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.

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) partonic 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_{hT} in semi-inclusive processes.

In this work we present a model independent extraction of the ratio of polarized, g_1, and umpolarized, 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 Ref. [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 the SIDIS process when a final state hadron is detected with the final state lepton,

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

where ℓ 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]:

$$\frac{d\sigma}{dxdydzd\mathbf{p}_\perp^2 d\mathbf{k}_\perp^2} \quad = \quad K\left[\sum_q J\left\{f_q(x,k_\perp)D_{q,h}(z,p_\perp) + \lambda\sqrt{1-\epsilon}g_q(x,k_\perp)D_{q,h}(z,p_\perp)\right\}\right] \quad (2)$$

where the summation runs over the quark flavors and ϵ, $K(x,y)$ and $J(x,Q^2,k_\perp)$ are some kinematic factors defined by the elementary scattering process [1], x is the Bjorken variable, $k_\perp$ is the initial quark transverse momentm, $p_\perp$ 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 $f_1(x,k_\perp)$ and $g_1(x,k_\perp)$ distribution functions and D_1 fragmentation function, with widths given by fits from available world data.

Figure 1 shows the two dimensional plot of $k_\perp^2/Q^2$ 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 requirement that the parton should move in the forward direction with respect to the parent hadron ($k_z > 0$). The red curves (solid for $Q^2 = 1$ GeV^2 and dashed $Q^2 = 3$ GeV^2) are calculated for a non-zero proton mass, requiring the parton to move in the forward direction with respect to the parent hadron (in Ref. [2] the proton mass was neglected).

We note that the portion of the data above the black dashed curve decreases with decreasing x. Thus, the smaller the x, the smaller is the difference between red solid and red dashed curves implying a diminshing role of the hadron mass at higher Q^2.

2 Bessel-weighted extraction of the double spin asymmetry A_{LL}

Extraction of the double spin asymmetry A_{LL}, defined as the ratio of difference and sum of electroproduction cross sections for antiparallel, σ^+, and parallel, σ^-, configurations of lepton and nucleon spins, has been performed using the Bessel-weighting procedure described in Ref. [5]. Within that approach one can extract the Fourier tarnsform of the double spin asymmetry, $A_{LL}^{J_0(b_T P_{hT})}(b_T)$, using measured double spin asymmetries as a function of the P_{hT} [6], for fixed x, y, and z bins.

$$A_{LL}^{J_0(b_T P_{hT})}(b_T) = \frac{\tilde{\sigma}^+(b_T) - \tilde{\sigma}^-(b_T)}{\tilde{\sigma}^+(b_T) + \tilde{\sigma}^-(b_T)} = \frac{\tilde{\sigma}_{LL}(b_T)}{\tilde{\sigma}_{UU}(b_T)} = \sqrt{1-\varepsilon^2}\frac{\sum_q \tilde{g}_1^q(x, z^2 b_T^2)\tilde{D}_1^q(z, b_T^2)}{\sum_q \tilde{f}_1^q(x, z^2 b_T^2)\tilde{D}_1^q(z, b_T^2)}, \quad (3)$$

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,

$$\tilde{\sigma}^{\pm}(b_T) \simeq S^{\pm} = \sum_{i=1}^{N^{\pm}} J_0(b_T P_{hT,i})\,. \quad (4)$$

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 $\frac{\tilde{g}_1(x,zb_T)}{\tilde{f}_1(x,zb_T)}$ using $< k_\perp^2 >_{g_1}$ and $< k_\perp^2 >_{f_1}$ from the fits to $k_\perp^2$ distributions from the same MC sample.

Within the b_T range of $b_T < 5 \sim 6$ GeV$^{-1} \simeq 1\ fm$ 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 deformes the Gaussian shapes of the $k_\perp$ 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_{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 estimated from the variation of the maximum P_{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_{max}^2 that we used for correction.

References

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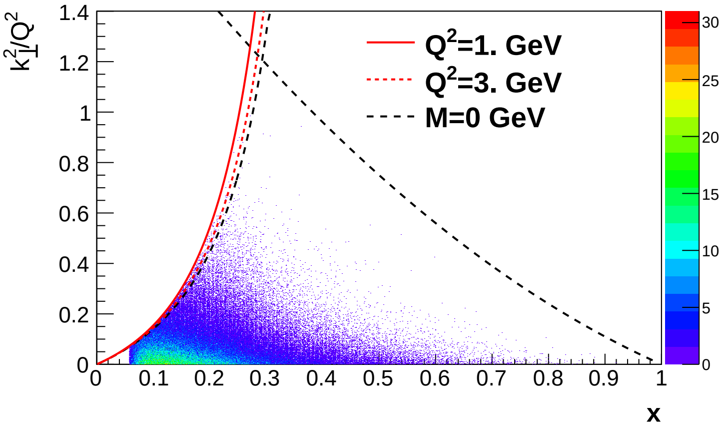

Figure 1: The $k_\perp^2/Q^2$ versus $x = x_B$ is presented for 11 GeV electron beam. Black dashed lines are from [2], with proton mass zero approximation. Events above black dashed curve are due to the hadron mass. Red curves are calculated under the $k_z > 0$ condition with non-zero hadron mass and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

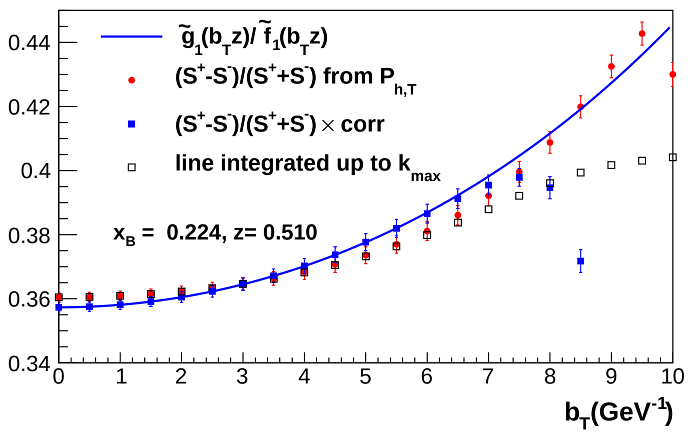

Figure 2: Extracted Bessel-weighted asymmetry versus b_T with and w/o correction, compared to values calculated analytically and numerically directly from the input. The MC sample was produced assuming simple Gaussian DFs and FFs with $< k_\perp^2 >_{g_1} = 0.8 < k_\perp^2 >_{f_1}$ and $g_1(x) = f_1(x)x^{0.7}$.