# The TMD program at CLAS and CLAS12

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## Abstract

Transverse-momentum-dependent parton distributions (TMDs) are now recognized as crucial ingredients for a complete understanding of the dynamics of confined partons especially in the non-perturbative regime of QCD. They allow for a 3-dimensional description of the nucleon in momentum space, and could provide insights into the yet unmeasured quark orbital angular momentum. At CLAS several TMDs are explored in Fourier analysis of azimuthal asymmetries measured in semi-inclusive DIS. An overview of the main CLAS results as well as selected CLAS12 projected results is presented.

# 1 The non-collinear structure of nucleons

Thanks to four decades of deep-inelastic-scattering (DIS) experiments performed in complementary kinematic regimes, we have nowadays a relatively precise knowledge of the longitudinal-momentum and longitudinal-spin distributions of quarks in the nucleon, where "longitudinal" refers to the direction parallel to that of the exchanged virtual photon (the hard probe). These distributions, described by the two collinear parton distribution functions (PDFs) $f_1(x)$ and $g_1(x)$, map the nucleon structure in a one-dimensional space, along the axis of the absorbed photon. Here $x$ denotes the Bjorken variable. When the transverse momentum $\mathbf{p}_T$ of the quarks is not integrated out, a variety of new PDFs arise, describing correlations between the quark or the nucleon spin with the quark transverse momentum (*spin-orbit correlations*). These poorly known transverse-momentum-dependent PDFs (TMDs) encode information on the 3-dimensional structure of nucleons and are increasingly gaining theoretical and experimental interest. Experimentally the TMDs can be probed in semi-inclusive DIS (SIDIS), where a final-state hadron is detected in coincidence with the scattered lepton. The identification of the final-state hadrons (e.g. $\pi$, $K$, etc) provides unique information on the quark flavors involved in the scattering process (*flavor tagging*). At leading-twist, eight TMDs enter the SIDIS cross section, parametrized in terms of structure functions (SFs), in conjunction with a fragmentation function (FF) [1]: the poorly known Collins function $H_1^{\perp}(z, \mathbf{k}_T^2)$, or the standard unpolarized $D_1(z, \mathbf{k}_T^2)$ FF. Here $z$ and $\mathbf{k}_T$ denote respectively the fraction of the energy of the exchanged virtual photon carried by the produced hadron and the transverse momentum arising from the fragmentation process.

## 2 Accessing TMDs at CLAS

The CLAS spectrometer [2] was divided into six identical sectors by the superconducting coils of the main toroidal magnet. It was operated with a highly-polarized (up to 85%) $0.8 - 6.0$ GeV continuous electron beam provided by the CEBAF accelerator facility and internal solid or liquid targets. Since no transversely polarized targets were used, three leading-twist TMDs were explored at CLAS (besides several higher-twist TMDs not discussed here): the Boer-Mulders function $h_1^\perp(x, p_T)$, the helicity function $g_1(x, p_T)$, and the "worm-gear" function $h_{1L}^\perp(x, p_T)$. The Boer-Mulders function contributes to the unpolarized cross section $\sigma_{UU}$ through the SF $F_{UU}^{\cos(2\phi)}$, the helicity function contributes to the doubly-polarized cross-section $\sigma_{LL}$ through the SF $F_{LL}$, requiring longitudinally polarized beam and target, and the worm-gear function contributes to the $\sigma_{UL}$ cross section through the SF $F_{UL}^{\sin(2\phi)}$, requiring unpolarized beam and longitudinally polarized target [1]. Here $\phi$ denotes the azimuthal angle of the produced hadron with respect to the scattering plane.

The Boer-Mulders function was probed through the $\langle\cos(2\phi)\rangle_{UU}$ asymmetry moment for positive pions. The results [3], extracted in a two-dimensional analysis ($z$ bins as a function of the squared hadron transverse momentum $P_T^2$ and *vice-versa*), show positive amplitudes in the low-z and high-$P_T^2$ regions, where they exhibit a strong kinematic dependence. The predicted amplitudes are very small and agree with data only in the high-$z$ and low-$P_T^2$ regions, where the measured amplitudes are consistent with zero. The results for the higher-twist $\langle\cos\phi\rangle_{UU}$ term, also sensitive to the Boer-Mulders function (together with the *Cahn effect*) are significantly far from zero in the full kinematic range and show a sign change (positive to negative) towards high $P_T^2$. In this case, the predicted amplitudes exhibit similar trends but are systematically and substantially larger.

The helicity function was probed through the $A_1$ double-spin asymmetry, extracted from the relation:

$$A_1 \propto \frac{F_{LL}}{F_{UU,T}} \propto \frac{g_1 \otimes D_1}{f_1 \otimes D_1} \approx K \cdot \frac{N^+ - N^-}{N^+ + N^-} \ , \tag{1}$$

where the coefficient $K$ takes into account the depolarization factor $D'(y)$, the $NH_3$ target dilution factor and the measured beam and target polarizations ($P_B \approx 70\%$, $P_t \approx 75\%$), and $N^+$ ($N^-$) denotes the luminosity-weighted yields for parallel (anti-parallel) beam and target polarizations. The symbol $\otimes$ stands for a convolution integral over quark transverse momenta. The published CLAS results [4] for charged and neutral pions show a positive asymmetry $A_1$ rising with $x$ and are well reproduced by leading-order GRSV calculations. In particular, the results for positive pions are consistent with the HERMES results, though with a significantly higher statistical precision and despite the relatively large (about a factor of 3) difference in average $Q^2$ between the two experiments. Results for $A_1$ were also reported as a function of the hadron transverse momentum $P_T$, showing fairly flat distributions for charged and neutral pions. These results were compared with theoretical calculations based on the use of different values for the ratio $R$ of the $p_T$ widths for $g_1(x, p_T)$ and $f_1(x, p_T)$, showing a preference for $R < 1$. New, high statistics data are currently being analyzed.

The worm-gear $h_{1L}$ was inspected through the single-spin asymmetry:

$$A_{UL} \approx K' \cdot \frac{N^+ - N^-}{N^+ + N^-} \propto A_{UL}^{\sin(2\phi)} \sin(2\phi) + \propto A_{UL}^{\sin(\phi)} \sin(\phi) \ . \qquad (2)$$

The published results for the leading-twist term $A_{UL}^{\sin 2\phi}$ [4] show non-zero amplitudes for $\pi^+$ and $\pi^-$ (in contrast to HERMES data, which are consistent with zero).

## 3 The TMDs physics at CLAS12

In the 12 GeV era of JLab the CLAS12 spectrometer, with its unique combination of large acceptance, high luminosity (up to $\sim 10^{35}$ cm$^{-2}$s$^{-1}$) and excellent particle identification (with the combined use of TOF and RICH detectors), will allow for precise measurements of azimuthal asymmetries over a broad kinematic range and in particular in the poorly explored large-$x$ (valence) and large-$P_T$ domains. In addition, the use of a transversely polarized H/D target (*HD-Ice*) will allow us to probe other TMDs (the Sivers function, transversity, "pretzelosity" and the worm-gear $g_{1T}$), not yet explored at CLAS. A dense program of TMDs experiments with polarized and unpolarized targets has already been approved for the first years of operation. In Fig. 1 the kinematic coverage and the expected statistical uncertainties for $\pi^+$, based on 100 days of data-taking, are shown in 4-dimensional bins.

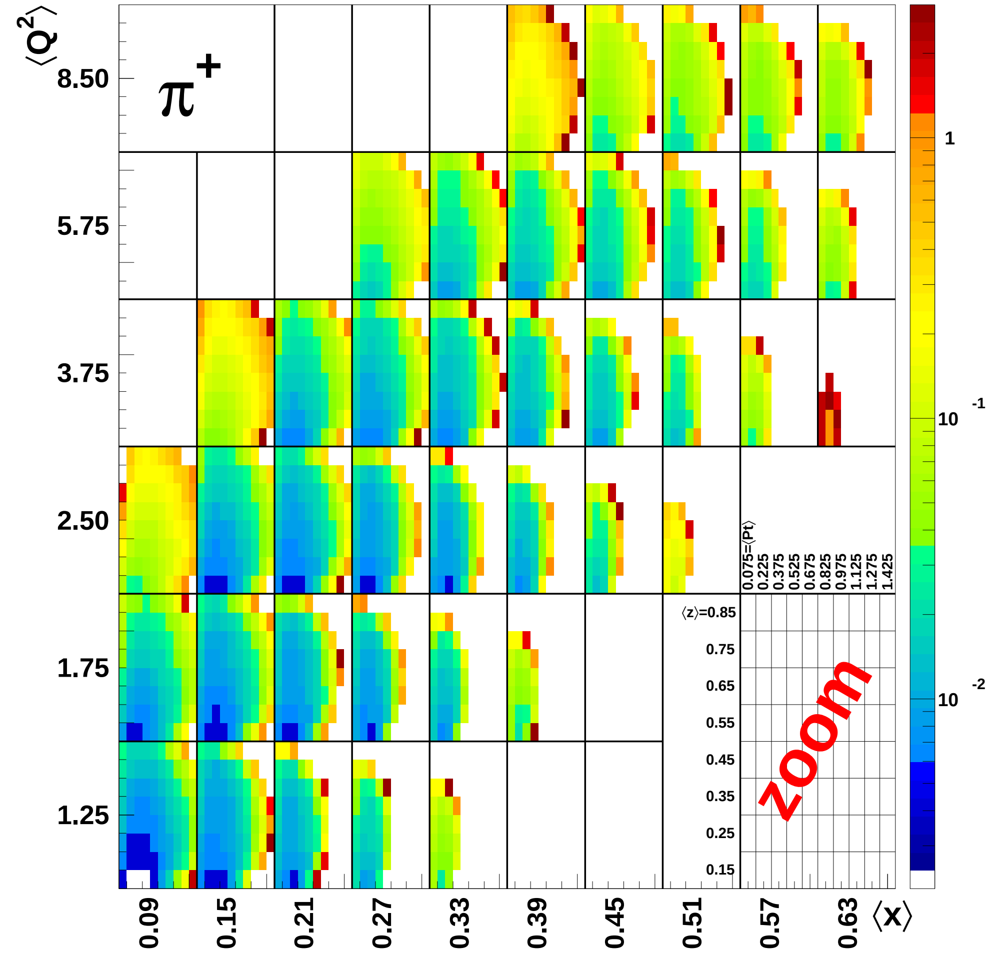

Figure 1: CLAS12 kinematic coverage in 4-dimensional bins ($x$, $Q^2$, $z$, $P_T$). Colors indicate the absolute statistical uncertainty expected in every bin for $\pi^+$ transverse target single-spin asymmetries after 100 days of data-taking.

# References

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