Extracting TMDs from CLAS12 Data

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Abstract—We present studies of double longitudinal spin asymmetries in semi-inclusive deep inelastic scattering using a new dedicated Monte Carlo generator, which includes quark intrinsic transverse momentum within the generalized parton model based on the fully differential cross section for the process. Additionally we employ Bessel-weighting to the MC events to extract transverse momentum dependent parton distribution functions and also discuss possible uncertainties due to kinematic correlation effects.

DOI: 10.1134/S1063779614010031

1. FULLY DIFFERENTIAL SIDIS CROSS SECTION

The study of the 3-dimensional structure of protons and neutrons is one of the central issues in hadron physics, with many dedicated experiments, either running (COMPASS at CERN, CLAS and Hall-A at JLab, STAR and PHENIX at RHIC), approved (JLab 12 GeV upgrade, COMPASS-II) or being planned (ENC/EIC Colliders). The transverse momentum dependent (TMD) parton distribution (PDF) and fragmentation functions (FF) play a crucial role in gathering and interpreting information towards a true 3-dimensional imaging of the nucleons. TMDs can be accessed in several experiments, but the main source of information is semi-inclusive deep inelastic scattering (SIDIS) of polarized leptons off polarized nucleon. For SIDIS, the theoretical formalism is described in a series of papers [1, 2] using tree level factorization [3] where the standard momentum convolution integral [4] relates the quark intrinsic transverse momentum to the transverse momentum of the produced hadron $P_{T}$ in semi-inclusive processes.

In this work we present a model independent extraction of the ratio of polarized, $g_1$, and unpolarized, $f_1$, TMDs using a Monte Carlo (MC) based on fully differential cross section, in which we re-construct the final hadron transverse momentum after MC integration over the intrinsic quark transverse momenta. In the MC generator we used the model described in Ref. [1] that was numerically further evolved in [2]. The Bessel-weighted asymmetry, providing access to the ratio of Fourier transforms of $g_1$ and $f_1$, has been extracted. The uncertainty of the extracted TMDs was estimated using different input models for distribution and fragmentation functions.

A fully differential Monte-Carlo generator has been developed to describe the SIDIS process when a final state hadron is detected with the final state lepton,

$$\ell (l) + N(P) \rightarrow \ell (l') + h(P_h) + X,$$

where $\ell$ is the lepton, $N$ the proton target and $h$ the observed hadron (four-momenta notations are given in parentheses). The virtual photon momentum is defined $q = l - l'$ and its virtuality $Q^2 = -q^2$.

The fully differential SIDIS cross section used in MC is given by [1]:

$$\frac{d\sigma}{dxdydzdp_{T}^{2}dk_{T}^{2}} = K\left[\sum_{q}J(f_{q}(x,k_{T})D_{q,h}(z,p_{T})
+ \lambda x\sqrt{1-\epsilon g_{q}(x,k_{T})D_{q,h}(z,p_{T})}\right],$$

where the summation runs over the quark flavors and $\epsilon$, $K(x, y)$ and $J(x, Q^2, k_{T})$ are some kinematic factors defined by the elementary scattering process [1], $x$ is the Bjorken variable, $k_{T}$ is the initial quark transverse momentm, $p_{T}$ is the transverse momentum of the final hadron with respect to scattered quark, and $y$ and $z$ are the fractional energies of the virtual photon and detected hadron. For our studies we used simple factorized Gaussians for the $f_{1}(x, k_{T})$ and $g_{1}(x, k_{T})$ distribution functions and $D_{1}$ fragmentation function, with widths given by fits from available world data.

Figure 1 shows the two dimensional plot of $k_{T}^{2}/Q^{2}$ versus $x$. One can see a clear correlation between the transverse and longitudinal momenta, where the dashed black curves [2] defining the upper bounds. Restrictions at large $x$ come from the energy and momentum conservation and at small $x$ from the

\textsuperscript{1}The article is published in the original.
Fig. 1. The $k_z^2/Q^2$ versus $x = x_B$ is presented for 11 GeV electron beam. Black dashed lines are from [2], with proton mass zero approximation. Events above black dashed curve are due to the hadron mass. Red curves are calculated under the $k_z > 0$ condition with non-zero hadron mass and for two $Q^2$ values. Electron beam energy is 11 GeV.

Fig. 2. Extracted Bessel-weighted asymmetry versus $b_T$ with and w/o correction, compared to values calculated analytically and numerically directly from the input. The MC sample was produced assuming simple Gaussian DFs and FFs with $\langle k_z^2 \rangle_{s_i} = 0.8 \langle k_z^2 \rangle_{\tilde{s}_i}$ and $g_{1i}(x) = f_{1i}(x)x^{0.7}$.

where $b_T$ is the Fourier conjugate of the $P_{hT}$. The Fourier transforms of 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 $J_0$.

$$\sigma^\pm(b_T) = S^2 = \sum_{i = 1}^{N^2} J_0(b_T P_{hT,i}).$$

In the Fig. 2 the red points represent the outcome of the Bessel-weighted asymmetries from the MC sample, while the blue curve represents the analytical expression $\tilde{g}_i(x, z b_T)/\tilde{f}_i(x, z b_T)$ using $\langle k_z^2 \rangle_{s_i}$ and $\langle k_z^2 \rangle_{\tilde{s}_i}$ from the fits to $k_z^2$ distributions from the same MC sample.

Within the $b_T$ range of $b_T < 5 \sim 6 \text{ GeV}^{-1} = 1 \text{ fm}$ the Bessel-weighted asymmetries could be extracted with a minimum of 2.5% accuracy, although with some systematic shift. The shift observed in the reconstructed value is due to the kinematical restriction introduced by energy and momentum conservation [2], which deforms the Gaussian shapes of the $k_z$ and $p_\perp$ distributions. In experiment there is always a cutoff at high $P_{hT}$ due to the acceptance and low cross section, as well as a cutoff at small $P_{hT}$, where the azimuthal angles are not well defined. A correction factor, accounting for the missing $P_{hT}$ range above the maximum value accessible ($P_{\text{max}}$) in a given experiment, was estimated, based on an analytic calculation of the contribution above that value. The systematic uncertainty of that correction could be esti-
mated from the variation of the maximum $P_{\text{max}}$ within the resolution of the experiment. In Fig. 2 the blue filled squares represent this correction using the Gaussian distributions and the open black squares represent the numerical integration up to that exact $k_{\text{max}}$ that we used for correction.

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