High-Statistics Measurement of Collins and Sivers Asymmetries for Transversely Polarized Deuterons

CERN

Maria Levonyan

Armenia

2025

Abstract

During a two-month research stay at CERN as part of the COMPASS experiment, I contributed to the study of the nucleon's transverse spin structure using semi-inclusive deep inelastic scattering ($SIDIS$) of a 160 GeV/c polarized muon beam off a transversely polarized ^{6}LiD target. This work is part of the high-statistics 2022 COMPASS run, which aims to provide the most precise deuteron-target measurements of the Collins and Sivers asymmetries to date, thereby enabling an improved extraction of the transversity distribution and Sivers function for $u-$ and $d-$ quarks.

My contribution focused on the experimental analysis chain for asymmetry determination. After applying standard DIS kinematic cuts to select high-quality events, the data were binned in the kinematic variables x, z, p_T and W, and separated for positive and negative hadrons. The asymmetries were extracted using the quadruple-ratio method, which cancels acceptance effects by exploiting the three-cell target design with regular polarization reversal. Raw Collins and Sivers amplitudes were obtained from sinusoidal fits to the azimuthal distributions of hadrons, then corrected for target polarization, dilution, and depolarization factors to yield the physical asymmetries.

These results, obtained period-by-period and averaged over all stable running periods, show significantly reduced statistical uncertainties—up to a factor of three improvement over previous deuteron measurements. The high precision of this dataset is expected to strongly impact global analyses of transverse-momentum-dependent parton distribution functions ($TMDPDFs$), improve the determination of the nucleon tensor charge, and deepen our understanding of the three-dimensional spin structure of the nucleon.

Contents

Introduction

Understanding the spin structure of the nucleon is a fundamental challenge in hadronic physics. In the framework of Quantum Chromodynamics (QCD), the three-dimensional description of a polarized nucleon involves transverse-momentum-dependent parton distribution functions ($TMDPDFs$), which encode correlations between parton momenta and spins. Of particular interest are the transversity distribution h_1^q and the Sivers function $f_{1T}^{\perp q}$, which can be accessed in SIDIS measurements off transversely polarized nucleon targets. The transversity function is chiral-odd and requires coupling to another chiral-odd function — the Collins fragmentation function — to be observable, leading to the Collins asymmetry in the azimuthal distribution of hadrons. The Sivers function, in contrast, describes a correlation between the intrinsic transverse momentum of an unpolarized quark and the transverse spin of the nucleon, manifesting as the Sivers asymmetry.

The COMPASS experiment at CERN has been a leading facility for such measurements, exploiting a high-energy polarized muon beam and large-acceptance spectrometer to study SIDIS on both proton and deuteron targets. While previous proton measurements showed clear nonzero Collins and Sivers effects, earlier deuteron data suffered from limited statistics, hampering precise extraction of $d-$quark $TMDs$. In 2022, COMPASS performed a dedicated high-statistics run with a transversely polarized ^6LiD target, aiming to significantly reduce uncertainties. The data-taking scheme employed three target cells with alternating spin orientation and regular spin reversal, enabling simultaneous collection of opposite polarization states and minimizing acceptance-related systematics.

Within this context, my work concentrated on the experimental analysis steps for Collins and Sivers asymmetry extraction. This included applying standard DIS kinematic cuts ($Q^2 > 1GeV^2/c^2, 0.1 < y < 0.9, z > 0.2, p_T > 0.1GeV/c$), dividing the data into fine kinematic bins, calculating quadruple ratios for different target cell configurations, and fitting the resulting azimuthal modulations to obtain raw asymmetry amplitudes. The corrected results, after accounting for target polarization, dilution, and depolarization factors, contribute directly to the global analysis of $TMDPDFs$ and the tensor charge.

1 Experimental Setup

The COMPASS physics programme imposes specific requirements to the experimental setup, as illustrated in the Introduction to this report. They are: large angle and momentum acceptance, including the request to track particles scattered at extremely small angles, precise kinematic reconstruction of the events together with efficient PID and good mass resolution. Operation at high luminosity imposes capabilities of high beam intensity and counting rates, high trigger rates and huge data flows. The basic layout of the COMPASS spectrometer, as it was used in 2004, is shown in Fig. 1. Three parts can be distinguished. The first part includes the detectors up stream of the target, which measure the incoming beam particles. The second and the third part of the setup are located downstream of the target, and extend over a total length of 50m. These are the large angle spectrometer (LAS) and the small angle spectrometer (SAS), respectively. The use of two spectrometers for the outgoing particles is a consequence of the large momentum range and the large angular acceptance requirements. Each of the two spectrometers is built around an analysing magnet, preceded and followed by telescopes of trackers and completed by a hadron calorimeter and by a muon filter station for high energy muon identification. A RICH detector for hadron identification is part of the LAS. The SAS includes an electromagnetic calorimeter. The flexibility required by the broad spectrum of the COMPASS physics programme has been implemented by mounting huge setup elements on rails, allowing them to be positioned at variable distances from the experimental target: the RICH, the first hadron calorimeter, the first muon filter, the second analysing magnet and the trackers fixed to it can move longitudinally on rails.

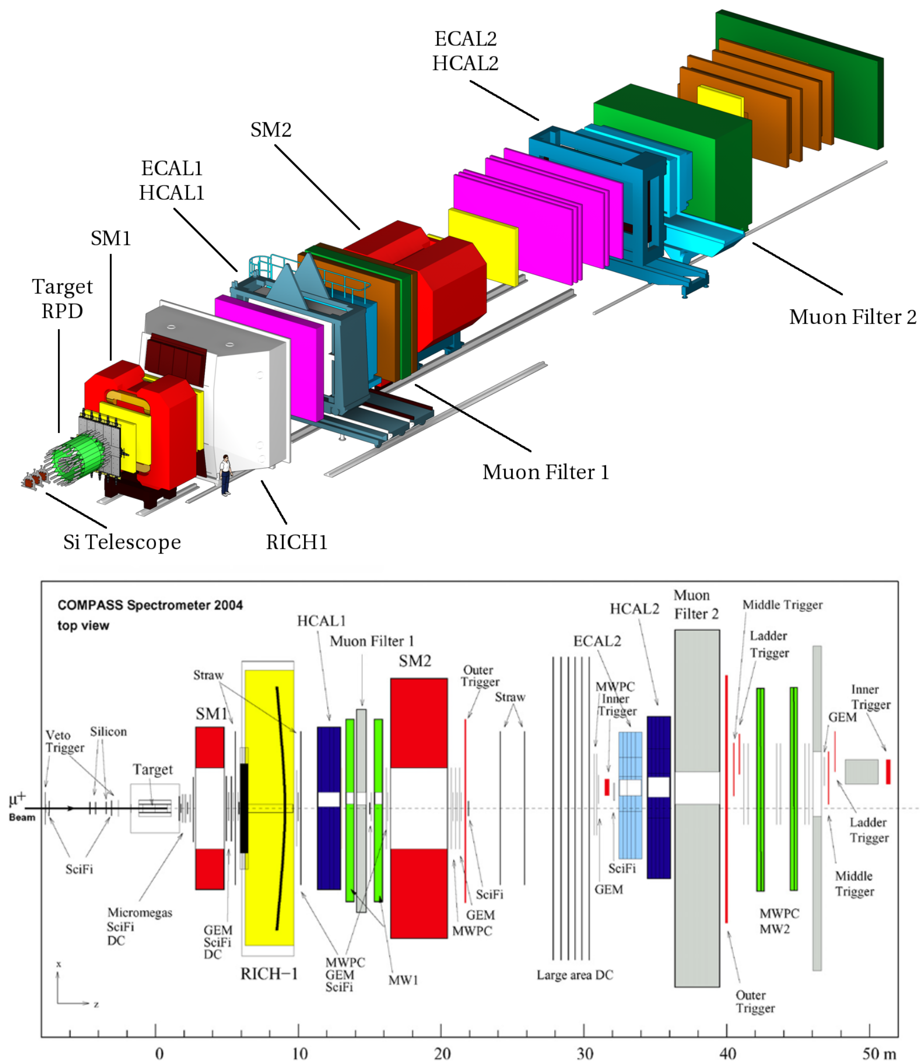

Figure 1: Compass 2004 muon setup (top) artistic view, (bottom) top view [1].

1.1 Beam and Target

The M2 beam line provides secondary beams from the SPS. A primary 400 GeV/c proton beam impinges on a beryllium target to produce secondary hadrons (mainly pions and kaons). A 1.1 km long transfer line allows these hadrons to decay, producing a naturally polarized muon beam through the weak decay mechanism. For the transverse spin program, a 160 GeV/c μ^+ beam is used, with a polarization of about -80% and a momentum spread of $\Delta p/p = \pm 5\%$. The beam's timing and position are measured using silicon strip detectors and scintillating fibre detectors, which are crucial for determining the interaction vertex within the target.

For the 2022 run, a transversely polarized ^{6}LiD target was used. This material was chosen for its favorable dilution factor (~ 0.4) and the high polarization (~ 0.5) achievable. The target consists of three cylindrical cells (3 cm diameter) mounted coaxially with the beam: a central cell (60 cm long) and two outer cells (30 cm long each), separated by 5 cm gaps. Neighboring cells were polarized in opposite vertical directions, allowing for the simultaneous collection of data for both spin orientations. The polarization was maintained by a ^{3}He/^{4}He dilution refrigerator, cooling the target to approximately 50 mK. The target magnet provided a dipole field of up to 0.6 T to hold the polarization transverse to the beam direction. The spin orientation in the entire target was reversed every 3–6 days to minimize systematic effects(Fig. 2).

1.2 Spectrometer

The two-stage magnetic spectrometer is designed for large geometrical acceptance and wide kinematic coverage.

- The **first stage** uses a 1 Tm dipole magnet with an acceptance of ± 200 mrad in both vertical and horizontal planes.
- The **second stage**, located 18 m downstream from the target, uses a 4.4 Tm spectrometer magnet with an acceptance of ± 50 mrad (horizontal) and ± 25 mrad (vertical).

The spectrometer is equipped with a variety of tracking detectors, a RICH counter for particle identification, hadron and electromagnetic calorimeters, and muon filters. This setup allows for the precise reconstruction of the

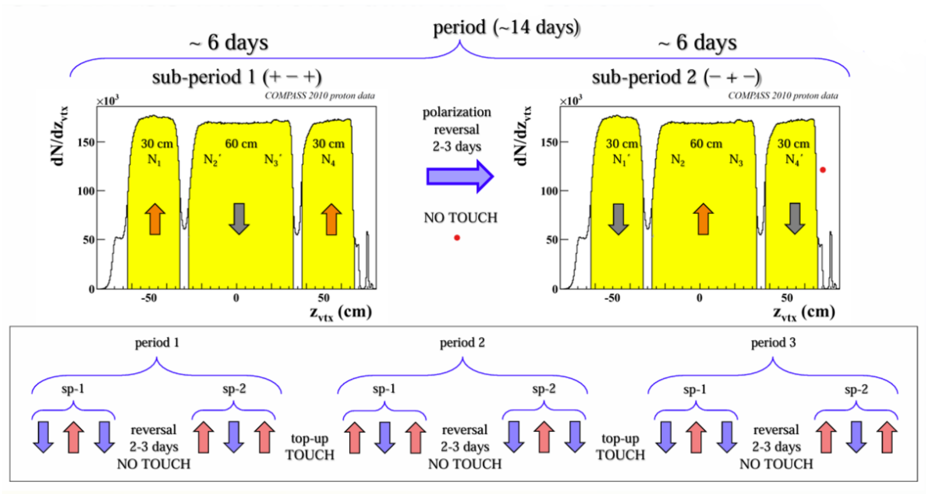

Figure 2: COMPASS transverse data taking scheme

incoming muon, the scattered muon, and the charged hadrons produced in the SIDIS process.

1.3 Data Selection

Candidate SIDIS events were selected according to standard DIS kinematic criteria to ensure the deep-inelastic regime and to suppress backgrounds. The following event-level cuts were applied:

- Photon virtuality: $Q^2 > 1$ $(\mathrm{GeV}/c)^2$.
- Fractional energy of the virtual photon: $0.1 < y < 0.9$.
- Invariant mass of the hadronic final state: $W > 5$ GeV$/c^2$.

Charged hadron selection requirements were:

- Fractional energy: $z = E_h/\nu > 0.2$.
- Transverse momentum: $p_T > 0.1$ GeV$/c$.

Analyses were performed separately for positively and negatively charged hadrons. The selected data sample consists of about 40×10^6 positive hadrons and 32×10^6 negative hadrons, the majority of which are pions. The data were binned following the COMPASS convention in the kinematic variables x, z, and p_T.

1.4 Asymmetry Extraction - Quadruple Ratio Method

The Collins and Sivers azimuthal angles were computed for each hadron:

$$\phi_{\mathrm{Coll}} = \phi_h + \phi_S - \pi, \tag{1}$$
$$\phi_{\mathrm{Siv}} = \phi_h - \phi_S, \tag{2}$$

where ϕ_h is the hadron azimuthal angle and ϕ_S the azimuth of the target spin.

For each kinematic bin and for each of 16 azimuthal intervals, event counts were recorded for the four target segments (two polarization states per cell, from the two sub-periods). The *quadruple ratio* (QR) is defined as:

$$QR(\phi) = \frac{N_1(\phi)N_2'(\phi)N_3'(\phi)N_4(\phi)}{N_1'(\phi)N_2(\phi)N_3(\phi)N_4'(\phi)}. \tag{3}$$

This construction cancels first-order acceptance and luminosity effects related to the three-cell target geometry and the periodic spin reversal.

The $QR(\phi)$ distribution was fitted with the function:

$$f_{\mathrm{QR}}(\phi) = p_0(1 + 8p_1 \sin\phi), \tag{4}$$

where p_1 is the raw amplitude related to the target transverse-spin dependent modulation. The fit parameter p_1 provides the raw Collins (for $\phi = \phi_{\mathrm{Coll}}$) or Sivers (for $\phi = \phi_{\mathrm{Siv}}$) amplitude.

1.5 Corrections

The raw amplitude p_1 was corrected to obtain the physical asymmetry:

1. **Target dilution factor f:** The fraction of polarizable nucleons in ^{6}LiD, calculated for semi-inclusive reactions as a function of x and y. Its mean value is $\simeq 0.38$.

2. **Target polarization P_T:** Measured for each cell and each period using NMR; typical values are about 0.4.

3. **Depolarization factor D_{NN}:** For the Collins asymmetry, the transverse spin transfer coefficient $D_{NN} = (1-y)/(1-y+y^2/2)$ is applied. For the Sivers asymmetry, $D_{NN} = 1$.

The final physical asymmetries are obtained as:

$$A_{\text{Coll}} = \frac{p_1}{f P_T D_{NN}}, \tag{5}$$

$$A_{\text{Siv}} = \frac{p_1}{f P_T}. \tag{6}$$

Systematic uncertainties were evaluated from false-asymmetry studies, splitting the dataset (e.g., by run period), and uncertainties on f and P_T.

2 Results and Discussion

During my research work at CERN Summer Student 2025 Programme with in the COMPASS Collaboration, I contributed to the study of the nucleon spin structure through the analysis of **semi-inclusive deep inelastic scattering (SIDIS)** of high-energy muons off transversely polarized deuteron targets. This effort was part of the recent high-statistics COMPASS program aimed at measuring the **Collins** and **Sivers asymmetries** with unprecedented precision.

Physics Motivation

The internal structure of the nucleon is described not only by the longitudinal momentum distributions of quarks, but also by their intrinsic transverse momentum and spin correlations. Among the eight leading-twist transverse momentum dependent parton distribution functions (TMD PDFs), two play a central role:

- The **transversity function** $h_1^q(x)$, which describes the difference between quarks polarized parallel and anti-parallel to a transversely polarized nucleon.
- The **Sivers function** $f_{1T}^{\perp q}(x, k_T)$, which encodes the correlation between the nucleon's transverse spin and the transverse momentum of unpolarized quarks.

The Sivers function is particularly intriguing, as it reflects final-state interactions of the struck quark and is directly sensitive to QCD dynamics beyond the naive parton model. Measuring Sivers asymmetries allows us to test TMD factorization and provides essential input for the global extraction of spin-dependent PDFs.

Experimental Setup

The COMPASS spectrometer at CERN's SPS M2 beamline provided a **160 GeV naturally polarized muon beam**, which was scattered on a **transversely polarized ^{6}LiD target**. The target design, with cells polarized in opposite directions, allowed for simultaneous collection of data with both spin orientations, minimizing systematic uncertainties. The dilution factor f of the deuteron material and the target polarization P_t enter as correction factors in the asymmetry extraction, combined into the factor $f_{DP} = f \cdot P_t$.

My Analysis Work

In my work, I specifically focused on the determination of **Sivers asymmetries** and the role of the f_{DP} **factors** in the data correction procedure.

Calculation of f_{DP}

Using the COMPASS methodology, I studied the behavior of the averaged dilution–polarization product $\langle f_{DP} \rangle$ across different kinematic variables (x, z, p_T, and W). My results show a stable value of $\langle f_{DP} \rangle \approx 0.35$, with only small variations across all kinematic bins. This confirms the robustness of the target parameters used in the extraction.

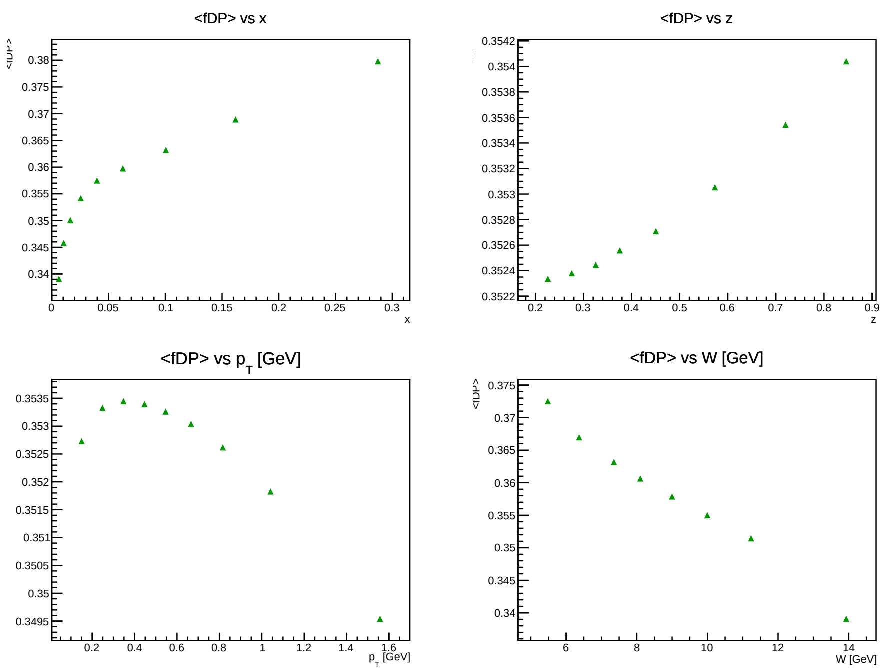

Figure 3: Calculation of f_{DP}

Extraction of Raw and Corrected Sivers Asymmetries

I obtained the **raw asymmetries** from hadron yields in different target polarization states and subsequently applied the f_{DP} corrections. The corrected asymmetries were studied as a function of the kinematic variables (x, z, p_T, and W). My plots demonstrate that the Sivers asymmetries remain statistically consistent with zero within uncertainties, but with significantly reduced error bars compared to earlier deuteron results.

In particular:

- **Asymmetry vs. x:** small fluctuations around zero, consistent with the expected cancellation of u- and d-quark contributions in the deuteron.
- **Asymmetry vs. z, p_T, and W:** no significant non-zero trends observed, confirming the findings of the 2024 COMPASS publication.

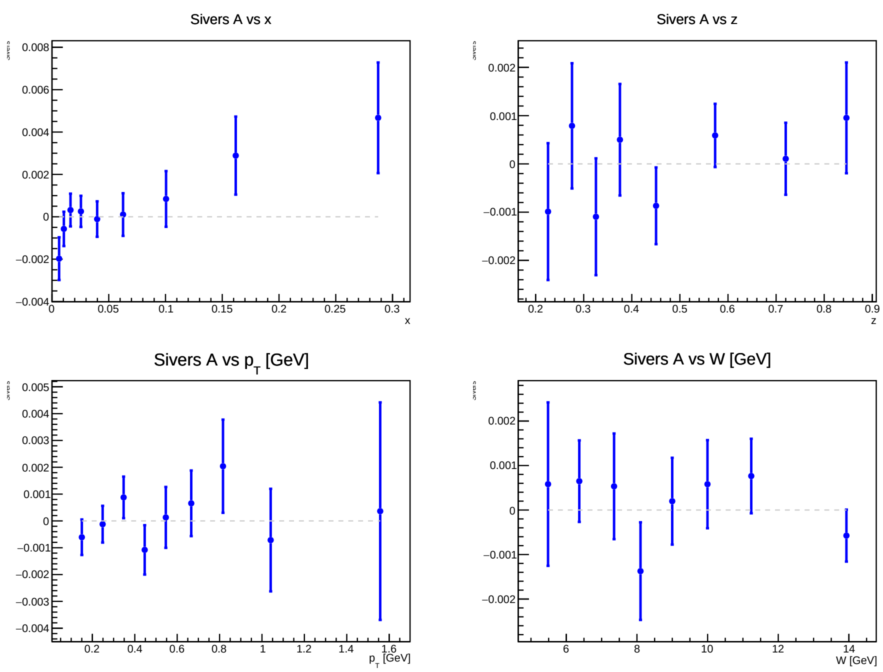

Figure 4: Extraction of Raw and Corrected Sivers Asymmetries

Results in the Broader Context

My analysis aligns with the **COMPASS high-statistics measurement** published in *Physical Review Letters* (2024), which reported that Sivers asymmetries on the deuteron remain compatible with zero, but with uncertainties reduced by up to a factor of three compared to earlier data. This improved precision plays a critical role in:

- Providing strong constraints on the ***d*-quark Sivers function**, which is now found to be clearly negative in the extracted global fits.
- Enabling more precise determination of the **nucleon tensor charge** and testing lattice QCD predictions.
- Balancing the proton and deuteron data sets, which is essential for disentangling u- and d-quark contributions.

Conclusion

Through my work at CERN, I obtained and analyzed the **Sivers asymmetries** using the COMPASS deuteron dataset, including careful evaluation of the f_{DP} **correction factors**. My results confirm that the deuteron Sivers asymmetry is consistent with zero across all kinematic variables, while providing much improved statistical precision. These findings contribute directly to the global effort of mapping the nucleon's three-dimensional spin structure and will serve as a cornerstone for future studies at the Electron-Ion Collider.

References

[1] G. D. Alexeev *et al.* (COMPASS Collaboration), "High-Statistics Measurement of Collins and Sivers Asymmetries for Transversely Polarized Deuterons," Phys. Rev. Lett. **133**, 101903 (2024).

[2] M. Alekseev *et al.* (COMPASS Collaboration), "Collins and Sivers asymmetries for pions and kaons in muon-deuteron DIS," Phys. Lett. B **692**, 240 (2010).

[3] C. Adolph *et al.* (COMPASS Collaboration), "Sivers asymmetry extracted in SIDIS at COMPASS," Phys. Lett. B **717**, 376 (2012); "Collins asymmetry extracted in SIDIS at COMPASS," Phys. Lett. B **717**, 383 (2012).

[4] J. C. Collins, "Fragmentation of transversely polarized quarks," Nucl. Phys. B **396**, 161 (1993).

[5] D. W. Sivers, "Single-spin production asymmetries from the hard scattering of point-like constituents," Phys. Rev. D **41**, 83 (1990).

[6] R. L. Jaffe and X. Ji, "Transverse polarization of quarks in hadrons," Phys. Rev. Lett. **67**, 552 (1991).