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Transversity and Transverse Spin in Nucleon Structure through SIDIS at Jefferson Lab

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0.1 Introduction

Spin is an intrinsic quantum-mechanical and relativistic property of the constituents of matter which plays a fundamental role in physical processes and in theories of fundamental interactions. Three decades of intensive experimental and theoretical investigation has resulted in a great deal of knowledge on the partonic origin of the nucleon spin structure. In particular, considerable knowledge has been gained from inclusive deep-inelastic scattering (DIS) experiments at CERN, SLAC, DESY and more recently at JLab and RHIC on the longitudinal structure – the x-dependence and the helicity distributions – in terms of the unpolarized (denoted $q(x)$ or $f_1^q(x)$) and helicity (denoted $\Delta q(x)$ or $g_1^q(x)$) parton distribution functions for the various flavors (indicated by q). We have also learned that precise knowledge of the transverse structure is an essential part of the partonic spin and momentum substructure of the nucleon. This information can only be obtained by a consideration of data beyond those obtained from the unpolarized and longitudinally polarized processes. Theoretically, this entails the exploration of the QCD parton model beyond the collinear approximation.

Indeed, the extension of the QCD parton model beyond the collinear approximation and the systematic study of semi-inclusive deep-inelastic lepton nucleon scattering (SIDIS) has emerged as an essential tool to probe both the nucleon's longitudinal and transverse momentum and spin structure. The azimuthal dependence in the scattering of leptons off transversely polarized nucleons is explored through the analysis of transverse single spin asymmetries (TSSAs). QCD predicts that these observables are factorized convolutions of leading-twist transverse momentum dependent parton distributions (TMDs) and fragmentation functions [1, 2, 3, 4]. These functions provide *essential non-perturbative* information on the partonic sub-structure of the nucleon; they offer a rich understanding of the motion of partons inside the nucleon, of the quark orbital properties and of spin-orbit correlations.

The Thomas Jefferson National Accelerator Facility (JLab) is exceptionally suited to carry out precision studies of the longitudinal and transverse spin and momentum structure of the nucleon as well as its flavor decomposition from SIDIS experiments due to its high luminosity in combination with large acceptance detectors and the kinematic coverage in longitudinal and transverse momentum.

0.2 Transversity and TMDs through SIDIS

In recent years new theoretical [6, 26] and experimental efforts [8, 9] have been devoted to explore the transverse spin and momentum structure of the nucleon. This concerns in particular the investigations of the chiral-odd transversely polarized quark distribution function (or transversity, denoted as $\delta q(x), h_1^q(x)$ or also $\Delta_T q(x)$ [5]). Like the axial charge $\Delta q = \int_0^1 dx\ (g_1^q(x) + \bar{g}_1^q(x))$, the nucleon tensor charge $\delta q = \int_0^1 dx (h_1^q(x) - \bar{h}_1^q(x))$ is a basic property of the nucleon, which is dominated by valence quarks. It is crucial to note that due to its chiral-odd property, h_1^q does not mix with gluons under evolution and it receives no contribution from quark-antiquark pairs in the *sea*. Thus, it is a non-singlet *valence-dominated* distribution function. Transversity, together with the unpolarized and helicity parton distribution functions, is one of the three basic functions describing the distribution of quarks in the nucleon. It satisfies the Soffer bound [7], $|2h_1^q(x, Q^2)| \leq f_1^q(x, Q^2) + g_1^q(x, Q^2)$ for each flavor at the scale Q^2. Its meaning is transparent in a transverse spin basis: h_1 describes the probability to find a quark with spin polarized along the transverse spin of a polarized nucleon minus the probability to find it polarized oppositely [6]. In terms of a helicity description, the transversity distribution is chiral odd, that is, the helicities of both the quark and nucleon flip. Thus, due to the helicity conservating property of the QCD interactions h_1 decouples at leading twist in an expansion of inverse powers of the hard scale in inclusive deep-inelastic scattering. However, paired with another hadron in the initial state, *e.g.* Drell-Yan Scattering [10], or in the final state, *e.g.* semi-inclusive deep-inelastic [11] scattering, the transverse structure of the nucleon can be accessed without suppression

by a hard scale. Thus, at leading twist h_1 can be accessed with another distribution or fragmentation function.

The most feasible way to access the transversity distribution function is via an azimuthal single spin asymmetry, in semi-inclusive deep-inelastic lepto-production of mesons on a transversely polarized nucleon target, $e\,N^{\uparrow} \to e\,\pi\,X$. In this case the other chiral-odd partner is the Collins [11] fragmentation function, $H_1^{\perp}$. Schematically from factorized QCD, this transverse single spin asymmetry (TSSA) contains h_1 and $H_1^{\perp}$, $A_{UT} \sim h_1 \otimes H_1^{\perp}$ ($U \equiv$ unpolarized electron beam, $T \equiv$ transversely polarized target) [2].

The first evidence of non-zero transversity has been observed in the HERMES experiment [8] where an unpolarized electron beam is scattered off a transversely polarized proton in SIDIS, $e\,p^{\uparrow} \to e'\,\pi\,X$, whereas the COMPASS measurements [9] of the Collins and Sivers asymmetries on the deuteron are consistent with zero within experimental uncertainties. By contrast to inclusive deep-inelastic lepton-nucleon scattering where transverse momentum is integrated out, these processes are sensitive to transverse momentum scales on the order of the intrinsic quark momentum $P_T \sim k_{\perp}$. This is evident by considering the generic structure of the TSSA for a transversely polarized nucleon target which is characterized by interference between helicity flip and helicity non-flip amplitudes $A_{UT} \sim \mathrm{Im}(f^{*+} f^{-})$. In the collinear limit of QCD partonic processes conserve helicity and Born amplitudes are real [12]. Thus, a reaction mechanism to account for the interference between helicity flip amplitudes at leading twist requires a probe of the nucleon at a scale sensitive to the intrinsic quark transverse momentum. This is roughly set by the confinement scale $k_{\perp} \sim \Lambda_{\mathrm{qcd}}$ [13].

Transverse spin asymmetries arise from *naive time reversal odd* (T-odd) correlations between transverse spin $\boldsymbol{S}_T$, longitudinal momentum $\boldsymbol{P}$ and intrinsic quark momentum $\boldsymbol{k}_{\perp}$ [14, 11]. This is depicted by the generic vector product $i\boldsymbol{S}_T \cdot (\boldsymbol{P} \times \boldsymbol{k}_{\perp})$. These correlations imply that the reaction mechanism is associated with leading twist-two helicity flip, T-odd transverse momentum dependent (TMD) parton distribution [14] and fragmentation [11] functions (PDFs & FFs). These ingredients enter the factorized [3, 4] hadronic tensor for semi-inclusive deep-inelastic scattering.

A crucial theoretical breakthrough [15, 16, 17] was that the reaction mechanism is due to non-trivial phases arising from the color gauge invariant property of QCD. This leads to the picture that TSSAs arise from initial and final state interactions [18, 19, 20] (ISI/FSI) of the active quark with the soft distribution or fragmentation remnant in SIDIS. Thus, T-odd TMDs are of crucial importance because they posses transversity properties as well as the necessary phases to account for TSSAs at leading twist.

Exploring the transverse spin structure of the TMD PDFs reveals evidence of a rich spin-orbit structure of the nucleon. When the transverse spin-momentum correlations are associated with the nucleon where the quark remains *unpolarized*, the so-called Sivers function associated with the helicity flip of a transverse spin nucleon target dominates at leading twist. Since the quark is unpolarized in the Sivers function, the orbital angular momentum of the quarks must come into play to conserve overall angular momentum in the process [21]. This result has a far-reaching impact on the QCD theory of generalized angular momentum [22].

When the single transverse spin-momentum correlation is associated with the fragmenting quark, we access the Collins fragmentation function. Indeed as stated earlier the Collins function couples to the chiral-odd transversity distribution function $h_1(x)$. Understanding its properties and accessing it through experiment is a crucial ingredient to pin down h_1.

First attemps [23] have been performed to extract the transversity distributions (up to a sign) by combining SIDIS [8, 9] data with $\mathrm{e}^+\mathrm{e}^-$ data [24] on the Collins function (see Fig. 1). Within the large errors, the Soffer bound is respected.

Complementing the new data from the HERMES [8], COMPASS [9], and BELLE [24] experiments,

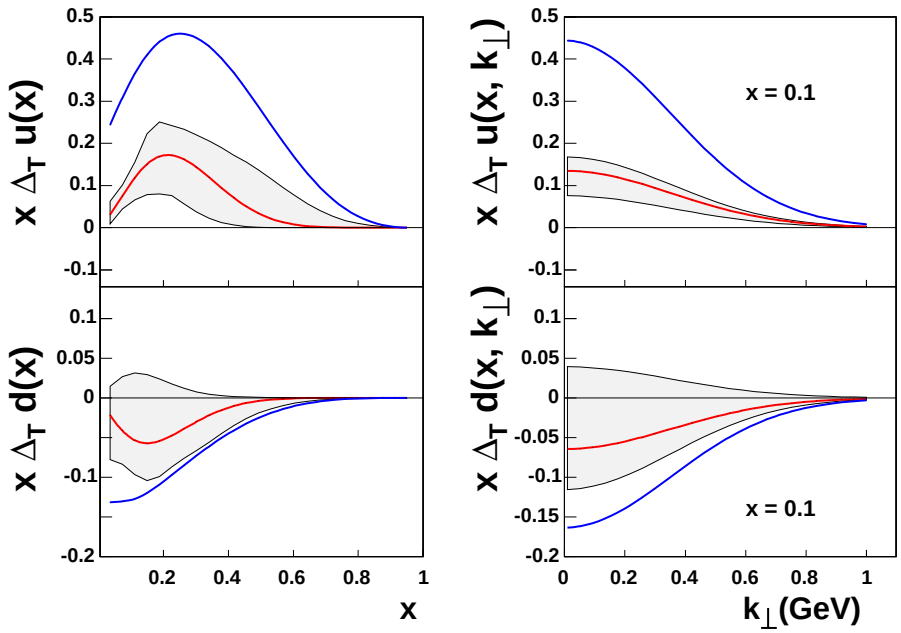

Figure 1: The transversity distribution functions $\Delta_T q(x)$ (also denoted as $\delta q(x)$ or $h_1^q(x)$) for u and d quarks as determined from the global best fit analysis [23]. Left panel, $x\,\Delta_T u(x)$ and $x\,\Delta_T d(x)$ upper and lower plot, shown as functions of x. The Soffer bound [7], bold blue line. Right panel, the unintegrated transversity distributions, $x\,\Delta_T u(x, k_\perp)$ and $x\,\Delta_T d(x, k_\perp)$ upper and lower plot, as defined in [23], as functions of $k_\perp$ for fixed x.

the approved Hall A experiments E06-010/E06-011 [25] on the neutron (with polarized ^{3}He) will facilitate a flavor decomposition of the transversity distribution function, h_1 [6, 26] and the first moment of the T-odd Sivers distribution function $f_{1T}^{\perp(1)}$ [14] in the proposed but limited kinematic regime with limited precision. However a model-independent determination of these leading twist functions demands a wider kinematic range with high precision in *three dimensions* $(x, z, \boldsymbol{P}_T)$.

0.3 Three Dimensional Kinematic Map of TMDs: JLAB 12 GeV with Large Acceptance

The prospect of mapping out the nucleon's partonic substructure through TMDs from SIDIS experiments is encouraging. The endeavor to determine the nucleon's spin-momentum structure from SSAs in SIDIS demands high-precision data in longitudinal and transverse momentum kinematics (x, z, and $\boldsymbol{P}_T$).

The JLab 12 GeV upgrade with the CLAS12 detector (with polarized proton and deuteron targets), and the proposed solenoid large-acceptance detector (with a polarized neutron target) in Hall A provide an unprecedented opportunity to obtain a *three-dimensional* map of the Collins and Sivers asymmetries in the kinematical region $0.1 \leq x \leq 0.5$, $0.3 \leq z \leq 0.7$ with $P_T \leq 1.5$ GeV, necessary to precisely determine the nucleon's partonic substructure.

Fig. 2 shows a sample plot of the projection of the Sivers and the Collins asymmetry measurement

for $z = 0.5 - 0.6$ as a function of P_T and x for 60 days of running using the solenoid detector with a transversely polarized ^{3}He (neutron) target detecting π^+ in coincidence with the scattered electrons. Also shown in the figure are theoretical predictions from a model [27] which fits the HERMES data.

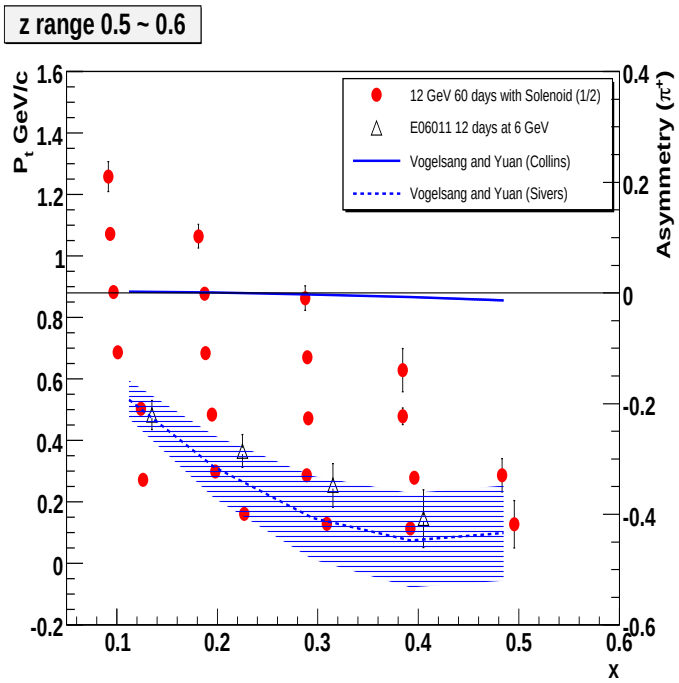

Figure 2: The projection of the Sivers and the Collins asymmetry measurement for π^+ production on the neutron with the proposed selonoid detector for $z = 0.5 - 0.6$ as a function of P_T and x. The size of the error bar follows the axis on the right while the left axis shows the P_T range. The solid (dashed) line shows a model prediction [27] of the Collins (Sivers) asymmetry.

This new precision measurement on the neutron together with the CLAS12 measurement on the proton and the deuteron and the world data will allow for the first time an extraction of the Sivers distribution function, the transversity distribution function as well as the Collins fragmentation function. The Collins function can be cross-checked with the e^+e^- annihilation measurement. This will provide an accurate determination of the transversity distribution function h_1, its first x moment – the nucleon tensor charge, δq – as well as the flavor dependence of the first $\boldsymbol{k}_\perp$-moment of the Sivers function, $f_{1T}^{\perp(1)}$. The tensor charge is a fundamental property of the nucleon, similar to electric charge or total spin, and can be calculated from Lattice QCD.

0.4 Long Range Impact

As stated in the pre-conceptual design report (pCDR) for the 12GeV upgrade of JLab [28] the measurement of TSSAs in SIDIS is a central tool to measure the leading twist transverse momentum dependent distribution and fragmentation (TMD) functions. In particular, the Collins mechanism provides access to the *valence-dominated* quark transversity function and the nucleon's tensor charge, while the Sivers mechanism provides information on the spin-orbit interactions of quarks within the nucleon.

The theoretical and experimental endeavor to analyze the Sivers and Collins asymmetries serves the purpose of exploring quantum chromodynamics (QCD) beyond the collinear limit *down* to transverse

momentum scales $P_T \sim \Lambda_{\rm qcd}$. This provides an unprecedented three-dimensional kinematic map of the spin-momentum partonic sub-structure of the nucleon. Recent evidence of the Collins and Sivers effect from the HERMES [8], COMPASS [9] and BELLE [24] experiments have set the groundwork for the next phase at performing high-precision measurements.

The JLab 12 GeV upgrade with the proposed solenoid detector and the CLAS12 detector will provide the granularity and three-dimensional kinematic coverage in longitudinal and transverse momentum, $0.1 \leq x \leq 0.5$, $0.3 \leq z \leq 0.7$ with $P_T \leq 1.5$ GeV to measure these leading twist chiral-odd and T-odd quark distribution and fragmentation functions. We close by emphasizing that due to the large x experimental reach of these detectors JLab 12 GeV is the *ideal setting* to obtain precise data on the *valence-dominated* transversity distribution function and the tensor charge.

Acknowledgments

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