PROCEEDINGS OF SCIENCE

TMD program at JLab

Harut Avakian[a,*]

[a] *Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA*

E-mail: avakian@jlab.org

Measurements of multiplicities and asymmetries of multiparticle final states in wide kinematics, including dihadrons and vector mesons, will be crucial for a separation of different structure functions, and different contributions to specific structure functions, used in phenomenological studies of Semi-Inclusive DIS (SIDIS). Measurements of various beam Single Spin Asymmetries are discussed as a possible tool to separate different kinematical regions as well as different dynamical contributions. Precision measurements in JLab, including detailed studies of the Q^2 dependences of observables, would also allow testing the impact of several theoretical assumptions used in phenomenological studies of generalized PDFs (GPDs, TMDs) , also providing a mechanism for validation of the extraction frameworks, which is critical for the proper evaluation of systematic uncertainties.

25th International Spin Physics Symposium (SPIN 2023)
24-29 September 2023
Durham, NC, USA

*Speaker

https://pos.sissa.it/

PoS(SPIN2023)034

1. Introduction

Semi-inclusive deep inelastic scattering (SIDIS), where an electron scatters off a nucleon target at a high enough energy such that it can be described by scattering off a single parton in the target, emerged as a powerful tool for investigating nucleon structure and quark-gluon dynamics. Measurements of the SIDIS cross sections for various hadron production processes provide essential information about the underlying quark distributions and their interactions within the nucleon.

The quark-gluon dynamics manifests itself in a set of non-perturbative functions describing all possible spin-spin and spin-orbit correlations. Production of correlated hadron pairs plays an increasingly important role in the interpretation of pion electroproduction data in general, and hadronization process of quarks, in particular. More significant, than originally anticipated, fraction of pions coming from correlated di-hadrons, indicated by recent measurements at JLab, and supported by various realistic models describing the hadronization process, may have a significant impact on various aspects of data analysis, including the modeling, composition, and interpretation of semi-inclusive DIS data, as well as calculations of radiative corrections. In this contribution, we will present ongoing studies and some future measurements related to hadron transverse momentum distributions in SIDIS at Jefferson Lab.

In the one-photon exchange approximation, SIDIS reactions can be decomposed into contributions from 18 structure functions (SFs) [1] depending on combinations of beam and target polarizations. The SFs contain various convolutions of twist-2 or higher twist PDFs and fragmentation functions that are multiplied by specific kinematic pre-factors [1], each offering unique information about quark-gluon dynamics in the nucleon. In addition to the standard DIS kinematic variables x and Q^2, the SFs responsible for different azimuthal modulations in ϕ_h (azimuthal angle between hadronic and leptonic planes) and ϕ_S (azimuthal angle of the transverse spin), depend also on the fraction of the virtual photon energy carried by the final-state hadron, z, and its transverse momentum with respect to the virtual photon, P_T. The cross section for a longitudinally polarized beam and target can be expressed in a model-independent way by a subset of structure functions [1–4].

$$
\begin{aligned}
&\frac{d\sigma}{dx dQ^2 dz dP_T^2 d\phi_h} = \\
&\quad \frac{\pi\alpha^2}{x^2 Q^4}\frac{(2x+\gamma^2)}{(1+\gamma^2)}K(y)\Bigg\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\qquad + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\qquad + S_{\|}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\qquad + S_{\|}\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]\Bigg\}. \qquad (1)
\end{aligned}
$$

The subscripts in the structure functions (SFs) $F_{UU,LU,LL...}$, specify the beam (first index) and target (second index) polarization, U, L for the unpolarized and longitudinally polarized case, respectively, and λ and $S_{||}$ are longitudinal polarizations of the lepton and nucleon, and the elasticity $y = Q^2/2MxE_{beam}$. The depolarization factors represent the fraction of the initial electron polarization that is transferred to the virtual photon, which influences the virtual photon's polarization state and are described by the variable

$$K(y) = 1 - y + y^2/2 + \gamma^2 y^2/4, \qquad \varepsilon = \frac{1 - y - \frac{1}{4}\gamma^2 y^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}\gamma^2 y^2}, \qquad \gamma = 2Mx/Q \tag{2}$$

Phenomenological analyzes of SIDIS data require a complete understanding of the mechanism of hadron production in lepton-nucleon interactions in terms of QCD factorization theorems, including hadron production in the current fragmentation region (CFR), the target fragmentation region (TFR), and correlations between them (Sections 2,4). The complexity of the SIDIS reaction poses significant experimental challenges to isolate each SF from cross sections / asymmetries, since SFs have intricate kinematic dependencies, such as x, Q^2, and P_T. In particular, measuring each of these requires the full ϕ dependence of the reaction and, in some cases, the ϵ dependence, which defines the relative cross section contributions from longitudinal (σ_L) and transverse photons (σ_T). Separation of these contributions will be important for future phenomenological studies, in particular, for large hadronic transverse momenta, where theory is heavily based on the assumptions for dominance of the transverse photon contributions (Section 3). Moreover, their determination becomes increasingly difficult in the valence region at high energies, where certain SFs, such as helicity-dependent SFs sensitive to longitudinal spin-dependent TMDs, are suppressed due to kinematic factors (Section 5).

SIDIS cross sections, hadron multiplicities, polarization-independent, and spin-dependent azimuthal asymmetries are multidifferential in nature. Therefore, a multidimensional analysis is mandatory to disentangle the intricate dependencies on the kinematical variables x, Q^2, P_T, z. In addition, comparing results obtained by different SIDIS experiments operating with different beam energies and phase-space coverage is often impractical and error-prone if the comparisons are done on a one-dimensional basis. Looking at single-dimensional kinematic dependencies of cross sections or asymmetries obtained from different experiments while integrating over other dimensions of non-equal phase space contours, may result in significant discrepancies. High-statistics data that precisely cover full relevant kinematics will be also critical for the separation of contributions from different production mechanisms into observables defining the given SF of interest (Section 4). A good example are the exclusive diffractive processes contributing to the SIDIS spin-dependent and even spin-independent observables. Precision measurements in multidimensional space involving all relevant variables are also critical for understanding effects induced by phase-space limitations. It was suggested that even at COMPASS energies the phase space available for single-hadron production in deep-inelastic scattering should be taken into account to describe data in the standard pQCD formalism. Precision measurements of single and dihadron SIDIS, also allowing for detailed studies of the Q^2 dependences of observables, one can test the impact of several theoretical assumptions used in the phenomenology of TMDs. This will also provide validation of the extraction frameworks, which is critical for the proper evaluation of systematic uncertainties. Additionally, the detection of multiparticle final states and the study of multiplicities and asymmetries of dihadrons and vector mesons will offer crucial insights into the source of single-spin asymmetries and the dynamics of the polarized quark hadronization process.

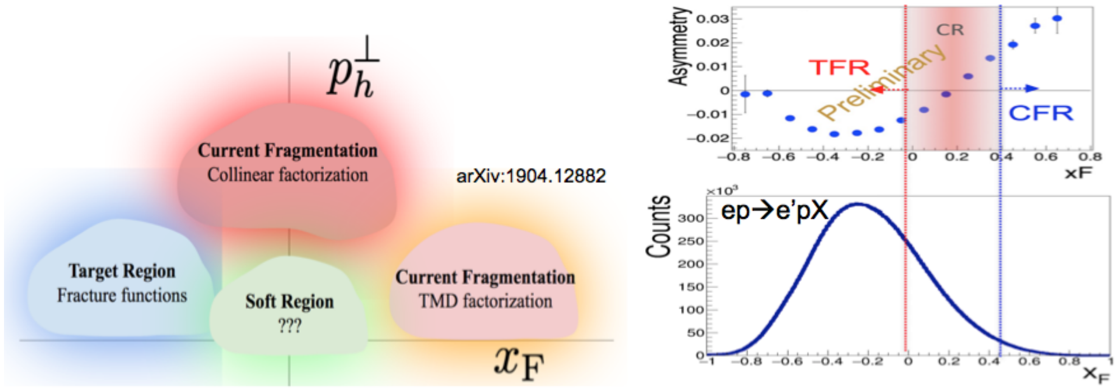

Figure 1: Kinematical regions, where the QCD dynamics could be interpreted in terms of factorization of different soft and hard scattering contributions depending on the fraction of the longitudinal momentum (x_F) of hadrons in CM frame (left). The beam SSA (F_{LU}/F_{UU}) in $ep \to e'pX$ (right).

2. Separating Current and Target Fragmentation Kinematics

QCD factorization theorems, defined for specific kinematic regions, are critical to building the phenomenology to study 3D partonic distributions. Some estimates of the consistency of particular regions of overall hadronic kinematics (see Fig. 1) with the kinematics of a given underlying partonic picture were theoretically studied [5]. Recent studies of beam Single Spin Asymmetries (SSAs) by CLAS12 collaboration allow one to validate the separation of CFR and mixed, transition region looking at the x_F-dependence of the beam SSA for inclusive protons in the final state. The helicity asymmetry, providing access to the SF $F_{LU}^{\sin\phi}$ in $ep \to e'pX$ changes the sign when the longitudinal momentum of the proton in the CM frame crosses 0 (see Fig. 1). However, the CFR region is not set at $x_F > 0$, but at higher values of x_F. The stable SSA for protons below $x_F = 0$ supports the expectation that protons are in the TFR for negative x_F. In the TFR, processes are traditionally described using the so-called fracture functions (FrFs), originally established in [6] and later extended to the spin- and transverse-momentum-dependent case [7]. Similar to PDFs and Fragmentation Functions (FFs), FrFs describe the conditional probability of forming a specific final state hadron after the ejection of a particular quark. TFR processes can also be studied in terms of the quark GPDs of the nucleon, in the approximation of semi-exclusive production of nucleons [8]. Studies of the TFR [9] are not only interesting in their own right, but are also critical to properly interpreting many CFR measurements, which have been the driving force behind numerous experiments over the past few decades.

3. Separating Longitudinal Photon Contributions

Interpretation of hard scattering processes in electroproduction assuming the dominance of the leading-twist contributions to the corresponding SFs requires the separation of longitudinal (σ_L) and transverse (σ_T) photon contributions. In case of exclusive processes, the longitudinal photon contributions are leading-twist, while in case of semi-inclusive hadron production, the leading-twist contributions will come from transverse photons. Understanding the evolution properties of

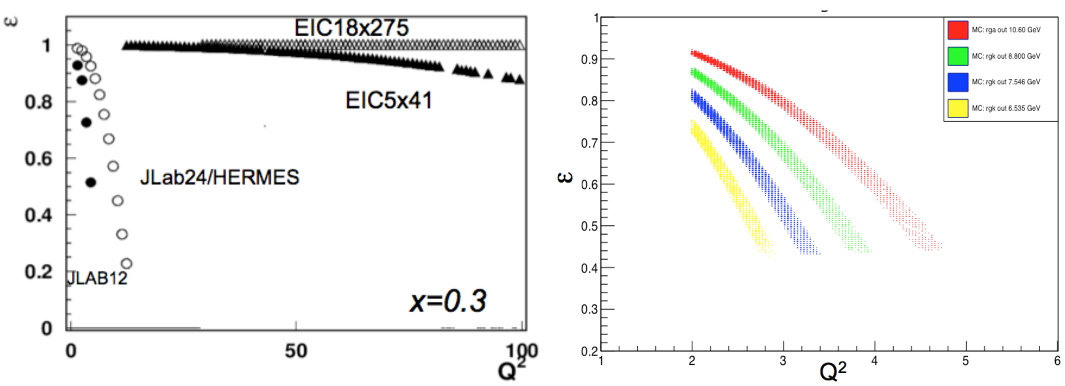

Figure 2: The ratio of fluxes of longitudinal to transverse photons, ϵ, as a function of Q^2 for different experiments (left). The variation of ϵ vs Q^2 in a small bin in x ($0.3 < x < 0.32$) for CLAS12 experiments with different beam energies.

observables, accessible in measurements of their Q^2 dependence, can provide validation tools for the phenomenology, to ensure that the leading-twist contributions are properly separated. The JLab experiments, combining high-luminosity and multiparticle final-state detection, are clearly the only place where such separation could be done, providing test grounds for all kinds of approximations used in theoretical studies. Although some measurements of R have been made for inclusive deep inelastic scattering [10–12], the values of R in the multidimensional space of various semi-inclusive and hard exclusive processes are practically unknown. The R is clearly process dependent, and measurements of R, requiring a wide range in ϵ (see Fig. 2) for all relevant processes in multidimensional space, will be critical for future interpretation of those measurements. Several experiments have already been approved to measure the most precise ratios of longitudinal to transverse cross sections $R = \sigma_L/\sigma_T$ [13–15].

4. Correlations in hadronization

Dihadron production in the CFR provides access to details of QCD dynamics that are not accessible through single-hadron SIDIS measurements. Dihadron production, in particular, becomes essential to understanding the systematics arising from various simplifying assumptions (such as independent fragmentation and isospin symmetry) used in the extraction of TMD PDFs from single-hadron SIDIS. The data from polarized SIDIS experiments, such as HERMES, COMPASS, and more recently CLAS, have enabled access to multiparton correlations. Given the current state-of-the-art in extracting PDFs within the realm of pQCD, it is crucial to undertake a comprehensive analysis of the Q^2 behavior of different relevant observables needed for validation of underlying frameworks for analysis of single hadron SIDIS, neglecting hadronic correlations, and separation of different contributions to relevant SFs, such as the SF describing the hadronization of transversely polarized quarks. For dihadron observables, the spectra in (z, M_h), where z is the fragmentation variable and M_h is the invariant mass of the hadron pair, could provide insights into contributions beyond the expected two-pion mass distribution, as illustrated in Fig. 3.

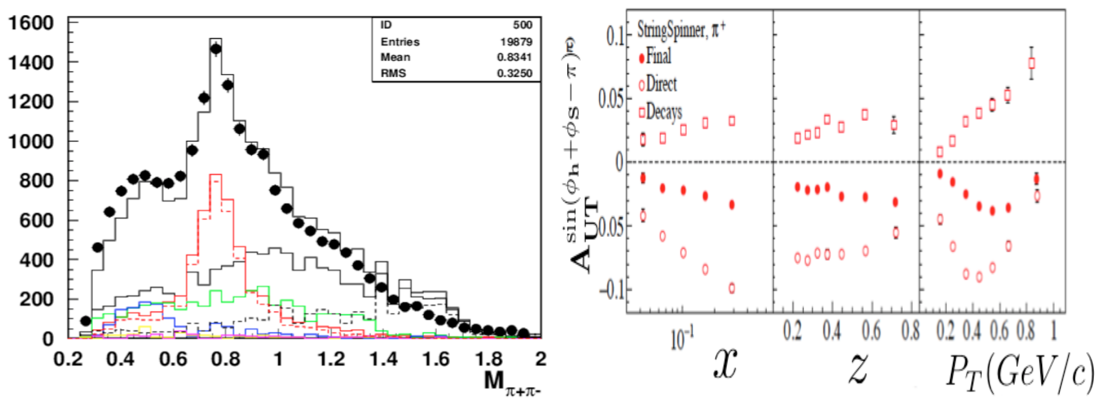

Figure 3: Invariant mass M_h distribution (left panel) for $\pi^+\pi^-$ hadron pairs from CLAS12 (black points) compared to LUND MC (upper solid line). The colored distributions represent dihadrons where one (solid) or both (dashed) of the pions are produced from the parent vector meson, with different colors used for different VMs. The dominant contributions are from ρ^0 and ω (left shoulder) decays. The right panel shows the possible impact of decay pions on the measured single transverse spin asymmetries by comparing direct-pion SSAs with total. Prediction for the Collins asymmetries including all final state π^+ (filled circles), direct π^+ (open circles) and π^+ coming from ρ decays (squares) in SIDIS off transversely polarized protons in the JLab kinematic. Simulations are carried out using the StringSpinner package [16] and the PYTHIA 8.2 [17] event generator.

Since the inclusive pion and kaon samples are dominated by decay products from corresponding vector mesons (VMs), the understanding of the VM contributions will be critical for interpretation of the kinematic dependence of multiplicities, and most importantly, SSAs of pions and kaons. As shown in Fig. 3 the pion sample is dominated by the VM decay products. Large differences in the SSAs of the pions and kaons measured by HERMES [18] and COMPASS [19] Collaborations can come to a significant extent from different fractions of pions and kaons from the corresponding VM decays, further diluting the SSA of the pions. Even though the relative fraction of strange VMs versus non-strange is higher, the relative contributions of strange VMs to kaon sample is lower, than VM decays to pion sample. The recently developed “string+$^3P_0$ model" of polarized hadronization [20] provided the first glimps into the hadronization of polarized quarks. The asymmetries from decay pions lead to significant dilution of the measured asymmetry for the inclusive pions, indicating that a direct comparison of polarized fragmentation functions with models accounting for spin-orbit correlations in hadronization will require separation of direct pion contributions.

Since the contamination of the ρ meson sample from decays of heavier resonances is expected to be negligible according to simulations, the produced VMs are mostly sensitive to the direct mechanisms of quark fragmentation and can be used in studies of the underlying transverse momentum distribution of quarks and spin-orbit correlations. In the exclusive limit, both the ρ^0 and ρ^+ asymmetries were measured to be very significant (see Fig. 4). The asymmetry values for ρ^0 and ρ^+ are consistent with each other for the values of z below 0.85, and are also consistent with the beam SSAs measured for exclusive π^+ and π^0 [21], indicating that all contributions come from polarized u quarks. The asymmetries for the exclusive π^- [22], dominated by the d quarks, were found to have similar magnitude, but opposite sign, consistent with the negative polarization of

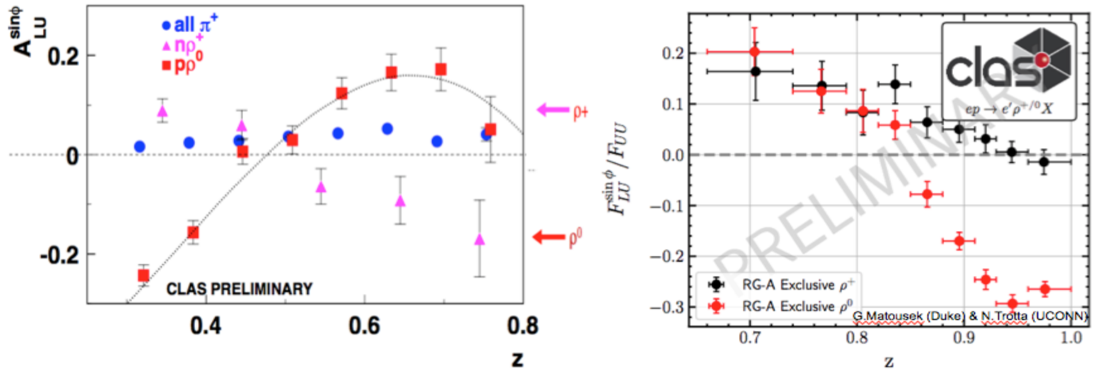

Figure 4: The left panel shows the beam SSA for inclusive π^+ versus the z of the π^+ for the full sample (circles) and subsamples coming from exclusive ρ^0 (squares) and ρ^+ (triangles). The arrows show the values of SSA extracted for the corresponding exclusive rhos. The right panel shows the actual dependence of the beam SSA extracted for exclusive channels $ep \to e'p\rho^0$ and $ep \to e'n\rho^+$ versus the z of the rho.

the d quarks. The significant SSA for very large z, corresponding to a small momentum transfer t ($z = 1 + tx_B/Q^2$) for ρ^0 with negative sign, may indicate dominant contributions of diffractive ρ^0 contributions with negative polarization of the gluons. The higher the x, the higher the minimum t, t_{min}, accessible kinematics, suppressing diffractive contributions in the valence region of large x, leading to suppression at relatively large Q^2, also correlated kinematically with large x.

In general, the measured SSAs [23] clearly demonstrate a dependence on the invariant mass of the pion pair, indicating significant correlation effects in hadron production in the CFR. Measurements of correlations between hadrons in target and current fragmentation regions [9], on the other hand, open new possibilities to quantify the relationship between the spin and transverse momenta of quarks in the nucleon and provide a new avenue for studies of the complex nucleonic structure in terms of quark and gluon degrees of freedom.

5. Studies of the helicity distributions

One of the most important questions about the 3D structure of the nucleon is the transverse momentum dependence of the distribution and fragmentation TMDs and the flavor and spin dependence of these shapes. For precision studies of TMDs, it is also important to understand the role of medium, and the effects of in medium modifications of TMDs. That is crucial since both COMPASS and JLab use nuclear targets to study polarization effects. Understanding the dynamics of partons, including the non-perturbative sea quarks, is crucial for gaining insights into strong interactions. The correlations between the spin of the target and/or the momentum and spin of quarks, along with final state interactions, determine the azimuthal distributions of produced particles. Measurements of flavor asymmetries in sea-quark distributions from E866 and SeaQuest Collaborations suggest a significantly larger $\bar{d}$ distribution compared to $\bar{u}$ across the accessible range of x [24]. Non-perturbative $q\bar{q}$ pairs, which are also correlated with spins, play a crucial role in spin-orbit correlations and the measurement of single-spin asymmetries observed in various experiments over the past few decades.

The transverse momentum of hadrons is most sensitive to spin-orbit correlations, providing a direct access to partonic transverse momenta. Predictions indicate that the distribution of unpolarized sea quarks exhibits a power-like tail, approximately proportional to $1/k_T^2$, extending up to the chiral symmetry-breaking scale [25]. A similar behavior is observed in the flavor-nonsinglet polarized sea. The transverse momentum distributions of the valence and sea quarks are predicted to have distinct shapes, particularly at high values of k_T. The effect of dynamical chiral symmetry breaking on the partonic structure of nucleons has important implications for the transverse momentum distributions of particles produced in hard scattering processes.

The frequently used assumption of factorization of x and (or z and p_T) dependencies [26] can be significantly violated (see Fig. 10 of [27]). For instance, the predicted average transverse momentum square $\langle k_T^2 \rangle$ of quarks and antiquarks may depend strongly on their longitudinal momentum fraction x within the framework of the chiral quark soliton model. In the fragmentation process, one would expect [28] that the *disfavored* fragmentation of a quark into a hadron would be broader in the transverse momentum with respect to the *favored* fragmentation (fragmentation of a quark into a hadron that has this type of quark as a valence quark).

Multiplicities of charged pion and kaon mesons have been measured by HERMES using the electron beam scattering off hydrogen and deuterium targets [29]. The multiplicities of charged hadrons produced in deep inelastic muon scattering off a ^{6}LiD target have been measured in COMPASS [30]. These high-statistics data samples have been used in phenomenological analyzes [26, 27, 31] to extract information on the flavor dependence of the unpolarized TMD distribution and fragmentation functions. Restricting the ranges of the available data to $Q^2 > 1.69$ (GeV$/c)^2$, $z < 0.7$ and 0.2 GeV$/c < P_T <$ 0.9 GeV$/c$, the authors of [26] obtained a reasonable description of the experimental data within a Gaussian assumption for TMDs with flavour independent and constant widths, $\langle k_T \rangle$ and $\langle p_T \rangle$. However, indications have been reported that favored fragmentation functions into pions have smaller average transverse momentum width than unfavoured functions and fragmentation functions into kaons [31], consistent with predictions based on the NJL-jet model [28].

Collinear PDFs have flavour dependence, therefore it is not unexpected that the transverse momentum dependence may also be different for the different flavours [31]. Model calculations of the transverse momentum dependence of TMDs [32–35] and lattice QCD results [36, 37] suggest that the dependence of the widths of TMDs on the quark polarization and flavor may be significant. Measurements of the P_T-dependence in double-spin asymmetries (DSAs) in charged pion electroproduction, conducted for the first time across different x-bins, have revealed interesting insights. These measurements suggest the existence of different average transverse momenta for quarks aligned or anti-aligned with the nucleon spin [38, 39], consistent with findings from LQCD simulations [37]. The double spin longitudinal asymmetries, providing access to SF F_{LL} and underlying helicity TMD $g_1(x, k_T)$ due to its ϵ-dependent prefactor (see Eq.1) in the valence region, are significantly suppressed at higher energies. Indeed, as shown in Fig. 5, with $\epsilon \to 1$ the kinematic prefactor is rapidly decreasing with energy, making the JLab a unique place to study helicity TMDs in the valence region. The latest CLAS measurements using a small fraction ($\sim 1\%$) of data with the 10.6 GeV longitudinally polarized beam scattering of longitudinally polarized NH_3 target are shown in Fig.5.

To achieve a detailed understanding of the contributions to measured cross sections and asym-

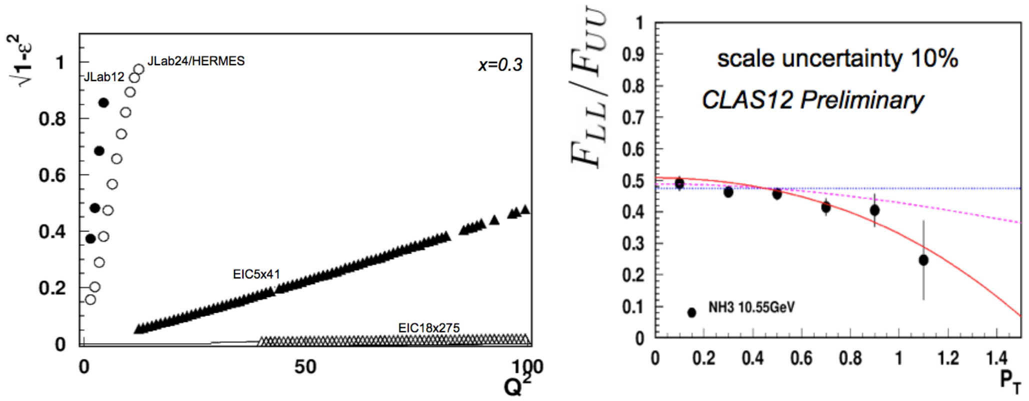

Figure 5: The double spin asymmetry as a function of P_T in $ep \to e'\pi^+X$ in a given bin in x (left) and the Q^2-dependence of the double spin asymmetry in a given bin in x for $ep \to e'pX$ (right). The curves correspond to different widths in k_T of $g_1(x, k_T)$ compared to $f_1(x, k_T)$.

metries in SIDIS with controlled systematics, it is necessary to consider all the kinematical variables involved (x, Q^2, z, P_T and ϕ). JLab is the only facility capable of separating different structure functions involved in polarized SIDIS, including longitudinal photon contributions. By performing precision multidimensional measurements of single and dihadron SIDIS with an upgraded CEBAF accelerator, and by studying the Q^2 dependences of observables, we can test the impact of several theoretical assumptions used in TMD phenomenology. This will also provide validation of the extraction frameworks, which is critical for the proper evaluation of systematic uncertainties. Additionally, the detection of multiparticle final states and the study of multiplicities and asymmetries of dihadrons and vector mesons will offer crucial insights into the source of single-spin asymmetries and the dynamics of the polarized quark hadronization process.

Acknowledgements

We thank Aram Kotzinian, Albi Kerbizi, and Feng Yuan for useful discussions and correspondences. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC05-06OR23177.

References

[1] Alessandro Bacchetta, Markus Diehl, Klaus Goeke, Andreas Metz, Piet J. Mulders, and Marc Schlegel. Semi-inclusive deep inelastic scattering at small transverse momentum. *JHEP*, 02: 093, 2007. doi: 10.1088/1126-6708/2007/02/093.

[2] Aram Kotzinian. New quark distributions and semiinclusive electroproduction on the polarized nucleons. *Nucl. Phys.*, B441:234–248, 1995. doi: 10.1016/0550-3213(95)00098-D.

[3] P. J. Mulders and R. D. Tangerman. The Complete tree level result up to order 1/Q for polarized deep inelastic leptoproduction. *Nucl. Phys. B*, 461:197–237, 1996. doi: 10.1016/0550-3213(95)00632-X. [Erratum: Nucl.Phys.B 484, 538–540 (1997)].

[4] M. Diehl and S. Sapeta. On the analysis of lepton scattering on longitudinally or transversely polarized protons. *Eur. Phys. J. C*, 41:515–533, 2005. doi: 10.1140/epjc/s2005-02242-9.

[5] M. Boglione, A. Dotson, L. Gamberg, S. Gordon, J. O. Gonzalez-Hernandez, A. Prokudin, T. C. Rogers, and N. Sato. Mapping the Kinematical Regimes of Semi-Inclusive Deep Inelastic Scattering. *JHEP*, 10:122, 2019. doi: 10.1007/JHEP10(2019)122.

[6] L. Trentadue and G. Veneziano. Fracture functions: An Improved description of inclusive hard processes in QCD. *Phys. Lett. B*, 323:201–211, 1994. doi: 10.1016/0370-2693(94)90292-5.

[7] Mauro Anselmino, Vincenzo Barone, and Aram Kotzinian. SIDIS in the target fragmentation region: Polarized and transverse momentum dependent fracture functions. *Phys. Lett. B*, 699: 108–118, 2011. doi: 10.1016/j.physletb.2011.03.067.

[8] Yuxun Guo and Feng Yuan. Explore the Nucleon Tomography through Di-hadron Correlation in Opposite Hemisphere in Deep Inelastic Scattering. 12 2023.

[9] H. Avakian et al. Observation of Correlations between Spin and Transverse Momenta in Back-to-Back Dihadron Production at CLAS12. *Phys. Rev. Lett.*, 130(2):022501, 2023. doi: 10.1103/PhysRevLett.130.022501.

[10] C. J. Bebek, C. N. Brown, M. Herzlinger, Stephen D. Holmes, C. A. Lichtenstein, F. M. Pipkin, S. Raither, and L. K. Sisterson. Scaling Behavior of Inclusive Pion Electroproduction. *Phys. Rev. Lett.*, 34:759, 1975. doi: 10.1103/PhysRevLett.34.759.

[11] C. J. Bebek, A. Browman, C. N. Brown, K. M. Hanson, R. V. Kline, D. Larson, F. M. Pipkin, S. W. Raither, A. Silverman, and L. K. Sisterson. Charged Pion Electroproduction from Protons Up to Q**2 = 9.5-GeV**2. *Phys. Rev. Lett.*, 37:1525–1528, 1976. doi: 10.1103/PhysRevLett.37.1525.

[12] C. J. Bebek, C. N. Brown, M. S. Herzlinger, Stephen D. Holmes, C. A. Lichtenstein, F. M. Pipkin, S. W. Raither, and L. K. Sisterson. Inclusive Charged Pion Electroproduction. *Phys. Rev. D*, 15:3085, 1977. doi: 10.1103/PhysRevD.15.3085.

[13] P. Bosted et al. Measurement of the ratio r=sigmal/sigmat in semi-inclusive deep-inelastic scattering. *JLab Experiment E12-06-104*, 2013. URL https://www.jlab.org/exp_prog/PACpage/updated_proposals/PAC40_pi0_sidis_rev15.pdf.

[14] H. Avakian et al. Separation of the σ_l and σ_t contributions to the production of hadrons in electroproduction. *JLab Experiment E12-16-010C*, 2023. URL https://www.jlab.org/exp_prog/PACpage/updated_proposals/PAC40_pi0_sidis_rev15.pdf.

[15] P. Bosted et al. Measurements of the ratio r = l/t,p/d ratios, pt-dependence, and azimuthal asymmetries in semi-inclusive dis 0 production form proton and deuteron targets using the nps in hall c. *JLab Experiment E12-23-014*, 2013. URL https://www.jlab.org/exp_prog/PACpage/updated_proposals/PAC40_pi0_sidis_rev15.pdf.

[16] Albi Kerbizi and Leif Lönnblad. StringSpinner - adding spin to the PYTHIA string fragmentation. *Comput. Phys. Commun.*, 272:108234, 2022. doi: 10.1016/j.cpc.2021.108234.

[17] Torbjörn Sjöstrand, Stefan Ask, Jesper R. Christiansen, Richard Corke, Nishita Desai, Philip Ilten, Stephen Mrenna, Stefan Prestel, Christine O. Rasmussen, and Peter Z. Skands. An introduction to PYTHIA 8.2. *Comput. Phys. Commun.*, 191:159–177, 2015. doi: 10.1016/j.cpc.2015.01.024.

[18] A. Airapetian et al. Observation of the Naive-T-odd Sivers Effect in Deep-Inelastic Scattering. *Phys. Rev. Lett.*, 103:152002, 2009. doi: 10.1103/PhysRevLett.103.152002.

[19] C. Adolph et al. Collins and Sivers asymmetries in muonproduction of pions and kaons off transversely polarised protons. *Phys. Lett. B*, 744:250–259, 2015. doi: 10.1016/j.physletb.2015.03.056.

[20] A. Kerbizi, X. Artru, and A. Martin. Production of vector mesons in the String+$^3P_0$ model of polarized quark fragmentation. *Phys. Rev. D*, 104(11):114038, 2021. doi: 10.1103/PhysRevD.104.114038.

[21] S. Diehl et al. A multidimensional study of the structure function ratio σLT'/σ0 from hard exclusive π+ electro-production off protons in the GPD regime. *Phys. Lett. B*, 839:137761, 2023. doi: 10.1016/j.physletb.2023.137761.

[22] S. Diehl et al. First Measurement of Hard Exclusive π-Δ++ Electroproduction Beam-Spin Asymmetries off the Proton. *Phys. Rev. Lett.*, 131(2):021901, 2023. doi: 10.1103/PhysRevLett.131.021901.

[23] T. B. Hayward et al. Observation of Beam Spin Asymmetries in the Process $ep \to e'\pi^+\pi^- X$ with CLAS12. *Phys. Rev. Lett.*, 126:152501, 2021. doi: 10.1103/PhysRevLett.126.152501.

[24] Kei Nagai. Measurement of Antiquark Flavor Asymmetry in the Proton by the Drell–Yan Experiment SeaQuest at Fermilab. *JPS Conf. Proc.*, 13:020051, 2017. doi: 10.7566/JPSCP.13.020051.

[25] P. Schweitzer, M. Strikman, and C. Weiss. Intrinsic transverse momentum and parton correlations from dynamical chiral symmetry breaking. *JHEP*, 01:163, 2013. doi: 10.1007/JHEP01(2013)163.

[26] M. Anselmino, M. Boglione, J.O. Gonzalez Hernandez, S. Melis, and A. Prokudin. Unpolarised Transverse Momentum Dependent Distribution and Fragmentation Functions from SIDIS Multiplicities. *JHEP*, 04:005, 2014. doi: 10.1007/JHEP04(2014)005.

[27] Alessandro Bacchetta, Filippo Delcarro, Cristian Pisano, Marco Radici, and Andrea Signori. Extraction of partonic transverse momentum distributions from semi-inclusive deep-inelastic scattering, Drell-Yan and Z-boson production. *JHEP*, 06:081, 2017. doi: 10.1007/JHEP06(2017)081. [Erratum: JHEP 06, 051 (2019)].

[28] Hrayr H. Matevosyan, Wolfgang Bentz, Ian C. Cloet, and Anthony W. Thomas. Transverse Momentum Dependent Fragmentation and Quark Distribution Functions from the NJL-jet Model. *Phys.Rev.*, D85:014021, 2012. doi: 10.1103/PhysRevD.85.014021.

[29] A. Airapetian et al. Multiplicities of charged pions and kaons from semi-inclusive deep-inelastic scattering by the proton and the deuteron. *Phys. Rev. D*, 87:074029, 2013. doi: 10.1103/PhysRevD.87.074029.

[30] C. Adolph et al. Hadron Transverse Momentum Distributions in Muon Deep Inelastic Scattering at 160 GeV/c. *Eur.Phys.J.*, C73:2531, 2013. doi: 10.1140/epjc/s10052-013-2531-6.

[31] Andrea Signori, Alessandro Bacchetta, Marco Radici, and Gunar Schnell. Investigations into the flavor dependence of partonic transverse momentum. *JHEP*, 11:194, 2013. doi: 10.1007/JHEP11(2013)194.

[32] B. Pasquini, S. Cazzaniga, and S. Boffi. Transverse momentum dependent parton distributions in a light-cone quark model. *Phys. Rev.*, D78:034025, 2008.

[33] Zhun Lu and Bo-Qiang Ma. Sivers function in light-cone quark model and azimuthal spin asymmetries in pion electroproduction. *Nucl. Phys.*, A741:200–214, 2004. doi: 10.1016/j.nuclphysa.2004.06.006.

[34] M. Anselmino, A. Efremov, A. Kotzinian, and B. Parsamyan. Transverse momentum dependence of the quark helicity distributions and the cahn effect in double-spin asymmetry a(ll) in semi inclusive dis. *Phys. Rev.*, D74:074015, 2006.

[35] Claude Bourrely, Franco Buccella, and Jacques Soffer. Semiinclusive DIS cross sections and spin asymmetries in the quantum statistical parton distributions approach. *Phys.Rev.*, D83:074008, 2011. doi: 10.1103/PhysRevD.83.074008.

[36] Ph. Hagler, B. U. Musch, J. W. Negele, and A. Schafer. Intrinsic quark transverse momentum in the nucleon from lattice QCD. *Europhys. Lett.*, 88:61001, 2009.

[37] Bernhard U. Musch, Philipp Hagler, John W. Negele, and Andreas Schafer. Exploring quark transverse momentum distributions with lattice QCD. *Phys. Rev. D*, 83:094507, 2011. doi: 10.1103/PhysRevD.83.094507.

[38] H. Avakian et al. Measurement of Single and Double Spin Asymmetries in Deep Inelastic Pion Electroproduction with a Longitudinally Polarized Target. *Phys. Rev. Lett.*, 105:262002, 2010. doi: 10.1103/PhysRevLett.105.262002.

[39] S. Jawalkar et al. Semi-Inclusive π_0 target and beam-target asymmetries from 6 GeV electron scattering with CLAS. *Phys. Lett. B*, 782:662–667, 2018. doi: 10.1016/j.physletb.2018.06.014.

PoS(SPIN2023)034