Measuring Gluon Sivers Function at a Future Electron-Ion Collider

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In this work, we present a systematic study on the feasibility of probing the largely unexplored gluon Sivers function (GSF) based on the open charm production, charged dihadron and dijet method at a future high energy, high luminosity Electron-Ion Collider (EIC). Sivers function describes the anisotropy of parton distributions inside a transversely polarized nucleon in the momentum space and provides us a complete picture of the 2+1D structure of the nucleons. It is proposed that the GSF can be studied through

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the single spin asymmetry (SSA) measurement in the photon-gluon fusion channel with electron proton collisions at the EIC. Using a well tuned Monte Carlo model for deep inelastic scatterings, we estimate the possible constraints of the gluon Sivers effect one can draw from the future EIC data. Comparisons of all the possible measurements further illustrate that the dijet method is the most promising way to demonstrate the presence of GSF and pin down its evolution effect.

Keywords: Gluon Sivers; EIC; dijet.

1. Introduction

In recent years, an important quest in hadron physics is to explore the multi-dimensional structure of the nucleon based on the partonic degrees of freedom. Beyond rather sophisticated studies on collinear parton distribution functions, the current forefront of hadronic structure research has led us to a three-dimensional tomographic view of the nucleon structure by including parton transverse momentum and space information. These extensions can provide unique ways of connecting underlying parton dynamics with the nucleon properties.

The transverse momentum extensions to the longitudinal parton momentum distributions can be utilized in the transverse momentum dependent (TMD) factorization framework. With the information of confined parton motion in TMD, correlations between parton transverse momentum and their spin, as well as the spin of their parent nucleon can be matched to a group of TMD parton distributions (TMDs) ¹. The Sivers function $f_{1T}^{\perp 2}$, which describes the azimuthally asymmetric distribution of unpolarized partons in transverse momentum space inside a transversely polarized nucleon, has received the widest attention both phenomenologically and experimentally among all TMDs.

The Sivers effect arises due to the color exchanges between the struck parton and the nucleon remnant during the initial- and final-state interactions. It was found that, due to the gauge invariance in QCD, the Sivers function is not universal in different high energy scattering processes ³. Experimentally, the quark Sivers function has been measured in the semi-inclusive DIS data by the HERMES, COMPASS, and JLab Hall A collaborations, , and the polarized proton-proton data by the STAR and PHENIX collaborations over the years. There is a prospective hint that the W boson measurement ⁴ at STAR favors a sign change for the Sivers function relative to that in SIDIS, which represents an important proof for the non-universality of the Sivers function. However, due to the large uncertainties and limited low Q^2 coverage of the SIDIS experimental data, only valence quark Sivers function at high x can be constrained with the phenomenological studies ⁵. No solid constraint can be drawn on the low x or sea quark Sivers function till this moment. With the coming of the future high energy, high luminosity Electron-Ion Collider ⁶, the unexplored sea quark region could be ideally studied with dramatical improvement to the current data situation.

The gluon Sivers function (GSF), on the other hand, is poorly known at the current stage ⁷. Fits to the Sivers asymmetry for SIDIS data favors a 30% gluon to

quark Sivers ratio based on the theoretical expectation from large N_c considerations for $x \sim 1/N_c$ ⁵. It has been shown in Ref. 8, 9 that gluon transverse momentum distribution can be mapped through quark-antiquark jet correlation in deep inelastic scattering (DIS). The open charm production in electron-proton scattering $ep^\uparrow \rightarrow e'c\bar{c}X$, for instance, is supposed to be a direct probe to the gluon Sivers effect ⁶. A model study has been carried out in and the related experimental considerations are discussed in Ref. 1, 6. Besides, we can also utilize the high p_T charged dihadron pair or dijet measurements, which are more statistically favored than the charm production channels. In this work, we will illustrate the detailed information on the EIC projections for these measurements.

2. Single spin asymmetry (SSA) arising from the gluon Sivers effect

The production of high transverse momenta hadron pairs in DIS through $\gamma^*g \rightarrow q\bar{q}$ is sensitive to the gluon contributions, although it may have small contribution from the quark channel. If k_1 and k_2 are the four momenta of the outgoing quarks, one can obtain the dihadron cross section as a generalization to the unpolarized case in Ref. 10 with the transverse momentum imbalance $k_\perp = |\vec{k}_{1\perp} + \vec{k}_{2\perp}|$ and the dijet transverse momentum scale $P_\perp = |\vec{k}_{1\perp} - \vec{k}_{2\perp}|/2$:

$$\frac{d\sigma_{\text{tot}}^{\gamma^*+p^\uparrow \rightarrow h_1+h_2+X}}{dz_{h1}dz_{h2}d^2p_{h1\perp}d^2p_{h2\perp}} = C \int_{z_{h1}}^{1-z_{h2}} \sum_q dz_q \frac{z_q(1-z_q)}{z_{h2}^2 z_{h1}^2} d^2p_{1\perp} d^2p_{2\perp} \hat{f}_{g/p^\uparrow}(x_q, k_\perp) \\ \times H_{\text{tot}}^{\gamma^*g \rightarrow q\bar{q}}(z_q, k_{1\perp}, k_{2\perp}) e_q^2 D_{h1/q}(\frac{z_{h1}}{z_q}, p_{1\perp}) D_{h2/\bar{q}}(\frac{z_{h2}}{1-z_q}, p_{2\perp}), \quad (1)$$

where C gives the normalization factor, z_q is the momentum fraction of produced quark q with respect to the incoming virtual photon and $H_{\text{tot}}^{\gamma^*g \rightarrow q\bar{q}}(z_q, k_{1\perp}, k_{2\perp})$ gives the combined hard factor that incorporates both longitudinal and transverse component of the virtual photon. In our analysis, we restrict ourselves to a kinematic configuration with $k_\perp \ll P_\perp$ known as the correlation limit ¹¹.

There exists to be a strong correlation between the kinematics of a selected hadron and its quark parent. Therefore, one can use the measurable hadron variables $P'_T = |p_{h1\perp} - p_{h2\perp}|/2$ and $k'_T = |p_{h1\perp} + p_{h2\perp}|$ to access the underlying parton kinematic variables $P_\perp$ and $k_\perp$. The GSF can be studied in the dihadron single spin asymmetry (SSA) with the notation of $\Delta^N f_{a/p^\uparrow}(x, k_\perp) = -\frac{2k_\perp}{M_p} f_{1T}^{a\perp}(x, k_\perp)$ as follows:

$$A_{UT}(\phi_{Sk'}, k'_T) = \frac{d\sigma^\uparrow(\phi_{Sk'}, k'_T) - d\sigma^\downarrow(\phi_{Sk'}, k'_T)}{d\sigma^\uparrow(\phi_{Sk'}, k'_T) + d\sigma^\downarrow(\phi_{Sk'}, k'_T)} \propto \frac{\Delta^N f_{g/p^\uparrow}(x, k_\perp)}{f_1^g(x_g, k_\perp)}, \quad (2)$$

where subscript “U” represents the unpolarized electron beam and “T” indicates the proton beam is transversely polarized. $\phi_{Sk'} = \phi_S - \phi_{k'_T}$ indicates the angular difference between total dihadron transverse momentum $\vec{k}'_T$ and the polarized proton spin direction $\vec{S}_\perp$. The size of SSA is proportional to the corresponding Sivers function divided by the unpolarized parton distributions.

We provide an estimate to the possible size of single spin asymmetry in the following studies with three model assumptions. The maximized one can be obtained with an ansatz which saturates the positivity bound $f_{1T}^{\perp g} = -\frac{2\sigma M_p}{k_{\perp}^2 + \sigma^2} f_g(x, k_{\perp})$, $\sigma = 0.8$ GeV. An intermediate size gluon Sivvers function has been set with 5% level or 10% of the positivity bound. In the end, a minimized set of gluon Sivvers parameterization has been taken from the SIDIS1 fits to the $\pi^0 A_N$ data in pp collisions at RHIC¹².

3. Results and discussions

The laboratory coordinate system has been defined with a convention the proton beam moving in $+z$ and the incoming electron along $-z$. The event kinematics has been constrained to $0.01 < y < 0.95$ and $1 \text{ GeV}^2 < Q^2 < 20 \text{ GeV}^2$. The selection of this kinematic range delivers the average event properties as $\langle x_{Bj} \rangle = 0.0012$, $\langle Q^2 \rangle = 2.5 \text{ GeV}^2$, $\langle W \rangle = 54.6 \text{ GeV}$. An integrated luminosity of $\mathcal{L}_{int} = 10 \text{ fb}^{-1}$ has been assumed for the following study.

3.1. gluon SSA with $D\bar{D}$ pair

The $D^0 \rightarrow \pi K$ decay channel is used in this analysis by taking the advantage with the vertex tracking detector at an EIC. The D meson decay products are not allowed to exceed the acceptance range region $|\eta_{Lab}^{\pi/K}| < 3.5$. To guarantee the decay products of D^0 can reach time projection chamber for particle identification, a transverse momenta cut $p_{T,Lab}^{\pi/K} > 0.2 \text{ GeV}$ has been applied to the decay products. As the kinematics of a directly generated D^0 is of little difference compared to that of a heavier D meson state generating it, we include all the D^0 in our study.

The sensitivity of this measurement to the possible gluon Sivvers size has been shown in Fig. 1.

Fig. 1. (Color online) Projection for the $D\bar{D}$ pair SSA shown with different gluon Sivvers inputs.

Fig. 2. (Color online) Projection on the charged dihadron pair SSA shown with different gluon Sivers magnitude.

Fig. 3. (Color online) Projection on the dijet pair SSA shown with different gluon Sivers magnitude.

3.2. gluon SSA with high p_T charged dihadron pair and dijet pair

The acceptance for the charged hadrons has been set to fit in the eRHIC main detector design $|\eta_{Lab}| < 4.5$. A transverse momentum cut $p_T^h > 1.4$ GeV is assumed for the hadron pair candidates. The energy fraction of the involved particles must fulfill the requirement that $z_h > 0.1$. To select hadron pairs from back-to-back jets, we perform a back-to-back cut as $k_T < 0.7P_T$ with $P_T = |\vec{p}_T^{h1} - \vec{p}_T^{h2}|/2$ in this study. In this way, one can eliminate the effect of two hadrons fragmented from the same parton. The corresponding estimation of the projected statistical resolution has been shown in Fig. 2.

In our analysis, the jet has been reconstructed through charged π , K and protons in the tracking device together with photons accepted in the calorimeter with minimum transverse momentum $p_{T,Lab} > 0.25$ GeV within the acceptance range $|\eta_{Lab}| < 4.5$. The radius parameter is assumed to be $R = 1$ in the anti- k_T jet reconstruction scheme. Dijet events are selected with trigger jet $p_T^{jet1} > 4.5$ GeV and associate jet $p_T^{jet2} > 4$ GeV.

It can be observed in the comparison that dijet SSA provides a better proxy to the underlying gluon kinematics information. Additionally, due to the statistical advantage of dijet events, the SSA from dijet method is more sensitive to the

underlying gluon Sivers behavior. Thus, it can even offer us a potential window to peer into the evolution feature of gluon Sivers function.

4. Summary

In this work, we have performed a study on the feasibility of measuring the gluon Sivers with open charm, dihadron and dijet production in the polarized $ep^\uparrow$ collisions at an EIC. It is found that although the heavy quark pair production process through $D\bar{D}$ final state observable is a very clean channel to tag the gluon distribution, the charged dihadron and dijet measurements are statistically more favored and can be used to distinguish the existence of a gluon Sivers with about 5% level to the positivity bound. More importantly, the dijet probe at an EIC can serve as a precise analyzer to distinguish the different models and pin down the evolution of the gluon Sivers function. It is thus a very appealing experimental program to demonstrate and study the features of the gluon Sivers effect at the future EIC, the results of which will largely improve our understanding to the TMD parton distributions and provide a unique test to the QCD theory.

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