# Jet-based measurements of Sivers and Collins asymmetries at the future Electron-Ion Collider

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We present predictions and projections for hadron-in-jet measurements and electron-jet azimuthal correlations at the future Electron-Ion Collider (EIC). These observables directly probe the threedimensional (3D) structure of the nucleon, in particular, the quark transversity and Sivers parton distributions and the Collins fragmentation functions. We explore the feasibility of these measurements with parametrized detector simulations, and discuss detector requirements. We conclude that jet observables have the potential to boost the experimental program for 3D imaging at the EIC.

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## I. INTRODUCTION

Jets, collimated sprays of particles observed in high energy particle collisions, offer a unique opportunity to study Quantum Chromo-Dynamics (QCD). Measurements of jets at the Large Hadron Collider (LHC) have 25 triggered new theoretical and experimental techniques for

detailed studies of QCD [1].

Jets observables can probe the three-dimensional (3D) nucleon structure encoded in transverse momentum dependent parton distribution functions (TMD PDFs) and

<sup>30</sup> fragmentation functions (TMD FFs), collectively called TMDs. For example, Higgs plus jet production at the LHC gives access to the gluon TMD PDF [2], while hadron transverse momentum distribution inside jets probes TMD FFs [3–5]. Jets produced in polarized

35 proton-proton collisions probe the Sivers [6–8], transversity and Collins TMDs [9–11]. Recently, jet production in deep-inelastic scattering (DIS) regime was hailed as a key channel for TMD studies [12–14].

The advent of the Electron-Ion Collider [15] will un-40 lock the full potential of jets as a tool for TMD studies with its high luminosity and polarized beams. Measurements of jets in DIS make it possible to control parton

kinematics in a way that is not feasible in hadronic collisions. The measurement of jets in DIS will complement <sup>45</sup> semi-inclusive DIS (SIDIS) observables. Generally, jets are better proxies of parton-level dynamics, and they allow for a clean separation of the target and current fragmentation regions. The measurement of both SIDIS and jet observables is critical to test universality aspects of <sup>50</sup> TMDs within QCD factorization and probe TMD evolution effects.

The TMD factorization for SIDIS involves a convolution of TMD PDFs and TMD FFs. The observed hadron transverse momentum,  $\vec{P}_{hT} = z\vec{k}_T + \vec{p}_T$ , receives contri-<sup>55</sup> butions from both TMD PDFs ( $k_T$ ) and TMD FFs ( $p_T$ ). Here z is the longitudinal momentum fraction of the quark momentum carried by the hadron. Therefore, it is not possible to separately extract TMD PDFs and TMD FFs via hadron SIDIS alone. Instead, one has to rely on addi-<sup>50</sup> tional processes, such as  $e^+e^-$  annihilation and Drell-Yan production. One major advantage of jet measurements is that they isolate TMD PDFs from TMD FFs.

We consider back-to-back electron-jet production in the laboratory frame (see Figure 1),

$$e + p(\vec{s}_T) \rightarrow e + (\operatorname{jet}(\vec{q}_T) h(z_h, \vec{j}_T)) + X,$$
 (1)

where the imbalance  $\vec{q}_T$  of the transverse momentum of the final-state electron and jet is measured, and additionally the transverse momentum  $\vec{j}_T$  of hadrons inside the

jet with respect to the jet axis. The imbalance  $\vec{q}_T$  is only sensitive to TMD PDFs [14, 16], while the  $\vec{j}_T$  is sensitive to TMD FFs alone [5, 17, 18]. As a consequence, indepen-

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Figure 1. Illustration of the neutral current DIS process where a jet is recoiling the final state electron in the laboratory frame.

dent constraints of both TMD PDFs and TMD FFs can <sup>70</sup> be achieved through a single jet measurement in DIS. In addition, the process considered in this work can be related to similar cross sections accessible in proton-proton collisions, see for example Refs. [19, 20].

An alternative way to isolate TMD PDFs was proposed 75 in Refs. [12, 13], using the Breit frame. In this case, the evaluated purely perturbatively and TMD FFs are not required.

The use of jets at the EIC will further benefit from <sup>80</sup> developments at the LHC and RHIC such as jet reclustechniques [23, 24] which can test QCD factorization [25], probe TMD evolution effects [26, 27] and explore novel hadronization effects [28, 29].

- At RHIC, the first and the only polarized proton-proton 85 collider, the STAR collaboration pioneered the use of jets for TMD studies. In particular, measurements of the azimuthal asymmetries of hadrons with respect to the jet axis in transversely polarized proton-proton col-
- so lisions  $(pp^{\uparrow})$  probe the Collins fragmentation functions and the collinear transversity distribution [9]. As shown in [10, 30], the in-jet dynamics or the final state TMD FFs is decoupled from the purely collinear initial state, which provides direct constraints for the Collins TMD FF. The

- 95 STAR data agree with theoretical predictions [10] that rely on transversity functions extracted from SIDIS and  $e^+e^-$  data. The current precision of STAR measurements does not allow for clear tests [10] of TMD evolution effects
- Previous work on EIC projections of TMD measure-100 ments focused mainly on SIDIS observables involving either single hadrons or di-hadrons as well as charmed mesons to access gluon TMDs [15, 31, 32]. The feasibility of a gluon Sivers function measurement with di-jets from
- 105 photon-gluon fusion process at the EIC was explored in Ref. [33].

In this work, we consider the process in Eq. (1) in transversely polarized electron-proton collisions, which probes the quark Sivers function, the transversity distribution, 110 and the Collins fragmentation functions. We present the first prediction of hadron-in-jet asymmetries at the EIC. In addition, we estimate the precision of EIC data compared to the predicted asymmetries. We use parametrized detector simulations to estimate resolution effects and dis-115 cuss requirements for the EIC detectors.

This paper is organized as follows. First we introduce the perturbative QCD framework in Section II. We then describe the PYTHIA8 simulations used for this study in Section III. In Section IV, we present predictions and 120 statistical projections. We discuss jet kinematics as well as detector requirements in Section V and we conclude in Section VI.

#### PERTURBATIVE QCD FRAMEWORK II.

We consider both Sivers and Collins asymmetries at final state TMD dynamics contribute but they can be 125 the EIC which can be accessed through jet-based measurements. At parton level, we consider the leading-order DIS process  $eq \rightarrow eq$ . We consider the cross section differential in the electron rapidity  $y_e$  and transverse momentum  $p_T^e$ , which is defined relative to the beam direction tering with a recoil-free jet axis [21, 22] or jet grooming 130 in the laboratory frame. The leading-order cross section can be written as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_e\,\mathrm{d}^2\vec{p}_T^{\,e}} = \sigma_0 \sum_q e_q^2 f_q(x,\mu)\,,\tag{2}$$

where the scale is chosen at the order of the hard scale of the process  $\mu \sim p_T^e = |\vec{p}_T^e|$ . The prefactor  $\sigma_0$  is given by

$$\sigma_0 = \frac{\alpha \alpha_s}{sQ^2} \frac{2(\hat{s}^2 + \hat{u}^2)}{\hat{t}^2} \,. \tag{3}$$

The Bjorken x variable can be expressed as:

$$x = \frac{p_T^e e^{y_e}}{\sqrt{s - p_T^e e^{-y_e}}} \,. \tag{4}$$

Also the partonic Mandelstam variables in Eq. (3) can be expressed in terms of the kinematical variables of the electron and the center-of-mass energy. We have

$$\hat{s} = xs \,, \tag{5}$$

$$\hat{t} = -Q^2 = -\sqrt{s} \, p_T^e e^{y_e} = -x\sqrt{s} \, p_T^{\text{jet}} e^{-y_{\text{jet}}} \,, \qquad (6)$$

$$\hat{u} = -x\sqrt{s} \, p_T^e e^{-y_e} = -\sqrt{s} \, p_T^{\text{jet}} e^{y_{\text{jet}}} \,, \tag{7}$$

<sup>135</sup> where  $p_T^{\text{jet}}$  and  $y_{\text{jet}}$  denote the jet transverse momentum and rapidity, respectively. From Eq. (6), we see that a cut on  $Q^2$  translates to an allowed range of the observed  $p_T^e, y_e$ . The event inelasticity y, can be written as

$$y = 1 - \frac{p_T^e}{\sqrt{s}} e^{-y_e},$$
 (8)

which is an important quantity for experimental consid-140 erations as discussed below.

### The Sivers asymmetry and electron-jet Α. decorrelation

To access TMD dynamics we study back-to-back electron-jet production,

$$e + p(\vec{s}_T) \to e + \text{jet}(\vec{q}_T) + X$$
, (9)

where we require a small imbalance  $q_T = |\vec{p}_T^e + \vec{p}_T^{\text{jet}}| \ll p_T^e \sim p_T^{\text{jet}}$  [14]. For an incoming transversely polarwith the imbalance momentum  $\vec{q}_T$ , which leads to a  $\sin(\phi_s - \phi_q)$  modulation of the electron-jet cross section. Using TMD factorization in Fourier transform space, the cross section is

$$\frac{\mathrm{d}\sigma(\vec{s}_T)}{\mathrm{d}\mathcal{PS}} = F_{UU} + \sin(\phi_s - \phi_q) F_{UT}^{\sin(\phi_s - \phi_q)}, \qquad (10)$$

where  $d\mathcal{PS} = dy_e d^2 \vec{p}_T^e d^2 \vec{q}_T$ . The Sivers asymmetry is then given by

$$A_{UT}^{\sin(\phi_s - \phi_q)} = \frac{F_{UT}^{\sin(\phi_s - \phi_q)}}{F_{UU}} \,. \tag{11}$$

The unpolarized differential cross section for electron-jet production can be written as

$$F_{UU} = \sigma_0 H_q(Q,\mu) \sum_q e_q^2 J_q(p_T^{\text{jet}} R,\mu) \\ \times \int \frac{\mathrm{d}^2 \vec{b}_T}{(2\pi)^2} e^{i \vec{q}_T \cdot \vec{b}_T} f_q^{\mathrm{TMD}}(x, \vec{b}_T, \mu) S_q(\vec{b}_T, y_{\text{jet}}, R, \mu) ,$$
(12)

where  $H_q$  is the hard function taking into account virtual corrections at the scale Q. The jet function  $J_q$  takes 145 into account the collinear dynamics of the jet formation which depends on the jet algorithm and the jet radius. Throughout this work we use the anti- $k_T$  algorithm [34] and R = 1. The quark TMD PDF  $f_q^{\text{TMD}}$  includes the appropriate soft factor to make it equal to the one that 150 appears in the SIDIS factorization. The remaining soft function  $S_q$  includes the contributions from the global soft function which depends on Wilson lines in the beam and jet direction, as well as the collinear-soft function that takes into account soft radiation along the jet direc-155 tion. We summarize the fixed order results for the different function in the appendix A. In addition, we include non-global logarithms [35] to achieve next-to-leading logarithmc (NLL') accuracy. See also Refs. [14, 16, 36, 37] for more details.

The Sivers structure function  $F_{UT}^{\sin(\phi_s - \phi_q)}$  can be obtained from Eq. (12) by replacing the unpolarized TMD PDF  $f_q^{\text{TMD}}$  with the quark Sivers distribution  $f_{1T}^{\perp q}$  in the momentum space and by performing the corresponding Fourier transform to  $b_T$ -space

$$f_q(x,k_T) \to \frac{1}{M} \epsilon_{\alpha\beta} \, s_T^{\alpha} \, k_T^{\beta} \, f_{1T}^{\perp q}(x,k_T) \,, \qquad (13)$$

160 where M is the mass of the incoming proton. The remaining soft function  $S_a$  is the same in the polarized and unpolarized case. Therefore, its nonperturbative contributions largely cancel in the Sivers asymmetry in Eq. (11). In addition, the nonperturbative contribution of  $S_q$  is expected ized proton, the transverse spin vector  $\vec{s}_T$  is correlated 165 to be subleading compared to the TMD PDF. Final state hadronization effects are also expected to be small for the jet radius of R = 1, which we choose for our numerical results presented below. The numerical size of the nonglobal logarithms is relatively small in the unpolarized 170 case  $\mathcal{O}(< 4\%)$  and is expected to largely cancel out for the asymmetries we consider below. Therefore, we expect that the cross section here provides a very clean handle on the quark TMD Sivers function.

#### в. The Collins asymmetry and jet substructure

Next, we consider the measurement of hadrons inside jets which is sensitive to the Collins TMD FF in the polarized case. In back-to-back electron-jet production, we now also include the hadron distribution inside the jet,

$$e + p(\vec{s}_T) \rightarrow e + (\operatorname{jet}(\vec{q}_T) h(z_h, \vec{j}_T)) + X.$$
 (14)

Here we consider both the longitudinal momentum fraction  $z_h = \vec{p}_T^h \cdot \vec{p}_T^{\text{jet}} / |\vec{p}_T^{\text{jet}}|^2$  and the transverse momentum  $\vec{j}_T = \vec{p}_T^h \times \vec{p}_T^{\text{jet}} / |\vec{p}_T^{\text{jet}}|^2$  of the hadron with respect

to the jet axis. In this case, the spin-vector  $\vec{s}_T$  of the incoming proton correlates with  $j_T$ , which leads to a  $\sin(\phi_s - \phi_h)$  modulation usually referred to as Collins asymmetry for hadron in-jet production. Following the work of [5, 10, 17, 18, 30, 38-40], the relevant cross section can be written as

$$\frac{\mathrm{d}\sigma^h(\vec{s}_T)}{\mathrm{d}\mathcal{P}\mathcal{S}\,\mathrm{d}z_h\,\mathrm{d}^2\vec{j}_T^{\,h}} = F_{UU}^h + \sin(\phi_s - \phi_h)F_{UT}^{\sin(\phi_s - \phi_h)}\,, \quad (15)$$

where  $\phi_s$  is the azimuthal angle of the transverse spin of the incoming proton relative to the reaction plane and  $\phi_h$ is the azimuthal angle of the hadron inside the jet. The Collins asymmetry for hadron in-jet is then given by

$$A_{UT}^{\sin(\phi_s - \phi_h)} = \frac{F_{UT}^{\sin(\phi_s - \phi_h)}}{F_{UU}^h} \,. \tag{16}$$

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 $10^{34} \text{ cm}^{-2} \text{s}^{-1}$ .

production is given by

$$F_{UU}^{h} = \sigma_{0} H_{q}(Q,\mu) \sum_{q} e_{q}^{2} \mathcal{G}_{q}^{h}(z_{h},\vec{j}_{T},p_{T}^{\text{jet}}R,\mu)$$

$$\times \int \frac{\mathrm{d}^{2}\vec{b}_{T}}{(2\pi)^{2}} e^{i\vec{q}_{T}\cdot\vec{b}_{T}} f_{q}^{\mathrm{TMD}}(x,\vec{b}_{T},\mu) S_{q}(\vec{b}_{T},y_{\text{jet}},R,\mu) .$$
(17)

captures the dependence on the jet substructure measurement. It replaces the jet function  $J_q$  in Eq. (12) and satisfies the same renormalization group evolution equation.

At the jet scale  $p_T^{\text{jet}} R$ , up to NLL we can write  $\mathcal{G}_q^h$  in 180 Fourier space as

$$\mathcal{G}_{q}^{h}(z_{h}, \vec{j}_{T}, p_{T}^{\text{jet}}R) = \int \frac{\mathrm{d}^{2}\vec{b}_{T}'}{(2\pi)^{2}} e^{i\vec{j}_{T}\cdot\vec{b}_{T}'/z_{h}} D_{h/q}^{\mathrm{TMD}}(z_{h}, \vec{b}_{T}', p_{T}^{\text{jet}}R) \,.$$
(18)

included the proper soft function to make it equal to the standard TMD FFs as probed in SIDIS and/or in back-to-185 back dihadron production in  $e^+e^-$  annihilation. We use the Fourier variable  $\vec{b}'_T$  to indicate that this integration is 220 entire  $Q^2$  range is considered. independent of the TMD PDF in Eq. (17).

The spin-dependent structure function  $F_{UT}^{\sin(\phi_s-\phi_h)}$  is obtained from Eq. (17) by replacing the unpolarized TMD the unpolarized TMD FF  $D_{h/q}$  with the Collins TMD fragmentation function  $H_1^{\perp q}$ , and using the appropriate polarized cross section  $\sigma_0^{\text{Collins}}$ . We thus have

$$f_q(x,k_T) \to h_1^q(x,k_T) , \qquad (19)$$

$$D_{h/q}(z_h, j_T) \to \frac{j_T}{z_h M_h} H_{1h/q}^{\perp}(z_h, j_T) , \qquad (20)$$

$$\sigma_0 \to \sigma_0^{\text{Collins}} = \frac{\alpha \alpha_s}{sQ^2} \frac{4\hat{s}\hat{u}}{-\hat{t}^2} \,, \tag{21}$$

where  $M_h$  is the mass of the observed hadron in the jet. See Ref. [10] for more details.

#### SIMULATION III.

We use simulations to explore the kinematic reach and statistical precision subject to the expected acceptance of EIC experiments, as well as to estimate the impact of the detector resolution. We use PYTHIA8 [42] to generate The unpolarized structure function  $F_{UU}^h$  for hadron in-jet 195 neutral-current DIS events in unpolarized electron-proton collisions, see Fig. 1. PYTHIA8 uses leading-order matrix elements matched to the DIRE dipole shower [43], and subsequent Lund string hadronization. For consistency with the calculations presented in Section II, we do not <sup>200</sup> include QED radiative corrections in the simulation.

We set the energies of the electron and proton to 10 GeV and 275 GeV, respectively. These beam energy values, which yield a center-of-mass energy of  $\sqrt{s} = 105$  GeV, correspond to the operation point that maximizes the lu-175 Here  $\mathcal{G}_q^h$  is a TMD fragmenting jet function [41] which 205 minosity in the eRHIC design [44]. We consider yields that correspond to an integrated luminosity of  $100 \text{ fb}^{-1}$ , which can be collected in about a year of running at

> We select events with  $Q^2 > 25 \text{ GeV}^2$  and 0.1 < y < 0.1210 0.85. The lower elasticity limit avoids the region where the experimental resolution of the DIS kinematic variables x and  $Q^2$  diverges and the upper limit avoids the phase space in which QED radiative corrections are significant.

We do not simulate jet photo-production, which is a Here  $D_{h/q}^{\text{TMD}}$  is the unpolarized TMD FF evaluted at the <sup>215</sup> negligible contribution at high  $Q^2$  [45, 46]. By lowering  $Q^2$  and including photo-production, the jet rate would increase but at the cost of sensitivity to photon PDFs [32]. See for example Refs. [47, 48] for EIC studies of jets in photo-production events and Refs. [45, 49, 50] where the

We use the FASTJET3.3 package [51] to cluster jets with the anti- $k_T$  algorithm and radius parameter R = 1.0. HERA studies showed that such a large value of R reduced hadronization corrections for inclusive jet spectra PDF  $f_q$  with the TMD quark transversity distribution  $h_1^q$ ,  $_{225}$  to the percent level [52]. The input for the jet clustering algorithm are stable particles that have transverse momentum  $p_T > 100$  MeV and pseudorapidity  $|\eta| < 4.0$  in



Figure 2. Yield of electrons and jets, and mean x as a function of the transverse momentum in the laboratory frame. The jets 265 were reconstructed with the anti- $k_T$  algorithm [34] and R = 1. The red error bars represent the standard deviation of the xdistribution for each electron  $p_T$  interval.

the laboratory frame<sup>1</sup>, excluding neutrinos and the scattered electron<sup>2</sup>.

Unlike most projection studies for the EIC, we do not 230 use the Breit frame but instead the laboratory frame. 270 This approach was advocated for by Liu et al. [14] in order to have a close connection to results from hadron colliders, such as dijet studies [7, 53]. As discussed in Ref. [54],

235 this is not a trivial change of reference frame because a low  $p_T$  threshold would suppress most of leading-order DIS events (called "quark-parton model background" in 275 most HERA jet studies [52]).

We impose a minimum cutoff of 5 GeV for both the 240 electron and jet to ensure a reasonable prospect of reconstruction efficiency as well as to provide a scale to control perturbative QCD calculations.

Figure 2 shows the differential yield of electrons and jets and the probed average x value as a function of  $p_T$  in 245 the lab frame. The yield of electrons and jets are similar at high  $p_T$ , as expected from leading-order DIS, whereas or out-of-jet emission, and hadronization effects. We have

verified that the PYTHIA8 cross section is within 5% of <sup>250</sup> next-to-next-to-leading order pQCD calculations [45, 46], which is sufficient for our estimates.

The sea-quark dominated region is probed with low $p_T$  jets,  $x \approx 0.05$  at  $p_T \approx 7$  GeV. The valence region, x > 0.1, is reached with  $p_T \sim 15$  GeV and the region 255 x > 0.3, which remains unconstrained for transverselypolarized collisions [55], is probed with  $p_T > 25$  GeV.

While  $100 \text{ fb}^{-1}$  of integrated luminosity would provide more than enough statistics for precise cross section measurements over the entire  $p_T$  range, the high luminosity 260 will be critical for for multi-dimensional measurements and to constrain the small transverse-spin asymmetries expected for EIC kinematics, as we show in the next section.

### IV. NUMERICAL RESULTS AND STATISTICAL PROJECTIONS

In this section, we present numerical results using the theory framework presented above and we estimate the statistical precision of future measurements at the EIC.

### Α. Unpolarized production of jets and jet substructure

Before we present the results for the asymmetry measurements, we first compare our numerical results for jets and jet substructure in unpolarized electron-proton collisions with Pythia8 simulations.

We start with the jet production results. Figure 3 shows the normalized distribution of the transverse momentum  $q_T$  for jets produced in unpolarized electronproton collisions. We integrate over the event inelasticity 0.1 < y < 0.85 and electron transverse momentum 280  $15 < p_T^e < 20$  GeV. The distribution shows the expected Gaussian-like behavior at small values of  $q_T$ , which is driven by the TMD PDF and soft gluon radiation, and a tail to high values of  $q_T$ , which is driven by perturbative QCD radiation (i.e. TMD evolution in our theoretical they differ at low  $p_T$  due to parton branching processes 285 framework). We observe a reasonable agreement with the PYTHIA8 results. Note that in this work we are primarily interested in uncertainties due to current extractions of the TMD PDFs and FFs. Therefore, we do not include uncertainty estimates due to QCD scale variations.

> We now turn to the jet substructure results, for which 290 we impose a selection  $q_T/p_T^{\rm jet} < 0.3$  to ensure the applicability of the TMD framework. Fig. 4 shows the hadron-injet distributions as a function of  $z_h$  integrated over  $j_T$ , as well as the  $j_T$  distribution integrated over  $0.1 < z_h < 0.5$ .

<sup>&</sup>lt;sup>1</sup> Throughout this paper, we follow the HERA convention to define the coordinate system. The z direction is defined along the proton beam axis and the electron beam goes toward negative z. The polar angle  $\theta$  is defined with respect to the proton (ion) direction.

 $<sup>^{2}</sup>$  We identify the scattered electron as the electron with the largest  $p_T$  in the event.



Figure 3. Normalized distribution of the transverse momentum broadening  $q_T$  for jets produced in unpolarized electronproton collisions. We integrate over the event inelasticity 0.1 <y < 0.85 and electron transverse momentum  $15 < p_T^e < 20$ GeV.

295 We use the DSS fit of the collinear FFs of Ref. [56], while the TMD parametrization is taken from Ref. [57]. We observe very good agreement for the  $z_h$  distribution with the PYTHIA8 simulation, and reasonable agreement for the  $j_T$  distribution. In the absence of experimental data, 300 this check provides confidence in our theoretical frame- 345

work.

#### в. Spin asymmetries

We are now going to study spin asymmetries in the collisions of electrons and transversely polarized protons. 305 Given that most of the systematic uncertainties cancel in the asymmetry measurements, statistical uncertainties will likely dominate the total uncertainties. We estimate the impact of detector resolution and other requirements in Section V.

- 310 To estimate the statistical uncertainties of the asymmetry measurements we assume an integrated luminosity of  $100 \text{ fb}^{-1}$  and an average proton beam polarization of 70%, following the EIC specifications of Ref. [15]. We also assume a conservative value of 50% for an overall efficiency
- reconstruction for electrons and jets. For small values of the asymmetry, the absolute statistical uncertainty can be approximated as  $\delta A \approx 1/(\sqrt{N}p)$ , with p the average nucleon polarization and N the yield summed over polar-

320 ization states. For the Collins asymmetry, we also include a penalty factor of  $\sqrt{2}$ , which arises from the statistical extraction of simultaneous modulations in the hadron azimuthal distribution [31]. We also estimate the increase of statistical uncertainty due to "dilution factors" caused 325 by smearing in either the Sivers angle (azimuthal direction of the  $q_T$ ) or the Collins angle (azimuthal direction of  $\vec{j_T}$ ; these are described in Section V.

### 1. Electron-jet azimuthal correlations

We start with the Sivers asymmetry which is accessed 330 through the measurement of the electron-jet correlation. Fig. 5 shows numerical results for the Sivers asymmetry  $A_{UT}^{\sin(\phi_s-\phi_q)}$  in Eq. (11) including an uncertainty band according to the extraction of Ref. [58]. In addition, we show the projected statistical uncertainty of the Sivers asym-335 metry measurement as a function of  $q_T/p_T^{\rm e}$ . We integrate again over  $15 < p_T^e < 20$  GeV and 0.1 < y < 0.85, and thus the probed x range for the quark Sivers function is integrated over. The theoretical uncertainty is calculated solely based on the uncertainty of the extracted quark Sivers function [58] from current SIDIS measurements. The projected statistical uncertainty is much smaller than the theoretical uncertainty, which implies that the EIC jet measurements will help to constrain better the quark Sivers function.

- While most systematic uncertainties cancel in the ratio of the asymmetry, including jet-energy scale and jetenergy resolution uncertainties, the differential measurement of the Sivers asymmetry demands resolution on the  $q_T/p_T^e$  measurement. We address this issue in Section V.
- The hard scale at which the jet-based Sivers measure-350 ment can be performed is much closer to analogous Drell-Yan measurements at RHIC [59]. This eliminates possible issues related to TMD evolution effects which would help confirm the sign-change of the Sivers function between 355 SIDIS and Drell-Yan reactions [60–62].

#### 2.Hadron-in-jet asymmetries

Next, we are going to study the Collins asymmetry via the distribution inside the jet. Figure 6 shows the projected precision for three x intervals: 0.05 < x < 0.1, 315 due to the trigger efficiency, data quality selection, and 360 0.15 < x < 0.2, and 0.30 < x < 0.80, along with our theoretical calculations for the in-jet Collins asymmetry for  $\pi^+$  and  $\pi^-$  as a function of  $z_h$ . The projected precision assumes a fully-efficient identification for  $\pi^{\pm}$  with negligible misidentification with other hadron species; we discuss



Figure 4. Theoretical (orange line) and PYTHIA8 (blue histogram) calculations for the longitudinal  $z_h$  (left panel) and transverse  $j_T$  (right panel) momentum distributions of charged hadrons inside jets at the EIC. The results shown here are for the unpolarized case.



Figure 5. Theoretical result for the electron-jet asymmetry sensitive to the Sivers distribution (red). The uncertainty band (orange) displays the current uncertainty of the Sivers function of Ref. [58]. In addition, we show projections of statistical uncertainties for an EIC measurement (black error bars).

<sup>305</sup> the requirements for particle-identification systems in Section V. The theory uncertainty bands are obtained from <sup>390</sup> the quark transversity and Collins fragmentation functions extracted in Ref. [57]. The extraction from Ref. [57] is based on a simultaneous fit of the SIDIS Collins asym<sup>370</sup> metry and the Collins asymmetry in back-to-back hadron

pair produced in  $e^+e^-$  collisions. The projected statistical uncertainties at the EIC are much smaller than the uncertainties obtained from current extractions. Therefore, future in-jet Collins asymmetry measurements at the **375** EIC will provide important constraints on both the quark transversity and the Collins fragmentation functions.

The region x < 0.1 (relevant to sea quarks) is not well known from current SIDIS measurements. The measurements at the EIC will provide excellent constraining power for the sea-quark distribution. The projected uncertainties in the valence-dominated region are larger, but still provide enough sensitivity compared to the predicted asymmetries. These measurements will complement future measurements from SoLID [63] and the STAR [64] see experiment.

Impact studies of the projected EIC data on quark transversity, similar to Ref. [65], are are beyond the scope of this work but will be addressed in future publications.

### V. DETECTOR PERFORMANCE

In this section, we estimate the detector performance for electron-jet and hadron-in-jet measurements. The measurement of the scattered electron defines the inclusive DIS measurement and has been discussed in detail [66], so we concentrate on jets.



Figure 6. Projection of statistical uncertainties (black error bars) for the  $z_h$  distribution for the  $\pi^{\pm}$ -in-jet Collins asymmetries as well as theoretical predictions (blue, orange). The displayed theoretical uncertainties (orange and blue bands) are based on the extraction of Ref. [57]. The horizontal error bar represents a jet-energy scale uncertainty of 3%.

### A. Jet kinematics

Figure 7 shows the momentum and pseudorapidity distribution of electrons (upper half plane), the struck-quark and jets (lower half plane). The jet distribution matches the struck-quark kinematics to a remarkable degree. The <sup>400</sup> polar plot on the right includes initial and final state radiation, hadronization and the beam remnants.

For this very asymmetric beam energy configuration (10 GeV electron and 275 GeV proton) jets are predominantly produced around  $\eta \approx 1.5$ . The larger the x of the 405 event, the more forward is the jet. While some of the jets are at mid-rapidity  $(-1.0 < \eta < 1.0)$ , they are predominantly produced in the challenging region between the that large-R jets are preferred to minimize hadronization 410 corrections associated with the jet clustering algorithm, this will impose a challenge for the detector design. While acceptance gaps and dead material due to services are inacceptance of large-x events, which is where the Sivers 415 and transversity functions have maximums. Gaps in acceptance, particularly in calorimeters, would lead to a mis-measurement of the jet energy that would make re-(event generator) and detector effects (detailed geometry 420 and material description).

### B. Fast simulations

We use the DELPHES package of Ref. [67] for fast detector simulations. We consider the geometry of a generalpurpose collider detector: tracking, electromagnetic and <sup>425</sup> hadronic calorimeters with hermetic coverage in pseudorapidity up to  $|\eta| = 4$  and full azimuthal coverage. The parametrization of momentum and energy resolutions used as input for DELPHES are shown in Table I. These values closely follow the requirements for a general-<sup>430</sup> purpose detector at the EIC [66], and are the same as used in Ref. [68]. While these parameters are preliminary and subject to change given ongoing studies, they are a reasonable choice for our feasibility studies.

inantly produced in the challenging region between the barrel and endcap of a typical collider detector. Given that large-R jets are preferred to minimize hadronization corrections associated with the jet clustering algorithm, this will impose a challenge for the detector design. While acceptance gaps and dead material due to services are inevitable, they should be limited to not compromise the acceptance of large-x events, which is where the Sivers and transversity functions have maximums. Gaps in ac-

ceptance, particularly in calorimeters, would lead to a mis-measurement of the jet energy that would make require corrections sensitive to modeling of hadronization 445 of the sPHENIX hadronic calorimeter [70], which is cur-(event generator) and detector effects (detailed geometry and material description). Table II shows the granularity used in the DELPHES simulation. At mid rapidity, the granularity follows that rently under construction. In the forward rapidity region  $(1.0 < |\eta| < 4.0)$ , we consider a granularity that roughly



Figure 7. The top half of each circle shows the pseudorapidity and 3-momentum of the scattered electron in the angular and radial direction, respectively. The bottom half of each circle shows the pseudorapidity and momentum of the struck-quark (left) and jets (right). The jets were reconstructed with the anti- $k_{\rm T}$  algorithm and R = 1.0.

Table I. Momentum and energy resolution parametrization
used as input for the DELPHES fast simulations. These fol-
low closely the baseline for an EIC general-purpose detector
in Ref. [66].

Tracker, $dp/p$	$0.5\% \oplus 0.05\% \times p$ for $ \eta  < 1.0$
	$1.0\%  \oplus  0.05\%{\times}p$ for $1.0 <  \eta  < 2.5$
	$2.0\% \oplus 0.01\%{\times}p$ for $2.5 <  \eta  < 3.5$
EMCAL, $dE/E$	$2.0\%/\sqrt{E}$ $\oplus$ 1% for $-3.5 {< \eta <} 2.0$
	$7.0\%/\sqrt{E}$ $\oplus$ 1% for $-2.0 {< \eta < -1.0}$
	$10.0\%/\sqrt{E} \oplus 2\%$ for $-1.0 < \eta < -1.0$
	$12\%/\sqrt{E}$ $\oplus$ 2% for 1.0< $\eta$ <3.5
HCAL, $dE/E$	$100\%/\sqrt{E} \oplus 10\%$ for $ \eta  < 1.0$
	$50\%/\sqrt{E}$ $\oplus$ 10% for 1.0< $ \eta $ <4.0

corresponds to  $10 \times 10$  cm<sup>2</sup> towers positioned at 3.5 m; 450 nology [71]. No longitudinal segmentation is considered for the calorimeters, as it is currently beyond the scope of Delphes.

radians) used as input for the DELPHES fast simulations.

EMCAL	$0.020 \times 0.020$ for $ \eta  < 1.0$
	$0.020 \times 0.020$ for for 1.0< $ \eta $ <4.0
HCAL	$0.100 \times 0.100$ for $ \eta  < 1.0$
	$0.025 \times 0.025$ for $1.0 <  \eta  < 4.0$

The calorimetric energy thresholds are set to 200 MeV for the EMCAL and 500 MeV for the HCAL, which is 455 possible for the expected noise levels [71]. A minimum significance,  $E/\sigma(E) > 1.0$ , is required. A minimum track  $p_T$  of 200 MeV is considered. The tracking efficiency is assumed to be 100% with negligible fake rate.

DELPHES simulates the bending of charged particles in 460 a solenoidal field, which is set to 1.5 T. The volume of the magnetic field is assumed to cover a radius of 1.4 m and a half-length of 1 m, which roughly follows the dimensions of the BaBar solenoid magnet that is currently being used for the sPHENIX detector [72].

Jets are reconstructed using DELPHES particle-flow ob-465 jects as inputs to the anti- $k_T$  algorithm [34] with R = 1.0implemented in FASTJET [51]. Given the relatively low energy of jets at the EIC and the superior tracking momentum resolution over the HCAL energy resolution, jets the tower size follows the STAR forward calorimeter tech- 470 reconstructed with purely calorimetry information yield worse performance and are not considered here.

Figure 8 shows an event display for a neutral-current DIS event reconstructed with the detector geometry described above. The signal for our studies is an iso-Table II. Calorimeter granularity parameters ( $\Delta \eta \times \Delta \phi$ , in 475 lated electron and a jet back-to-back in the transverse plane. The displayed event is representative for the particle multiplicity expected in high- $Q^2$  DIS events at the EIC [54, 73]. Very clean jet measurements will be possible given that underlying event and pileup will be negligible. 480 As shown in Ref. [54], the average number of particles in

jets ranges from about 5 at  $p_T^{\text{jet}} = 5$  GeV to about 12 at



Figure 8. Left: event display showing a general-purpose EIC detector implemented in DELPHES and a neutral-current DIS event at 105 GeV center-of-mass energy. Charged-particles are shown in green, hits in the electromagnetic calorimeter in red, hits in the hadronic calorimeter in blue. Right panel: event display with electron and jet in the back-to-back configuration studied in this work.

 $p_T^{\text{jet}} = 25 \text{ GeV}.$ 

Jet performance is estimated by comparing jets "at the generator level" and at the "reconstructed level". 485 The input for the jet clustering at the generator level are final-state particles in PYTHIA8, whereas the input for the reconstructed level are particle-flow objects from DELPHES. Reconstructed jets are matched to the generated jets with an angular distance selection of  $\Delta R$  = 490  $\sqrt{(\phi_{\rm jet}^{\rm gen} - \phi_{\rm jet}^{\rm reco})^2 + (\eta_{\rm jet}^{\rm gen} - \eta_{\rm jet}^{\rm reco})^2} < 0.3$ , which is fully efficient for for jets with  $p_T^{\text{jet}} > 10 \text{ GeV}$ .

Figure 9 shows the jet resolution, which is defined by a Gaussian fit to the relative difference between generated and reconstructed jet momentum. The resolution 495 is driven by the response of the calorimeters. The non-Gaussian tails of the detector response are quantified by comparing the jet energy resolution estimated by computing a standard deviation instead of the Gaussian fits. The difference is about 1-4%, which indicates that the 500 response matrix does not have large non-diagonal elements, which appear in detector designs that do not consider a hadronic calorimeter in the barrel region, as noted by Page et al. [73]. A diagonal response matrix (i.e. a Gaussian-like resolution) will enable accurate jet and 505 missing-transverse energy measurements.

Figure 10 shows the expected resolution on the 515 electron-jet azimuthal imbalance  $q_T$  normalized by  $p_T^e$ . This resolution informs the bin-widths presented in Figure 5 to ensure controllable bin-migration; we leave de-510 tailed unfolding studies for future work.

charged particles only, which would require to introduce



Figure 9. Relative energy resolution for jets produced in neutral-current DIS events. The jets are reconstructed with the anti- $k_T$  algorithm with R = 1.0 using DELPHES particleflow objects.

a track-jet function [74, 75] in the theoretical framework as done in Ref. [22].

We find that the resolution of the Sivers angle (azimuthal direction of the  $\vec{q_T}$  is about 0.3–0.45 radians depending on the jet energy. We use a Monte Carlo method to estimate the resulting "dilution factors" due to smearing on the amplitude of the sine modulation. We find A better resolution could be achieved defining  $q_T$  with 520 multiplicative factors of about 1.03, which is negligible

for the purposes of this study.



Figure 10. Absolute resolution for the normalized electronjet imbalance,  $q_T/p_T^e$ , as a function of at the generated jet energy. The jets are reconstructed with the anti- $k_T$  algorithm with R = 1.0 using Delphes particle-flow objects.

The resolution of the Collins angle (azimuthal direction of  $\vec{j_T}$  is driven by the interplay between the hadron momentum and jet energy resolutions; however, the jet 525 energy resolution always dominates for EIC energies (for the tracking resolution shown in Table I). Depending on the  $z_h$ , the relative resolution on the Collins angle ranges from 0.06 to 0.25 rad for  $20 < E^{\text{jet}} < 30$  GeV, from 0.05 to 0.20 rad for  $30 < E^{\text{jet}} < 40$  and from 0.05 to 0.10 530 rad for  $40 < E^{\text{jet}} < 50$ . These resolutions compare favorably to the performance achieved in the hadron-in-jet measurements by STAR in both the charged-pion channel [76] and neutral-pion channel [77]. We find that the associated "dilution factors" are negligible.

535

#### Particle ID requirements С.

The hadron-in-jet measurement requires particle idencritical for the interpretation of the data in terms of the Collins FF and quark transversity. While DELPHES does 540 have the capability of emulating PID detectors, we do not

- use that feature as estimates for a momentum-dependent study that illuminates the PID requirements for the studies presented in Section IV B 2.
- Figure 11 shows the momentum and pseudorapdity dis-545 tribution of charged pions in jets for events with 0.1 <



Figure 11. Pseudorapidity and momentum distribution for charged-pions in jets with  $p_T > 5$  GeV. The average longitudinal momentum fraction of the hadron with respect to the jet axis is shown by the red dots.

momentum interval. Positive particle identification of pions up to  $\approx$  40 GeV at  $\eta$   $\approx \! 1.5 \! - \! 2.0$  is required to reach 550  $z_h \approx 0.8$ . Smaller x ranges yield smaller jet momentum and thus less stringent requirements.

#### Systematic uncertainties D.

Most sources of systematic uncertainties in jet measurements, including jet energy scale (JES) and jet en-<sup>555</sup> ergy resolution (JER) uncertainties, cancel in the spin asymmetry ratios. Time drifts in the detectors response can be suppressed to a negligible level with the bunchto-bunch control of the beam polarization pioneered at RHIC, which will transfer to EIC.

While the JES uncertainty does not affect the scale of 560 the asymmetry, it affects the definition of  $z_h$  (jet momentum appears in the denominator) or  $q_T$  (proportional to jet momentum), so it translates on a horizontal uncertainty in the differential asymmetry measurements. We tification (PID) to provide the flavour sensitivity that is 565 show that a conservative estimate of 3% for JES uncertainty would still allow us to sample the predicted  $z_h$ dependence of the asymmetries shown in Fig 6 or the Sivers asymmetry shown in of Figure 5.

While the asymmetry measurements have the potenperformance is not yet available. Instead, we perform a 570 tial to be very accurate, the unpolarized cross section measurement will be much more challenging due to the JES uncertainty. HERA experiments ultimately achieved a JES uncertainty of about 1% [52], but there are several challenges for the EIC. The accelerator design that x < 0.2, as well as the average  $z_h$  value sampled in each 575 leads an improvement of the instantaneous luminosity compared to HERA requires focusing magnets closer to 625 jet capabilities from day one.

the interaction point. This limits the space for detectors, which will result in "thin" hadronic calorimeters that motivate the constant terms in Table I; this will also lead to 580 more difficult JES estimates.

cross sections is crucial to constrain nonperturbative aspects of TMD-evolution which is not only motivated by the need to understand the hadronization process itself

585 but ultimately improves the accuracy of the extractions of the Sivers function [58]. HERA data could play a crucial role for these studies.

Estimations of the jet energy scale uncertainty are notoriously difficult and involve several studies that cover

590 from beam-test data, in-situ calibrations, and Monte- 635 Carlo simulations (e.g. Ref. [78]), which are outside the scope of this work.

Systematic uncertainties that do not cancel in the asymmetry ratio are the ones associated with the rela-595 tive luminosity for each polarization state and the beam polarization. The relative luminosity uncertainty will be (< 0.1%), as demonstrated at RHIC. The relative uncertainty on the hadron polarization is expected to be <1%at the EIC. Given the absolute magnitude of the Sivers and Collins asymmetries we predict, neither of these uncertainties will be a limiting factor.

The systematic uncertainties associated to parton-tojet matching, which were dominant at low  $p_T^{\text{jet}}$  in Sivers 605 negligible given that high  $Q^2$  DIS is essentially free from the underlying event and matching is practically unambiguous (as illustrated in Figure 7).

#### VI. CONCLUSIONS

We have present predictions and projections of mea-610 surements of Sivers asymmetry with electron-jet azimuthal correlations and Collins asymmetry with hadronin-jet measurements at the EIC. In particular, we made the first prediction for Collins asymmetries for hadronsin-jet and argued that it will be a key way to access 615 quark transversity, Collins fragmentation functions and

their evolution.

We have explored the feasibility of these measurements based on fast simulations implemented with the DELPHES package and found that the expected performance of a

620 hermetic EIC detector with reasonable parameters is sufficient to perform these measurements. We have discussed detector requirements and suggested further studies to go along dedicated detector simulations to inform design of future EIC experiments, which we argue should include

While jet-based measurements of Sivers and transversity functions are powerful and novel ways to achieve some of the main scientific goals of the EIC, the potential of jets transcends these two examples. A promising case are While difficult, the measurement of the unpolarized 630 novel jet substructure studies for TMD studies, which we leave for future work. This work represents a new direction for the rapidly emerging field of jet studies for the future EIC [12-14, 25, 45, 48-50, 54, 68, 73, 79-112].

## CODE AVAILABILITY

The Delphes configuration file for the EIC generalpurpose detector considered in this work can be found at: https://github.com/miguelignacio/delphes\_EIC/ blob/master/delphes\_card\_EIC.tcl

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## Appendix A: Relevant perturbative results at one-loop

Here we summarize the different functions that appear in the factorization formulas in Eqs. (12) and (17). We work in Fourier transform space where all the associated renormalization group equations are multiplicative. They can be derived from the fixed order result along with the relevant anomalous dimensions. In the unpolarized case we have

$$H_q(Q,\mu) = 1 + \frac{\alpha_s}{2\pi} C_F \left[ -\ln^2 \left(\frac{\mu^2}{Q^2}\right) - 3\ln\left(\frac{\mu^2}{Q^2}\right) - 8 + \frac{\pi^2}{6} \right],$$
 (A1)

$$J_q(p_T R, \mu) = 1 + \frac{\alpha_s}{2\pi} C_F \left[ \frac{1}{2} \ln^2 \left( \frac{\mu^2}{p_T^2 R^2} \right) + \frac{3}{2} \ln \left( \frac{\mu^2}{p_T^2 R^2} \right) + \frac{13}{2} - \frac{3}{4} \pi^2 \right], \quad (A2)$$
$$S_q(\vec{b}_T, y_{\text{jet}}, R, \mu) = 1 + \frac{\alpha_s}{2\pi} C_F \left[ -\ln \left( \frac{e^{-2y_{\text{jet}}}}{R^2} \right) \ln \left( \frac{\mu^2}{\mu_b^2} \right) - \frac{1}{2} \ln^2 \left( \frac{1}{R^2} \right) \right], \quad (A3)$$

660 where  $\mu_b = 2e^{-\gamma_E}/b_T$ . The factorization here holds for  $R \sim \mathcal{O}(1)$ . Note that all  $\ln \mu$  terms cancel at fixed order.

The unpolarized TMD PDF and FF can be matched onto the collinear PDFs at low valued of  $b_T$  as

$$f_q^{\text{TMD}}(x_B, \vec{b}_T, \mu_b) \simeq \sum_i \int_{x_B}^1 \frac{dx}{x} C_{q \leftarrow i} \left(\frac{x_B}{x}, \mu_b\right) f_1^i(x, \mu_b),$$
(A4)

$$D_{h/q}^{\mathrm{TMD}}(z_h, \vec{b}_T, \mu_b) \simeq \sum_j \int_{z_h}^1 \frac{dz}{z} \, \hat{C}_{j \leftarrow q}\left(\frac{z_h}{z}, \mu_b\right) D_{h/j}(z, \mu_b).$$
(A5)

where [57, 113–115],

$$C_{q \leftarrow q'}(x, \mu_b) = \delta_{q'q} \Big[ \delta(1-x)$$

$$+ \frac{\alpha_s}{\pi} \left( \frac{C_F}{2} (1-x) - 2C_F \delta(1-x) \right) \Big],$$
(A6)
(A7)

$$C_{q \leftarrow g}(x, \mu_b) = \frac{\alpha_s}{\pi} T_R x(1-x) , \qquad (A8)$$

$$\hat{C}_{q' \leftarrow q}(z, \mu_b) = \delta_{q'q} \Big[ \delta(1-z) + \frac{\alpha_s}{\pi} \Big( \frac{C_F}{2} (1-z)$$
(A9)

$$-2C_F\delta(1-z) + P_{q\leftarrow q}(z)\ln z \bigg) \bigg], \quad (A10)$$

$$\hat{C}_{g\leftarrow q}(z,\mu_b) = \frac{\alpha_s}{\pi} \left( \frac{C_F}{2} z + P_{g\leftarrow q}(z) \ln z \right).$$
(A11)

with the usual splitting functions  $P_{q\leftarrow q}$  and  $P_{g\leftarrow q}$  given

by

$$P_{q \leftarrow q}(z) = C_F \left[ \frac{1+z^2}{(1-z)_+} + \frac{3}{2}\delta(1-z) \right], \qquad (A12)$$

$$P_{g \leftarrow q}(z) = C_F \frac{1 + (1 - z)^2}{z} .$$
 (A13)

The energy evolution of TMDs from the scale  $\mu_b$  to the scale Q is encoded in the exponential factor,  $\exp[-S_{sud}]$ , with the Sudakov-like form factor, the perturbative part of which can be written as

$$S_{\text{pert}}(Q,b) = \int_{\mu_b^2}^{Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} \left[ A(\alpha_s(\bar{\mu})) \ln \frac{Q^2}{\bar{\mu}^2} + B(\alpha_s(\bar{\mu})) \right] .$$
(A14)

Here the coefficients A and B can be expanded as a perturbative series  $A = \sum_{n=1}^{\infty} A^{(n)} (\alpha_s/\pi)^n$ ,  $B = \sum_{n=1}^{\infty} B^{(n)} (\alpha_s/\pi)^n$ . In our calculations, we take into account  $A^{(1)}$ ,  $A^{(2)}$  and  $B^{(1)}$  to achieve NLL accuracy. Because this part is spin-independent, these coefficients are the same for the polarized and unpolarized cross sections [116] and are given by [116–121]:

$$A^{(1)} = C_F ,$$
  

$$A^{(2)} = \frac{C_F}{2} \left[ C_A \left( \frac{67}{18} - \frac{\pi^2}{6} \right) - \frac{10}{9} T_R n_f \right] ,$$
  

$$B^{(1)} = -\frac{3}{2} C_F .$$
(A15)

In order to avoid the Landau pole  $\alpha_s(\mu_b)$ , we use the standard  $b_*$ -prescription that introduces a cutoff value  $b_{\max}$ and allows for a smooth transition from the perturbative for the nonperturbative region,

$$b_T \Rightarrow b_* = \frac{b_T}{\sqrt{1 + b_T^2/b_{\max}^2}},$$
 (A16)

where  $b_{\text{max}}$  is a parameter of the prescription. From the above definition,  $b_*$  is always in the perturbative region where  $b_{\text{max}}$  is typically chosen to be around 1 GeV<sup>-1</sup>. Using  $b_*$  in the Sudakov form factor, the total Sudakov-like or form factor can be written as the sum of the perturbatively calculable part and a nonperturbative contribution

$$S_{\text{sud}}(Q; b_T) \Rightarrow S_{\text{pert}}(Q; b_*) + S_{\text{NP}}(Q; b_T), \quad (A17)$$

where  $S_{\text{NP}}(Q; b_T) = S_{\text{NP}}^f(Q; b_T) + S_{\text{NP}}^D(Q; b_T)$  is defined as the difference between the original form factor and the perturbative one. Eventually, we have

$$f_q^{\text{TMD}}(x_B, \vec{b}_T, Q) = f_q^{\text{TMD}}(x_B, \vec{b}_T, \mu_b) \\ \times e^{-\frac{1}{2}S_{\text{pert}}(Q; b_*) - S_{\text{NP}}^f(Q; b_T)}$$
(A18)

$$D_{h/q}^{\text{TMD}}(z_h, \vec{b}_T, Q) = D_{h/q}^{\text{TMD}}(z_h, \vec{b}_T, \mu_b)$$
$$\times e^{-\frac{1}{2}S_{\text{pert}}(Q; b_*) - S_{\text{NP}}^D(Q; b_T)}$$
(A19)

In our calculations we use the prescriptions for the nonperturbative functions and the treatment of the Collins fragmentation and Sivers functions of Refs. [57, 58].

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