Extraction of first tranverse moment of Sivers and $g_{1T}^{\perp}$ TMD PDFs from polarized SIDIS COMPASS data

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Abstract

As part of its program, COMPASS is exploring the transverse spin structure of the nucleon by measuring nucleon spin dependent azimuthal asymmetries in semi-inclusive deep inelastic scattering (SIDIS). These asymmetries are related to the specific convolutions of certain transverse-momentum-dependent (TMD) *twist-2* and *higher twist* parton distribution functions (PDFs) and fragmentation functions (FFs). The TMD PDFs play a fundamental role describing the parton-longitudinal and -transverse momenta distributions and their correlations with nucleon and quark spins. In this work, the Sivers TMD PDF first k_T moment extraction is verified using the re-processed 2010 data. Using the same method, we have extracted the $A_{LT}^{\cos(\phi_h-\phi_S)}$ P_T-weighted asymmetries, which are related to the first moment of the $g_{1T}^{\perp}$ TMD PDF. This leading-twist distribution describes the correlation between the longitudinal polarization of a quark and the transverse spin of a nucleon. The first moment of the TMD PDF is evaluated for the first time for u and d quarks from COMPASS data.

I. INTRODUCTION

A. COmmon Muon Proton Apparatus for Structure and Spectroscopy (COMPASS)

Located in the North Area of the SPS at CERN, COMPASS is a high energy physics experiment and one of its main goals is to explore the transverse spin structure of the nucleon by measuring nucleon spin dependent azimuthal asymmetries in semi-inclusive deep inelastic scattering (SIDIS). In 2010 COMPASS measured the complete set of SIDIS transverse-spin-dependent asymmetries (TSAs), using a longitudinally polarized muon beam striking a transversely polarized NH_3 target. Particular attention was given to the study of hadron transverse momentum P_T-weighted Sivers asymmetry which is used to extract first transverse moments of the Sivers TMD PDF.

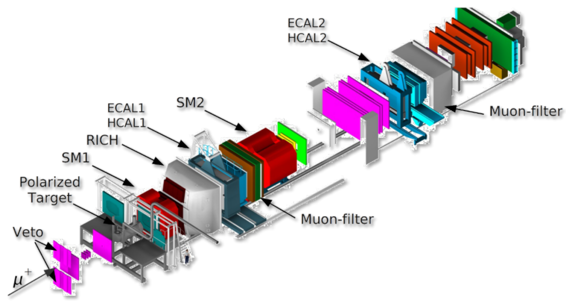

Figure 1. Two stage spectrometer setup for Muon 2010 Run

The data was taken with a longitudinally polarized muon beam and a transversely polarized solid NH_3 target, cooled to 0.6 mK. The two stage spectrometer was entirely downstream of the target, primarily detecting pions and kaons.

B. Parton Distribution Functions

According to Quantum Chromodynamics (QCD), the theory of strong interactions, the transverse-momentum-dependent (TMD) parton distribution functions (PDFs) play a crucial role in the theoretical description of high energy reactions, as they describe the internal structure of hadrons, providing a three-dimensional picture of a fast moving nucleon in momentum space. For a polarized nucleon, within the *twist-2* approximation there are eight quark intrinsic transverse-momentum k_T-dependent (TMD) PDFs describing the distributions of longitudinal and transverse momenta of partons and their correlations with nucleon and quark polarizations, as shown below in Table I, where the focus of this study is bolded (Ref. [1]).

		Nucleon Polarization		
		U	L	T
Quark Polarization	U	$f_1^q(x, k_T^2)$ Number Density		$f_{1T}^{\perp q}(x, k_T^2)$ **Sivers**
	L		$g_1^q(x, k_T^2)$ Helicity	$g_{1T}^{\perp q}(x, k_T^2)$ **Worm-Gear T**
	T	$h_1^{\perp q}(x, k_T^2)$ Boer-Mulders	$h_{1L}^{\perp q}(x, k_T^2)$ Worm-Gear L	$h_{1T}^q(x, k_T^2)$ Transversity $h_{1T}^{\perp q}(x, k_T^2)$ Pretzelosity

Table I. *Twist-2* TMD PDFs classified according to quark polarization (rows) and nucleon polarization (columns). U, L, and T mean unpolarized, longitudinally polarized, and transversely polarized respectively. Here, k_T is the quark transverse momentum and x is the longitudinal momentum fraction.

C. Semi-Inclusive Deep Inelastic Scattering

In the semi-inclusive deep inelastic scattering process, a lepton scatters off a nucleon target, in leading order, approximated as a single photon exchange, with the photon having a virtuality Q^2. The produced hadrons are also required to have a transverse momentum to be much lower than Q. This process probes the structure of the nucleon through the TMD PDFs by measuring the nucleon spin dependent azimuthal asymmetries. Applying the so-called TMD factorization theorem to the SIDIS cross section, one can express the cross section as a convolution of scale-dependent TMD PDFs, perturbatively calculable hard-scattering partonic cross sections, and parton TMD fragmentation functions (FFs)(see [2, 3] and references therein).

The SIDIS process is the reaction

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

where ℓ is the beam lepton, N the target nucleon, and h the measured hadron, with the corresponding four-momenta in parentheses. The lepton mass is considered negligible, and M and M_h are the masses of the nucleon and hadron, respectively. As is convention, $q = l - l'$ and $Q^2 \equiv -q^2$. The variables

$$x = \frac{Q^2}{2P \cdot q}, \quad y = \frac{P \cdot q}{P \cdot l}, \quad z = \frac{P \cdot P_h}{P \cdot q}, \tag{2}$$

are used throughout the analysis, all measured in the target rest frame. The interaction is diagrammed in Fig. 2. The azimuthal angle ϕ_h defines the orientation of the hadron momentum, while ϕ_S defines the orientation of the nucleon spin, both with respect to the lepton scattering plane and calculated about the virtual-photon momentum direction.

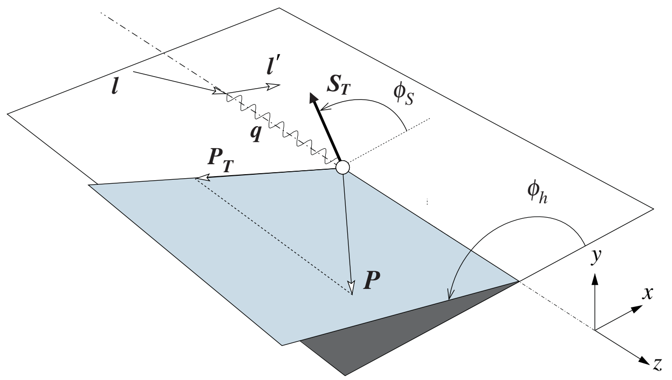

Figure 2. Definition of the kinematics of the interaction in the target rest frame

II. ASYMMETRIES STUDIED

This work is dedicated to the study of Sivers ($A_{UT}^{\sin(\phi_h - \phi_S)}$) [4] and the Kotzinian-Mulders ($A_{LT}^{\cos(\phi_h - \phi_S)}$) [5] asymmetries, where ϕ_h is the azimuthal angle of the hadron momentum, while ϕ_S defines the orientation of the nucleon spin (see Fig. 2). In the notation A_{BN}^{w}, B and N take on three values: U (Unpolarized), L (Longitudinally polarized), or T (Transversely polarized), describing the beam (B) and the nucleon (N) polarizations. The superscript represents the corresponding azimuthal modulation. The Sivers asymmetry, which is probed experimentally with an unpolarized lepton beam interacting with a transversely polarized nucleon, gives access to the Sivers TMD PDF describing the correlation between the parton intrinsic momentum and the nucleon spin. The $A_{LT}^{\cos(\phi_h - \phi_S)}$ term is extracted from measurements with a longitudinally polarized beam interacting with a transversely polarized nucleon and is related to the Worm-Gear TMD PDF, $g_{1T}^{\perp}$, which describes the correlation between the parton k_T and the nucleon spin when the parton is longitudinally polarized.

III. COMPUTATIONAL TOOLS

A. LHAPDF Library

For this analysis, three main C++ or FORTRAN based software tools were used. The first, LHAPDF [6], is a package designed to calculate the PDFs for each quark flavor from a set of x and Q^2 values. The PDF describes the probability density for a quark to have momentum fraction x at the given Q^2 within the nucleon. While the proton is considered to consist of two up quarks and a down quark, these are only valence quarks. There are also the sea-quarks arising from gluons splitting into quark-antiquark pairs within the proton, and these sea-quarks contribute to the overall cross-section for the SIDIS interaction. In Fig. 3, an example plot is shown, where the u and d carry a distinctive higher fraction than their antiquark counterparts, leading to the valence uud structure of the proton.

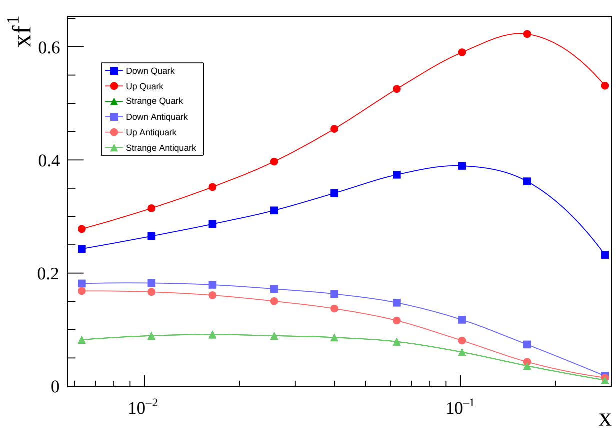

Figure 3. Example of PDF from LHAPDF showing the first three generations of quarks in proton

B. Fragmentation Function Library

The Fragmentation Function (FF) Library describes the fragmentation function, or the probability density of fragmented mesons from a collision to carry a fraction z of the parton's longitudinal momentum at a given Q^2. For this study, two common FF-sets were tested, DSS-07 [7] and Kretzer [8]. Final results are produced using the DSS-07 set (which is known to better describe the experimental data) and its integrated FF (over z), and an example of the latter is shown in Fig. 4. The kinematic cut forced $z > 0.2$.

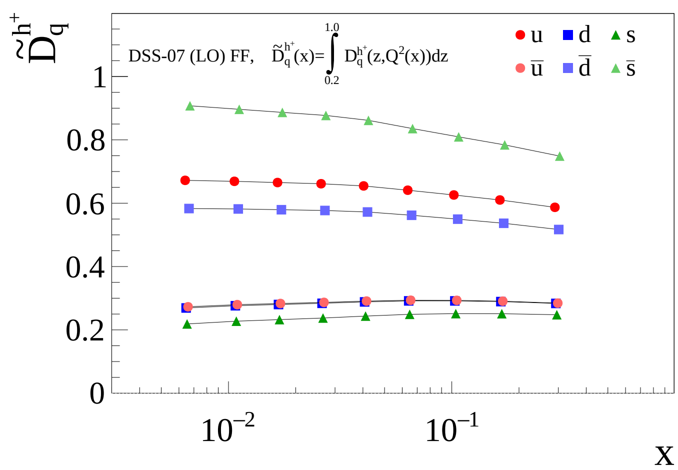

Figure 4. Integrated Fragmentation Function for positively charged hadrons.

C. ROOT

The integration and plotting were done by means of ROOT package [9], a software developed at CERN for data analysis purposes. A useful application of ROOT to this project was the TMultigraph class, which allowed each quark flavor to have its own graph generated individually, and then all the graphs could be combined onto one canvas easily. The TLatex features allow math symbols to be included as labels effortlessly, and the uncertainty handling features simplified graph creation.

IV. SIVERS FIRST TRANSVERS MOMENT VERIFICATION

The main project consisted of two parts, the first of which was a verification of the Sivers first transverse moment extraction by using reprocessed 2010 data, which has 10% more statistics than the original run, mostly from improved detector calibrations. The Sivers distribution (discussed more in Ref. [10]) describes the correlation of k_T for an unpolarized quark with the spin of a transversely polarized nucleon, and the first moments are extracted from the measurement of $A_{UT}^{\sin(\phi_h-\phi_S)}$, or Sivers, asymmetry (shown in Fig. 5). Using the equations derived in Ref. [10], the first transverse moments are presented in Fig. 6.

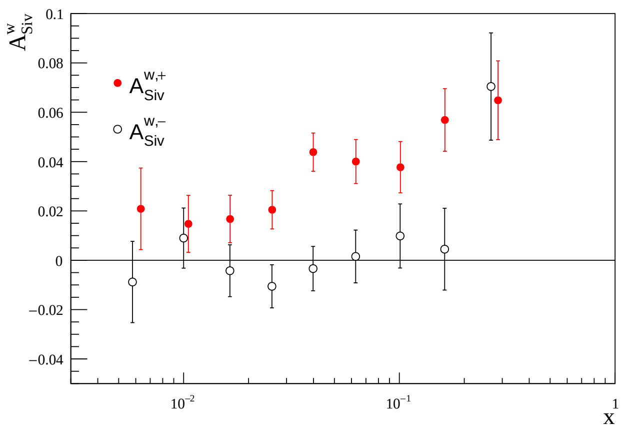

Figure 5. Sivers Asymmetry from reprocessed 2010 data.

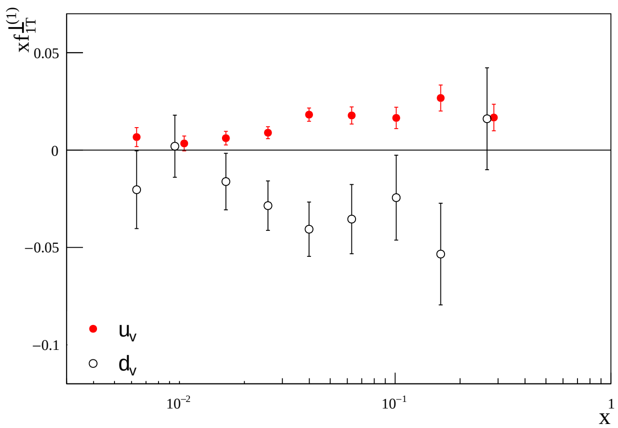

Figure 6. First transverse moment of Sivers distribution from reprocessed 2010 data.

The u-valence (u_V) distribution is clearly positive, while the d-valence (d_V) distribution is negative, however with larger uncertainties. The future COMPASS run in 2021 will use a deuteron target to improve the statistics on these measurements (mainly on d_V).

V. SIMILARITIES BETWEEN SIVERS AND $A_{LT}^{\cos(\phi_h-\phi_S)}$ P_T-WEIGHTED ASYMMETRIES

The formalism used to extract the Sivers first transverse moments can be used for the $g_{1T}^{\perp(1)}$ distribution because the structure functions and P_T-weighted asymmetries are similar. From Ref. [1, 3], the Sivers asymmetry is proportional to

$$F_{UT}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M} f_{1T}^{\perp} D_1\right], \tag{3}$$

while $A_{LT}^{\cos(\phi_h-\phi_S)}$ is proportional to

$$F_{LT}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M} g_{1T}^{\perp} D_1\right]. \tag{4}$$

Looking at Eqs. (3),(4), it is clear how similar the two asymmetries are. This allows us to use the same derivation as in Ref. [10] to extract the first moments of $g_{1T}^{\perp}$.

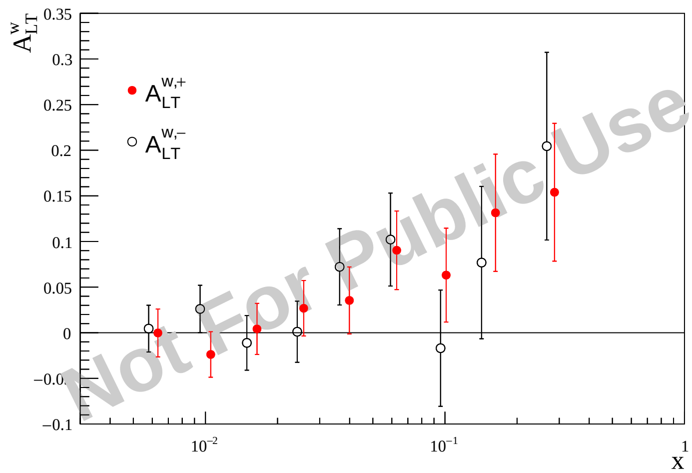

Figure 7. Preliminary $A_{LT}^{\cos(\phi_h-\phi_S)}$ P_T-weighted asymmetry values for u and d quarks.

VI. $A_{LT}^{\cos(\phi_h-\phi_S)}$ P_T-WEIGHTED ASYMMETRY

Following the derivation in Ref. [10], replacing $f_{1T}^{\perp(1)q}$ with $g_{1T}^{\perp(1)q}$ we arrive at the expression (dropping the Q^2 dependence)

$$A_{LT}^{w}(x,z) = \frac{2\sum_q e_q^2 x g_{1T}^{\perp(1)q}(x) D_1^q(z)}{\sum_q e_q^2 x f_1^q(x) D_1^q(z)}, \tag{5}$$

where $D_1^q(z)$ is the fragmentation function and $f_1^q(x)$ is the quark distribution, both integrated over the transverse momentum.

The P_T-weighted asymmetries were extracted separately for positive and negative hadron production. The preliminary P_T-weighted asymmetries are plotted in Fig. 7. At larger x, the positive hadron P_T-weighted asymmetry has positive values. Overall, the $A_{LT}^{\cos(\phi_h-\phi_S)}$ P_T-weighted asymmetry values are much larger than the Sivers P_T-weighted asymmetry.

VII. POINT-BY-POINT EXTRACTION OF FIRST TRANSVERSE MOMENTS

The P_T-weighted asymmetries were used to extract the first transverse moment of the polarized PDF. The asymmetries of Eq. (5) integrated over z produce the relation

$$A_{LT}^{w}(x) = \frac{2\sum_q e_q^2 x g_{1T}^{\perp(1)q}(x) \tilde{D}_1^q}{\sum_q e_q^2 x f_1^q(x) \tilde{D}_1^q}, \tag{6}$$

where

$$\tilde{D}_1^q = \int_{0.2}^1 \mathrm{d}z D_1^q(z). \tag{7}$$

Since the fragmentation functions are evaluated over positive and negative hadrons separately, there are two sets of P_T-weighted asymmetries. Omitting the sea-quark distributions (shown to be negligible [11]), the P_T-weighted asymmetries can be expressed as

$$A_{LT}^{w,\pm} = 2\frac{4xg_{1T}^{\perp(1)u_V}(x)\tilde{D}_1^{u,\pm} + xg_{1T}^{\perp(1)d_V}(x)\tilde{D}_1^{d,\pm}}{9\sum_q e_q^2 x f_1^q(x)\tilde{D}_1^{q,\pm}} \tag{8}$$

For simplicity, let

$$\delta^\pm \equiv 9\sum_q e_q^2 x f_1^q(x)\tilde{D}_1^{q,\pm}, \tag{9}$$

so the valence distributions can be extracted as

$$xg_{1T}^{\perp(1)u_V}(x) = \frac{1}{8}\frac{\delta^+ A_{LT}^{w,+}\tilde{D}_1^{d,-} - \delta^- A_{LT}^{w,-}\tilde{D}_1^{d,+}}{\tilde{D}_1^{u,+}\tilde{D}_1^{d,-} - \tilde{D}_1^{d,+}\tilde{D}_1^{u,-}} \tag{10}$$

$$xg_{1T}^{\perp(1)d_V}(x) = \frac{1}{2}\frac{\delta^- A_{LT}^{w,-}\tilde{D}_1^{u,+} - \delta^+ A_{LT}^{w,+}\tilde{D}_1^{u,-}}{\tilde{D}_1^{u,+}\tilde{D}_1^{d,-} - \tilde{D}_1^{d,+}\tilde{D}_1^{u,-}} \tag{11}$$

Using Eqs (10) and (11), the distribution can be calculated at each point. Using the CTEQ5d parametrization [12] for the distribution functions and the DSS-07 parametrization [7] for the fragmentation functions, the results for the positive P_T-weighted asymmetry as a function of x are displayed in Fig. 8, while the results for the negative P_T-weighted asymmetry as a function of x are in Fig. 9. The uncertainties in the first moments are calculated from the statistical errors of the measured P_T-weighted asymmetries, as in Ref. [10].

VIII. CONCLUSION

This represents the first extraction of the first transverse moments of the $xg_{1T}^{\perp}$ distribution from COMPASS measurements of the $A_{LT}^{\cos(\phi_h-\phi_S)}$ P_T-weighted asymmetries, following the formalism used to extract first transverse moment of the Sivers TMD PDF. While for large x, the u_V first moments tend towards positive nonzero values, large errors prevent drawing any strong conclusions about the first moment for the d_V distribution from this data set. Future COMPASS runs, especially the COMPASS 2021 deuteron run, will improve on these results, both through better statistics and more data on the sea-quark distribution, which was neglected in this analysis.

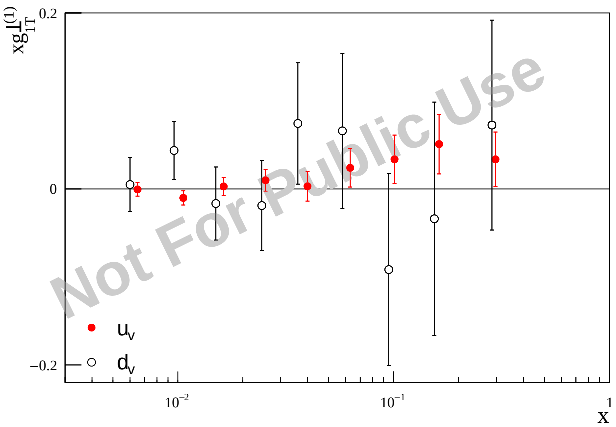

Figure 8. $xg_{1T}^{\perp(1)q}$ using the x, Q^2-values associated with positive hadrons with $z > 0.2$, u in closed red dots and d in open black dots.

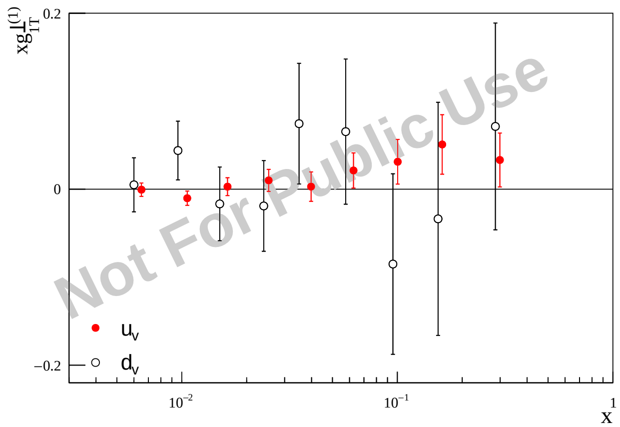

Figure 9. $xg_{1T}^{\perp(1)q}$ using the x, Q^2-values associated with negative hadrons with $z > 0.2$, u in closed red dots and d in open black dots.

IX. ACKNOWLEDGEMENTS

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