P_T^{h1} - P_T^{h2}|}{2} \]
\[ k_T' = \frac{|P_T^{h1} + P_T^{h2}|}{2} \]
\[ k_T' \ll P_T' \]
Theoretical framework for the model calculation

\[ \frac{d\sigma_{\text{tot}}}{dz_{h_1}dz_{h_2}d^2p_{h_1\perp}d^2p_{h_2\perp}} = C \int_{z_{h_1}}^{1-z_{h_2}} \sum_q d\frac{\rho_{q}(1-z_q)}{z_{h_2}z_{h_1}^2} d^2p_{1\perp}d^2p_{2\perp} \hat{f}_{g/p}^\uparrow(x_g,k_{\perp}) \]

\[ \times H_{\text{tot}}^{\gamma^*q\rightarrow q\bar{q}}(z_q,k_{1\perp},k_{2\perp}) e_q^2 D_{h_1/q}(\frac{z_{h_1}}{z_q},p_{1\perp}) D_{h_2/q}(\frac{z_{h_2}}{1-z_q},p_{2\perp}) \]

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

\[ f_{1T}^{\uparrow q}(x,k_{\perp}) = \frac{2\sigma_{Tq}}{k_{\perp}^2 + \sigma^2} f_1^q(x,k_{\perp}) \]

- A negative gluon Sivers saturating the positivity bound is assumed.
- Stronger asymmetry size observed for larger \( k_{T}' \).

\[ \phi_{Sk'} = \phi_S - \phi_{k_{T}'} \]
$D^0$ as charm quark proxy

$D$ meson takes a large fraction of the charm quark energy, serves as a proxy to the charm jet information.
Charged hadron vs kaon spectrum

Charged hadron

Charged Kaon

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Dihadron pair selection

$p_T > 1.7$ GeV effectively enhances the gluon initiated process.
D^0 feed-down from D*

D^0 from D* decay similar to the directly generated D^0s, therefore all D^0s are analyzed.
Dihadron pair selection

Kinematic cuts:
ep 20x250 GeV
0.01<y<0.95
1<Q^2<20 GeV^2
p_T>1.7 GeV, z_h>0.1, |η|<4.5
Back-to-back limit: k_T' < 0.7P_T'

![Graph showing hadron pair distribution with acceptance for all charge.]

Large z prefers forward rapidity

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Weighting strategy vs numerical estimation

$A_{UT}$ can be evaluated with the weighting based on input Sivers function

$$A_i = \frac{1}{N_i} \sum_{k=1}^{N_i} w_k,$$

$$w_k = \frac{\Delta^N f_{a/p}(x, k_{\perp})}{2 f_{a/p}(x, k_{\perp})}.$$

- Weighted results agree with the numerical estimations.
- Initial state parton shower suppresses the azimuthal asymmetry significantly.

W=100 GeV  
$Q^2=4 \text{ GeV}^2$  
$z_{h1}=z_{h2}=0.3$  
$P_T' > 4 \text{GeV}$
Numerical estimation of gluon SSA with positivity bound

\[ D^0 \langle p_T^2 \rangle_{\text{frag}} = 0.64 \]

\[ \text{Charged dihadron} \; \langle p_T^2 \rangle_{\text{frag}} = 0.2 \]
Collection of different probes

Event sample summary:
ep 20x250 GeV
\sqrt{s}=141 GeV
0.01<y<0.95
1<Q^2<20 GeV^2

\sigma_{\text{tot}} = 562.5 \text{ nb (all events)}
\sigma_{\text{dihadron}} = 5.0 \times 10^{-1} \text{ nb, Gluon initiated: 80%}
\sigma_{K^+K^-} = 1.6 \times 10^{-2} \text{ nb, Gluon initiated: 94%}
\sigma_{DD\text{bar \ pair}} = 2.4 \times 10^{-4} \text{ nb, Gluon initiated: 100%}
\sigma_{\text{dihadron}} \sim 31 \sigma_{K^+K^-} \sim 67 \sigma_{DD\text{bar \ pair}}

\text{dihadron cuts:}
Acceptance |\eta|<4.5
z>0.1, p_T>1.7 GeV, Correlation limit: k_T' < 0.7P_T'

\text{K+K- cuts:}
Acceptance |\eta|<1
z>0.1, p_T>1.7 GeV, Correlation limit: k_T' < 0.7P_T'

D^0 cut: D->K + pi (3.9%)
Acceptance |\eta|^{pi/K}<1
p_T^{pi/K}>0.2 GeV, z>0.1, Correlation limit: k_T' < 0.7P_T'

With 100 fb^{-1} statistics and P=70% polarization
\delta A_N = \frac{1}{P\sqrt{\sigma_L}} = \frac{1}{P\sqrt{N}}
\delta A_{UT}^{\text{dihadron}} \approx 6.4 \times 10^{-4}, \delta A_{UT}^{K^+K^-} \approx 3.8 \times 10^{-3}, \delta A_{UT}^{DD\text{bar}} \approx 2.8 \times 10^{-2} \text{ (Uncertainty divided into 10 bins in } \phi_{Sk})
Projections on the SSA with dijet probe

- Possible to do 2D binning in $x_B$ and $Q^2$
- Structures difficult to extract in 1D analysis observed
- Helpful to pin down the evolution feature of gluon Sivers
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.