Studies of TMDs with CLAS

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Studies of single and double-spin asymmetries in pion electro-production in semi-inclusive deep-inelastic scattering of 5.8 GeV polarized electrons from unpolarized and longitudinally polarized targets at the Thomas Jefferson National Accelerator Facility using CLAS will be discussed. We present a Bessel-weighting strategy to extract transverse-momentum-dependent parton distribution functions.

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The study of the transverse spin structure of protons and neutrons is one of the central issues in hadron physics, with many dedicated experiments running (COMPASS at CERN, CLAS and Hall-A at JLab, STAR and PHENIX at RHIC), approved (JLab 12 GeV upgrade, COMPASS-II) or planned (ENC/EIC Colliders). The transverse momentum dependent (TMD) partonic distributions (PDFs) and fragmentation functions (FFs) play a crucial role in the 3-dimensional imaging of nucleons. TMDs can be accessed in several types of experiments although, the main source of information is semi-inclusive deep inelastic scattering (SIDIS) of polarized leptons off polarized nucleons. Significant amounts of data on spin-azimuthal distributions of hadrons in semi-inclusive DIS, which provide access to TMDs, has been accumulated in recent years by several collaborations including HERMES, COMPASS, and Halls A, B and C at JLab[1, 2, 3, 4]. The extraction of actual TMDs as a fuction of transverse momentum $k_\perp$ and x from different single and double spin azimuthal asymmetries is hindered by the absence of a reliable, model-independent procedure for flavor decompositions of the underlying TMDs. Various assumptions involved in preliminary extractions of TMDs from available data did not allow for credible estimates of systematic errors due to those assumptions, which also prevented credible projections of the statistics needed for an extraction of relevant TMDs. The rigorous basis for studies of TMDs in SIDIS is provided by TMD factorization in QCD, which has been established in Refs. [5, 6, 7] for leading twist single hadron production from a quark with transverse momentum $k_\perp$ smaller than the hard scattering scale Q^2 (i.e. $k_\perp^2 \ll Q^2$). In this kinematic domain, the SIDIS cross section can be expressed in terms of structure functions that encode the strong-interaction dynamics of the hadronic subprocess $\gamma^* + p \to h + X$ [8, 9, 10, 11, 12], which are convolutions of transverse momentum dependent distribution and fragmentation functions.

In the recent paper by Boer, Gamberg, Musch and Prokudin (BGMP) [13] a new technique has been proposed, that allows a model-independent extraction of Fourier transforms of TMD distributions from observed azimuthal moments in SIDIS with polarized and unpolarized targets. A fully differential Monte Carlo (MC) generator has been developed [14, 15] to test the procedure for extraction of TMDs from SIDIS in a model independent way, based on the BGMP formalism.

Such a Monte Carlo generator is a crucial component in testing different procedures for flavor decomposition of TMDs. The Monte Carlo generator we used has been developed to study partonic intrinsic motion within the framework generalized parton model described in Ref. [16]. In SIDIS, the theoretical formalism is described in a series of papers [16, 17] using tree level factorization [9] where the standard momentum convolution integral relates the quark intrinsic momentum to the transverse momentum of the produced hadron $P_{h,T}$. Although based on simple assumptions, this model can be seen as a good approximation to understand some physical QCD features and kinematical constraints [17]. Adopting the kinematic relations described in [16], we keep the freedom of changing the distribution and fragmentation functions to check the sensitivity of the extraction procedure.

We discuss the process

$$\ell(l) + N(P) \to \ell(l') + h(P_h) + X, \tag{1}$$

where ℓ is the lepton, N is the proton target and h is the observed hadron (four-momenta given in parentheses). The virtual photon momentum q is along the z direction and the proton momentum P is in the opposite direction, as presented in Fig 1. The detected hadron has momenta P_h. In the

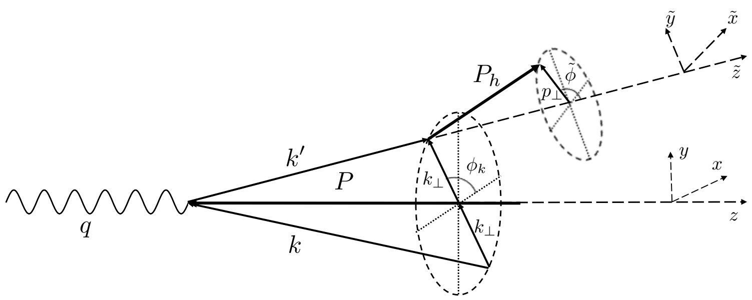

Figure 1: Kinematics of the SIDIS process. Here q is the virtual photon, k and k' are the initial and final quarks, $k_\perp$ is the quark transverse component. P_h is the final hadron with a $p_\perp$ component, transverse with respect to the fragmenting quark k' direction.

parton model the virtual photon scatters off a on-shell quark. The initial quark momentum k and scattered quark momentum k' have the same intrinsic transverse momentum component $k_\perp$ with respect to z axis. The initial quark has only the fraction x of the proton momenta in light-cone frame (see [16] for more details). The produced hadron P_h has fraction z of the scattered quark momentum k' in the $(\tilde{x},\tilde{y},\tilde{z})$ frame and transverse momentum $p_\perp$ with respect to scattered quark k'. The fully differential SIDIS cross section in MC is given by:

$$\frac{d\sigma}{dxdydzd^2\mathbf{p}_\perp d^2\mathbf{k}_\perp d\phi_{l'}} = K(x,y)J(x,Q^2,k_\perp)\times \times\sum_q e_q^2\left[f_{1,q}(x,k_\perp)D_{1,q}(z,p_\perp)+\lambda\sqrt{1-\varepsilon^2}g_{1L,q}(x,k_\perp)D_{1,q}(z,p_\perp)\right] \quad (2)$$

where the summation runs over quarks flavors. The kinematic factors $K(x,y)$ and ε and the Jacobian $J(x,Q^2,k_\perp)$ are defined in [16]. The product of target polarization and beam helicity represented with λ ($\lambda = \pm 1$). The scattered lepton azimuthal angle denoted $\phi_{l'}$ and e_q denotes the fractional charge of the struck quark or antiquark.

In many phenomenological studies of semi-inclusive deep inelastic scattering, the partonic transverse momentum dependence of TMDs $f_{1,q}(x,k_\perp)$ and $g_{1L,q}(x,k_\perp)$ and FFs $D_{1,q}(z,p_\perp)$ are factorized from the longitudinal momentum dependence x and z. In more general case the dependence is assumed to be a Gaussian, with widths depending on the fractions x and z.

$$f_1(x,k_\perp) = f_1(x)\frac{1}{\pi < k_\perp^2(x) >_{f_1}}e^{\frac{-k_\perp^2}{<k_\perp^2(x)>_{f_1}}}, \qquad g_{1L}(x,k_\perp) = \frac{g_{1L}(x)}{\pi < k_\perp^2(x) >_{g_1}}e^{\frac{-k_\perp^2}{<k_\perp^2(x)>_{g_1}}} \quad (3)$$

$$D_1(z,p_\perp) = D_1(z)\frac{1}{< p_\perp^2(z) >}e^{\frac{-p_\perp^2}{<p_\perp^2(z)>}} \quad (4)$$

where $f(x)$ and $D(z)$ are given by fits from available world data and the widths are free parameters to be extracted from the data. In our studies we used modified Gaussian (MG) DFs and FF from Eqs. 3-4, in which x and $k_\perp$ are inspired by AdS/QCD [18], with $< k_\perp^2(x) >= Cx(1-x)$ and $< p_\perp^2(z) >= Dz(1-z)$, in which constants C and D may be different for different flavors and polarization states. Similarly, an unfactorized DF in z and $p_\perp$ is also suggested by the NJL-jet model [19].

We present the extraction of the double spin asymmetry A_{LL}, defined as the ratio of the difference and the sum of electroproduction cross sections for antiparallel, σ^+, and parallel, σ^-, configurations of lepton and nucleon spins, using the Bessel-weighting procedure described in [13] and applied in [20]. Within this approach, one can extract the Fourier transform of the double spin asymmetry, $A_{LL}^{J_0(b_T P_{hT})}(b_T)$, defined as

$$A_{LL}^{J_0(b_T P_{hT})}(b_T) = \frac{\tilde{\sigma}^+(b_T) - \tilde{\sigma}^-(b_T)}{\tilde{\sigma}^+(b_T) + \tilde{\sigma}^-(b_T)} = \frac{\tilde{\sigma}_{LL}(b_T)}{\tilde{\sigma}_{UU}(b_T)} = \sqrt{1-\varepsilon^2}\frac{\sum_q \tilde{g}_1^q(x, z^2 b_T^2)\tilde{D}_1^q(z, b_T^2)}{\sum_q \tilde{f}_1^q(x, z^2 b_T^2)\tilde{D}_1^q(z, b_T^2)}, \tag{5}$$

using measured double spin asymmetries as functions of P_{hT} [4], for fixed x, y, and z bins. Here b_T is the Fourier conjugate of P_{hT}. The Fourier transforms of the helicity-dependent cross sections, $\sigma^{\pm}(b_T)$, can be extracted by integration (analytic models) or summation (for data and MC) over the hadronic transverse momentum, weighted by a Bessel function J_0,

$$\tilde{\sigma}^{\pm}(b_T) \simeq S^{\pm} = \sum_{i=1}^{N^{\pm}} J_0(b_T P_{hT,i})\,. \tag{6}$$

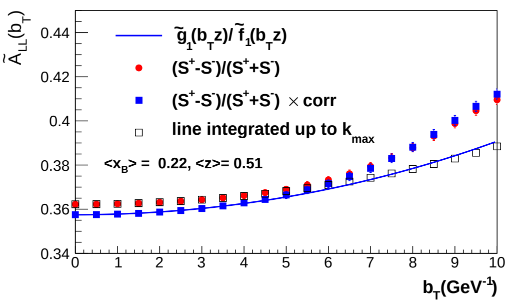

Figure 2: (Color online) Bessel-weighted asymmetry vs b_T with and without the correction, together with analytical and numerical comparison from the MC. See the text for more details.

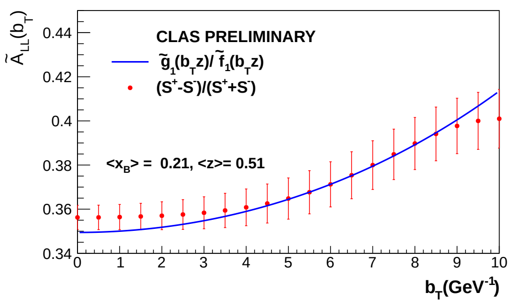

Figure 3: (Color online) Bessel-weighted asymmetry vs b_T from the electroproduction of neutral pions. Blue line is the same as in the Fig. 2. See the text for more details.

The Bessel-weighted asymmetry obtained from the simulated events is shown in Fig. 2 as function of b_T with filled (red) circles, while the analytic expression $\frac{\tilde{g}_1(x,b_T)}{\tilde{f}_1(x,b_T)}$ using $\langle k_\perp^2 \rangle_{g_1}$ and $\langle k_\perp^2 \rangle_{f_1}$ from the fits to $k_\perp^2$ distributions from the same MC sample is depicted by the (blue) full line. For values $b_T < 6$ GeV^{-1}, which corresponds to about 1 fm, the Bessel-weighted asymmetries could be extracted with an accuracy of 2.5%, although with a systematic shift. This clear systematic shift between the extracted and calculated asymmetries is due to the kinematic restrictions introduced by energy and momentum conservation, as well as binning effects, which deform the Gaussian shapes of the $k_\perp$ and $p_\perp$ distributions. In experiments, there is always a cutoff at high P_{hT} due to acceptance and the small cross section, as well as a cutoff at small P_{hT} where the azimuthal angles are not well defined due to the experimental resolution. These restrictions in P_{hT} directly affect the extracted $k_\perp$ and $p_\perp$ distributions and yield the mentioned distortion of Gaussian shapes which result in the systematic shift. Obviously, this shift depends on experimentally introduced restrictions for the accessible P_{hT} range.

We discussed two approaches in [14, 15] which take these conditions into account, one corrects the data (using asummptions) the other applies limits to the integration range for the intrinsic

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transverse parton momenta when calculating the asymmetry. The model-dependent correction of MC is shown in Fig. 2 by the (blue) filled squares. The extracted asymmetry now matches the theoretical curve for values $b_T < 6$ GeV^{-1}. Alternatively, limited numerical integration over intrinsic transverse momenta in the calculation of the asymmetry, where the integration limits correspond to the accessible experimental P_{hT} range, yields a calculated asymmetry that describes correctly the experimental situation without introducing a model dependence. This is shown in Fig. 2 by the (black) open squares.

In Fig. 3 we present a preliminary measurement from the E05113 CLAS dataset of the Bessel-weigthed asymmetry vs b_T for neutral pion electroproduction in SIDIS of 5.8 GeV polarized electrons from a longitudinally polarized ammonia target using the CEBAF Large Acceptance Spectrometer (CLAS) at the Thomas Jefferson National Accelerator Facility. The theoretical curve in Fig. 3 is the same as in the Fig. 2. Deep-inelastic scattering events were selected by requiring $Q^2 > 1\text{GeV}^2$ and $W^2 > 4\text{GeV}^2$. where W is the invariant mass of the hadronic final state. Events with missing-mass values for the $e\pi^0$ system that are smaller than 1.5 GeV ($M_x(e\pi^0) < 1.5\text{GeV}$) were discarded to exclude contributions from exclusive processes. Error bars are only statistical. An additional 5% scaling uncertainty due to the beam and target polarization measurements should be added. Another source of systematic uncertainty is the dilution factor which is estimated to be within a few percent for each b_T point. The measured Bessel-weigthed asymmetry vs b_T for neutral pions is consistent with the MC points, which is an indication that the ratio of relative widths of $g_{1L}(x,k_\perp)$ and $f_1(x,k_\perp)$ in the MC are realistic.

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