Transverse Momentum Dependent Parton Distributions at an Electron-Ion Collider

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We summarize the current status and future perspective of the transverse momentum dependent parton distributions at an electron-ion collider.

Transverse momentum dependent (TMD) parton distributions have attracted great attentions from both experiment and theory sides in recent years [1]. They open a new window to investigate the strong interaction physics and the fundamental properties of QCD theory. At the leading order, there are eight independent TMD quark distributions: three $k_\perp$-even distributions (unpolarized, longitudinal polarized quark distributions, and the quark transversity), and five $k_\perp$-odd distributions. Because of the correlations between the quark transverse momentum and the nucleon spin, the TMDs naturally provide important information on the dynamics of partons in the transverse plane in momentum space. Measurements of the $k_\perp$-odd quark distributions provide information about the correlation between the quark orbital angular momentum and the nucleon/quark spin because they require wave function components with nonzero orbital angular momentum.

One particular example is the quark Sivers function $f_{1T}^{\perp q}$ which describes the transverse momentum distribution correlated with the transverse polarization vector of the nucleon. There have been strong evidence of the Sivers effect in the DIS experiments observed by the HERMES, COMPASS, and JLab Hall A collaborations [2, 3, 4] (see Fig. 1). An important aspect of the Sivers functions which has been revealed theoretically in last few years is the process dependence and the color gauge invariance [5, 6]. Together with the Boer-Mulders function, they are denoted as naive time-reversal odd (T-odd) functions. In the semi-inclusive DIS (SIDIS), where a leading hadron is detected in coincidence with the scattered lepton, the quark Sivers function arises due to the exchange of (infinitely many) gluons between the active struck quark and the remnants of the target, which is referred as the final state interaction effects in DIS. On the other hand, for the Drell-Yan lepton pair production process, it is the initial state interaction effects. As a consequence, the quark Sivers functions differ by a sign in these two processes. This non-universality is a fundamental prediction from the gauge invariance of QCD [6]. The experimental check of this sign change is currently one of the outstanding topics in hadronic physics, and Sivers functions from Drell-Yan process can be measured at RHIC.

In high energy hadronic processes where we hope to study the transverse momentum dependent parton distributions, besides the transverse momentum, an additional hard momentum scale is essential to make the proper use of the TMD parton distributions and fragmentation functions. This hard momentum scale needs to be much larger than the transverse momentum scale. At the electron-ion collider, DIS processes naturally provide a hard momentum scale: Q, the virtuality for the virtual photon. More importantly, the EIC design has a wide range of Q^2 values, which will provide a unique opportunity to systematically investigate the strong interaction dynamics associated with the TMD physics.

There have been tremendous progresses in understanding TMDs and the related physics. However, without a new lepton-hadron collider many aspects of this fascinating field will remain unexplored or at best only on a qualitative level. Existing facilities either suffer from a much too restricted kinematic coverage or from low luminosity or from both. The advantage of the semi-inclusive DIS measurement discussed below is to have the two planes defined as the lepton plane and hadron plane, which allows to access to different angular dependences in the hadron production. These angular distributions are important to extract the TMDs since each of them has a unique angular dependence. Precision measurements of the various angular modulations are only possible with a dedicated detector at the EIC.

Based on the present status of research we see the following potentials in an EIC:

- precise, quantitative measurements of TMDs in the valence region due to high luminosity, and the ability to go to sufficiently large values of Q^2 in order to suppress potential higher twist contaminations;
- related to the wide kinematic coverage and the high luminosity, the ability to provide multi-dimensional representations of the observables, which is impossible on the basis of current experiments;
- measurements of the TMDs for antiquarks and gluons at an unprecedented level;
- systematic studies of perturbative QCD techniques (for polarization observables) and studies of QCD evolution properties of TMDs.

In the following, we will take semi-inclusive DIS as an example for the quark Sivers function and highlight the impact of the EIC machine. For the gluon Sivers function, we refer to the talk by Tom Burton [7].

In general, SIDIS depends on six kinematic variables. In addition to the variables for inclusive DIS, x, $y = (P \cdot q)/(P \cdot l)$, and the azimuthal angle ϕ_S describing the orientation of the target spin vector for transverse polarization, one has three variables for the final state hadron, which we denote by $z = (P \cdot P_h)/(P \cdot q)$ (longitudinal hadron momentum), P_{hT} (magnitude of transverse hadron momentum), and the angle ϕ_h for the orientation of $\boldsymbol{P}_{hT}$. In the one-photon exchange approximation, the SIDIS cross section can be decomposed in terms of structure functions. For example, for the spin-average and single-spin dependent contributions, we have

$$\frac{d\sigma}{dx_B\, dy\, d\phi_S\, dz\, d\phi_h\, dP_{hT}^2} \propto F_{UU,T} + |\boldsymbol{S}_\perp| \sin(\phi_h - \phi_S) F_{UT,T}^{\sin(\phi_h - \phi_S)} + ... \qquad (1)$$

To extract the quark Sivers function, experimentally, we measure the $\sin(\phi_h - \phi_s)$ modulation of the single transverse spin asymmetry (SSA), which is defined by the ratio of the two cross section terms in Eq. (1). This asymmetry depends on four kinematics: Q^2, x_B, z_h, P_{hT}.

In the following, we illustrate the expected impact of data from the EIC using the parameterization from Ref. [8] as an arbitrarily chosen model of the Sivers function. This parameterization, denoted $theor_i = F(x_i, z_i, P_{hT}^i, Q_i^2; \mathbf{a_0})$ with the M parameters $\mathbf{a_0} = \{a_1^0, ..., a_M^0\}$ fitted to existing data, serves to generate a set of pseudo-data in each kinematic bin i. In each x_i, Q_i^2, z_i and P_{hT}^i bin, the obtained values, $value_i$, for the Sivers function are distributed using a Gaussian smearing with a width σ_i corresponding to the simulated event rate at an center-of-mass energy of $\sqrt{s} = 45$ GeV obtained with an integrated luminosity of 10 fb^{-1}. To illustrate

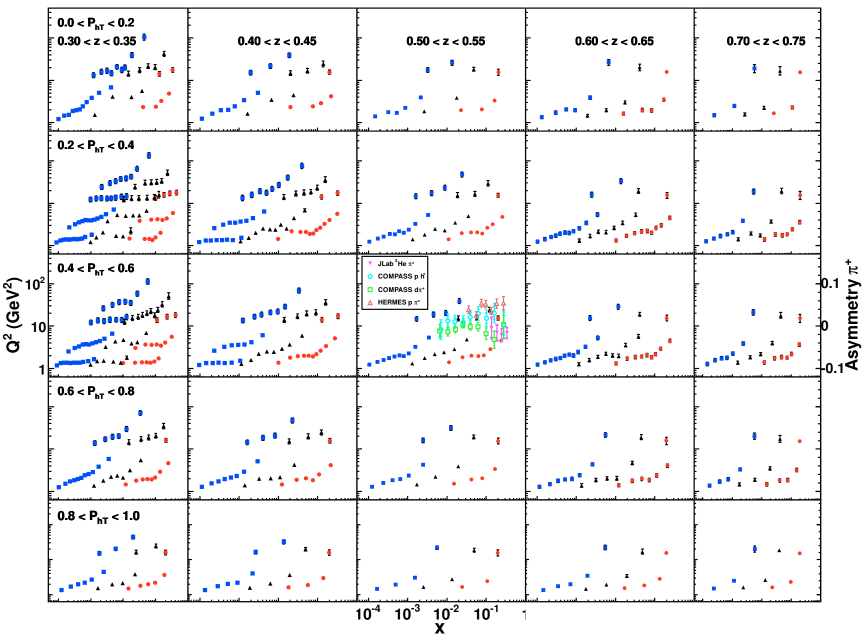

Figure 1: Four-dimensional representation of the projected accuracy for π^+ production in semi-inclusive DIS off the proton. Each panel corresponds to a specific z bin with increasing value from left to right and a specific P_{hT} bin with increasing value from top to bottom, with values given in the figure. The position of each point is according to its Q^2 and x value, within the range $0.05 < y < 0.9$. The projected event rate, represented by the error bar, is scaled to the (arbitrarily chosen) asymmetry value at the right axis. Blue squares, black triangles and red dots represent the $\sqrt{s} = 140$ GeV, $\sqrt{s} = 45$ GeV and $\sqrt{s} = 15$ GeV EIC configurations, respectively. Event counts correspond to an integrated luminosity of 10 fb^{-1} for each of the three configurations. Also shown in the center panel are the x-Q^2 distributions of current experimental data from HERMES, COMPASS, and JLab Hall A and their asymmetries, where z_h and P_{hT} have been integrated out for the appropriate kinematics.

the obtainable statistical precision the event rate for the production of π^+ in semi-inclusive DIS was used, see, for example, Fig. 1.

This new set of pseudo-data was then analysed like the real data in Ref. [8]. Figure 2 shows the result for the extraction of the Sivers function for the valence and sea u quarks. Similar results are obtained for the down quarks as well. The central value of $f_{1T}^{\perp u}$, represented by the red line, follows by construction the underlying model. The 2-sigma uncertainty of this extraction, valid for the specifically chosen functional form, is indicated by the dark grey area, which is hardly seen around the red line. This precision, obtainable with an integrated luminosity of 10 fb^{-1}, is compared with the uncertainty of the extraction from existing data, represented by the light grey band. Our current knowledge is restricted to an essentially qualitative picture of the Sivers function (and TMDs in general) only. From this comparison, we can clearly see that the EIC will be the unique facility for accessing the Sivers function (and TMDs in general) with unprecedented precision, and particularly in the currently unexplored sea quark region.

A more important kinematic reach of an EIC machine is the transverse momentum distri-

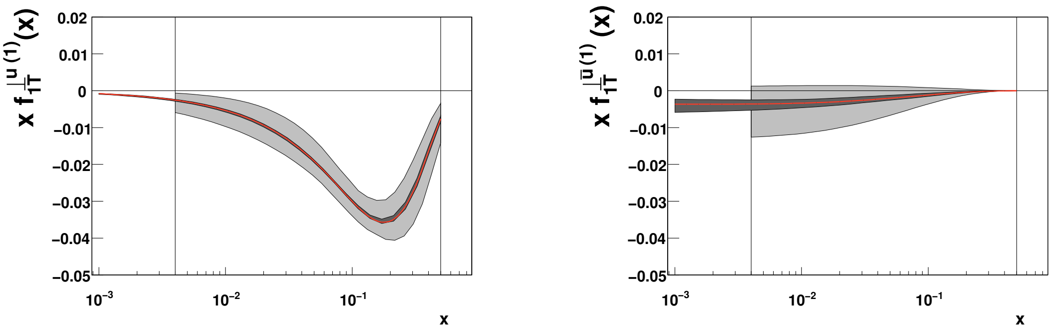

Figure 2: [color online] Comparison of the precision (2-σ uncertainty) of extractions of the Sivers function for the valence (left) and sea (right) u quarks from currently available data [8] (grey band) and from pseudo-data generated for the EIC with energy setting of $\sqrt{s} = 45$ GeV and an integrated luminosity of 10 fb^{-1} (dark grey band around the red line). The uncertainty estimates are for the specifically chosen underlying functional form.

butions of the physical observables. This is particularly important to connect to the collinear factorization approach in hadron physics to understand the long standing open question, which is the underlying mechanism giving rise to single spin asymmetry. Recent theoretical developments have revealed that the transverse momentum dependent Sivers mechanism and the twist-three collinear mechanism are unified to describe the same physics in the overlap region where both approaches apply [9]. High luminosities at the EIC machine provide a golden opportunity to explore the rich physics of the transverse momentum dependence of the SIDIS measurements.

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