SciPost Phys. Proc. 8, 002 (2022)

# Recent highlights from spin-physics experiments

**Caroline Riedl***

University of Illinois at Urbana-Champaign, USA

* criedl@illinois.edu

*Proceedings for the XXVIII International Workshop*
*on Deep-Inelastic Scattering and Related Subjects,*
*Stony Brook University, New York, USA, 12-16 April 2021*
doi:10.21468/SciPostPhysProc.8

## Abstract

**A snapshot of the current experimental status of spin-dependent nucleon structure prior to the arrival of the Electron Ion Collider will be attempted. Highlights of recent results from fixed-target experiments at JLab, Fermilab, CERN and DESY and collider experiments from RHIC are presented. Many of the recent results address the topics of transverse proton or parton spin and transverse parton momenta (TMDs), and their their (spin-orbit) correlations. Results on generalized parton distributions (GPDs), which provide an alternative pathway to mapping nucleon structure, are also discussed.**



Received 27-07-2021
Accepted 06-05-2022
Published 11-07-2022
Check for updates
doi:10.21468/SciPostPhysProc.8.002

## 1 Physics questions and observables

While matter composed of non-standard-model particles has attracted considerable attention in recent years, the proton as prominent constituent of the visible universe is not as well known as one may naively expect. Some fundamental questions about the proton yet remain to be answered - what is the proton's radius? Does the proton decay? Why is the proton as 3-quark compound so heavy, as compared to 2-quark compounds, the mesons? While these questions are discussed elsewhere, this article attempts to summarize the current status of the following questions: *where does the proton spin come from?* Secondly, *do partons undergo orbital motion?*, and lastly, *what is the multi-dimensional picture of the proton in transverse-momentum and position space?*

Proton spin structure is experimentally explored by analyzing the types of particles and their angular distributions produced in (1) lepton-nucleon deep inelastic scattering (DIS), (2) the hadron-hadron Drell-Yan (DY) process, (3) proton-proton collisions ($pp$), and (4) electron-positron annihilation ($ee$). The initial motivation for all these measurements was the finding in the late 1980's that the proton's spin of 1/2 is not the result of a simple spin-algebraic combination of the spin of its three spin-1/2 valence quarks. While a plethora of additional information is available nowadays, some missing pieces are needed for a full assembly of the proton spin puzzle.

The DIS ($\ell N \to \ell X$) cross section can be expressed in terms of the non-perturbative parton distribution functions (PDFs), which encode information about the momentum-dependent distribution of quarks and gluons inside the proton.[1] The intrinsic transverse parton momentum $k_\mathrm{T}$ is indirectly accessed by measuring the transverse momentum $p_\mathrm{T}$ of one or more hadrons (semi-inclusive, or SIDIS, $\ell N \to \ell X h(h_2)$). From the intense experimental and theoretical efforts over the past two decades, a quantum-chromo dynamics (QCD)-based framework has emerged based on transverse-momentum dependent, or TMD, PDFs that describe the SIDIS process, see Fig. 1. In the SIDIS cross section, each TMD PDF is convoluted with a fragmen-

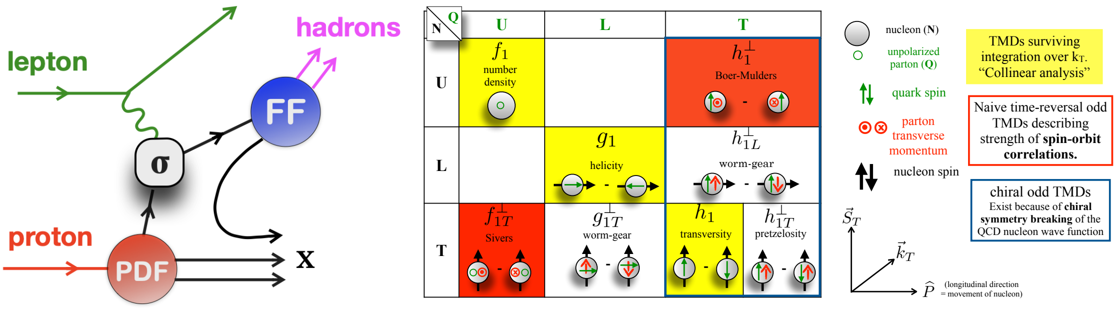


Figure 1: Left: semi-inclusive DIS. Right: TMD PDFs at leading twist for unpolarized (U), longitudinally (L) and transversely (T) polarized partons (Q) and nucleons (N).

tation function (FF), which encodes the fragmentation of a quark into a final-state hadron, and appears with a specific azimuthal modulation, for example, $\sin(\phi - \phi_S)\cdot$ (Sivers TMD) $\otimes$ (FF). Experimentally, the magnitude of a given convolution is determined by measuring an azimuth-dependent, transverse-spin-dependent asymmetry in suitably normalized count rates $N$ for one proton-spin orientation ($\uparrow$) versus that for the other ($\downarrow$),

$$A_\mathrm{T}(\varphi) = \frac{1}{S_\mathrm{T}} \cdot \frac{N^\uparrow(\varphi) - N^\downarrow(\varphi)}{N^\uparrow(\varphi) + N^\downarrow(\varphi)}, \tag{1}$$

with $S_\mathrm{T}$ the proton polarization. Similarly, observables related to generalized parton distributions (GPDs) are spin- or beam-charge asymmetries or differential cross sections of the exclusive process, for which all final-state particles are measured or assumed to be known. On the one side, TMDs assess the question, *How is the proton spin correlated with the motion of quarks and gluons?*, encoding the deformation of the parton's distribution of **transverse momentum** when the proton is polarized. On the other side, with GPDs it is investigated, *How does the proton spin influence the spatial distribution of partons?*, encoding the deformation of the parton's **spatial** distribution when the proton is polarized. These two separate concepts of nucleon tomography are unified in the framework of the so-called Wigner functions [1].

## 2 Spin-independent and longitudinal spin effects

The simultaneous extraction of the experimental observables in multiple kinematic variables has become, where possible, state of the art in recent years. TMD effects in spin-independent ("unpolarized") SIDIS that are presented in modern multi-dimensional binnings ($p_\mathrm{T}, Q^2, x, z, W$) allow for TMD evolution studies and facilitate comparison between experiments. The newly available preliminary $p_\mathrm{T}$-dependences and azimuthal asymmetries from COMPASS [2] and

[1]Two independent kinematic variables are measured, which are typically Bjørken-$x$, the longitudinal momentum fraction of the struck parton, and $Q^2$, the four-momentum of the virtual photon mediating the interaction.

pion mulitplicities from CLAS12 [3] will help to clarify the double-Gauss structures observed in the $p_{\mathrm{T}}$-dependences [4] and to develop a more complete mapping of the SIDIS landscape [5].

New results on the flavor composition of sea quarks have recently been published by SeaQuest and STAR using two independent experimental approaches. SeaQuest measured the proton-induced DY cross section on hydrogen and deuterium targets in the sea-quark domain [6], while STAR measured $W^+$ and $W^-$ cross-section ratios at the momentum scale of the weak-boson mass [7]. The two experiments are complementary in their kinematic coverage and both find a flavor asymmetry in the sea: $\bar{\mathrm{d}}(x) > \bar{\mathrm{u}}(x)$.

Quark helicity distributions $\Delta q$, or in other words the quark-spin contribution to the spin of the proton, from longitudinally polarized protons were determined by HERMES in SIDIS for the valence-quark region [8] and by STAR and PHENIX via $W^{\pm}$ production in $pp$ for the sea-quark region [9] [10]. The data provide strong evidence for flavor-symmetry breaking in the polarized sea sector opposite to that in the unpolarized sector: $\Delta\bar{\mathrm{u}}(x, Q^2) > \Delta\bar{\mathrm{d}}(x, Q^2)$. The recent RHIC data improve the precision of NNPDF fits.

The gluon helicity distribution, or contribution of the gluon spin to the proton spin, can be directly determined from RHIC $pp$ data as a consequence of the dominance of quark-gluon and gluon-gluon interactions in those data. The recent high-precision mid-rapidity measurements from collisions of longitudinally polarized protons from PHENIX in charged-pion production [11] and from STAR in di-jet and inclusive-jet production [12] are consistent with global QCD fits that indicate a non-zero positive and large (60%) gluon-spin contribution to the proton spin in the region $0.05 < x < 0.2$.

## 3 Spin-orbit correlations in the proton

Some of the TMDs in the table of Fig. 1 - namely the Sivers and the Boer-Mulders TMDs -, and the Collins FF describe the amplitude of spin-orbit correlations in the proton. Non-vanishing spin-orbit correlations indicate the presence of orbital angular momentum of partons, even though there exists no quantitative relation to date.

### Sivers TMD

The Sivers effect, $\sim \vec{S}_{\mathrm{T}} \cdot (\widehat{P} \times \vec{k}_{\mathrm{T}})$, is the correlation between the nucleon transverse-spin direction and the parton transverse momentum in the polarized nucleon, relating the motion of unpolarized quarks and gluons to the nucleon spin. While the Sivers function was originally thought to vanish [13], a non-zero Sivers function was later shown to be allowed due to QCD final-state interactions in SIDIS between the outgoing quark and the target remnant [14]. Indeed, significant non-zero Sivers asymmetries have been measured in SIDIS.

The final compendium of HERMES TMD results from SIDIS with refined analysis, multi-dimensional binnings, and first (anti-)proton measurements has recently been published [15]. Remarkably, as seen in Fig. 2, the kaon Sivers amplitudes are larger than those for pions, which is unexpected if $u$-quark scattering dominates and which may point to a role of sea quarks. The Sivers functions for $u$- and $d$-quarks are known to have different signs, as demonstrated in a recent COMPASS publication for SIDIS data [16] and in Fig. 2 (see also Fig. 5). This analysis with $p_{\mathrm{T}}$-weighted asymmetries provides a direct measurement of TMD $k_{\mathrm{T}}^2$ moments. The Sivers signal is measured to be smaller at COMPASS [18] than at HERMES [19] with its lower lepton-beam energy, which may be interpreted as an effect of TMD evolution.

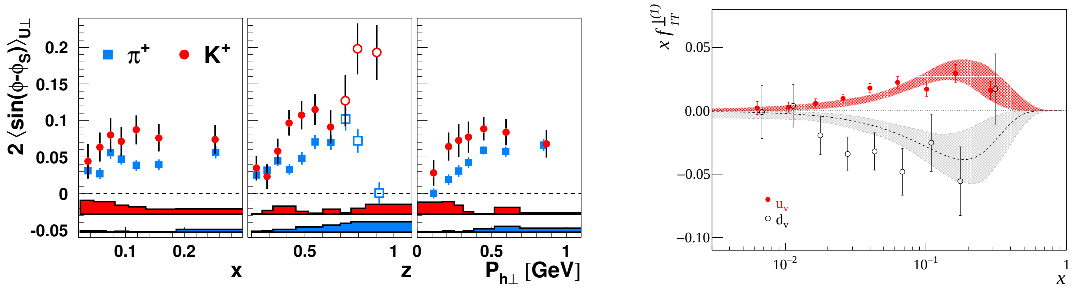


Figure 2: Left: Sivers asymmetries from HERMES SIDIS for positive pions and kaons [15]. Right: first Sivers moments for valence $u$- and $d$-quarks from COMPASS $p_T$-weighted asymmetries in SIDIS [16], together with a fit to SIDIS world data [17].

## Experimental TMD probes and TMD (modified) universality

There is a worldwide effort to access proton structure and in particular TMD-related observables using different types of scattering processes. While the SIDIS cross section contains combinations of the type $\sim$ TMD $\otimes$ FF, with the TMD PDF describing the structure of the probed hadron and the FF the fragmentation process, the DY cross section is composed of terms $\sim$ TMD $\otimes$ TMD, one TMD for each colliding hadron species.[2] Related to fundamental intrinsic features of the nucleon (the fragmentation process) and to basic QCD properties, the TMDs (FFs) are expected to be process independent. Interestingly, the naive time-reversal odd Sivers and Boer-Mulders TMDs are expected to switch sign when measured in SIDIS compared to DY[3], which is strikingly different from previously studied quark-momentum and quark-spin distributions in the nucleon. Experimentally probing TMD universality, and modified universality, thus is an important test of the underlying TMD-QCD framework.

As shown in Fig. 3, the currently available data support the sign switch and thus modified universality concept of the Sivers TMD, albeit still within large experimental uncertainties. COMPASS measured Sivers asymmetries in SIDIS [20] and DY [21] with almost the same

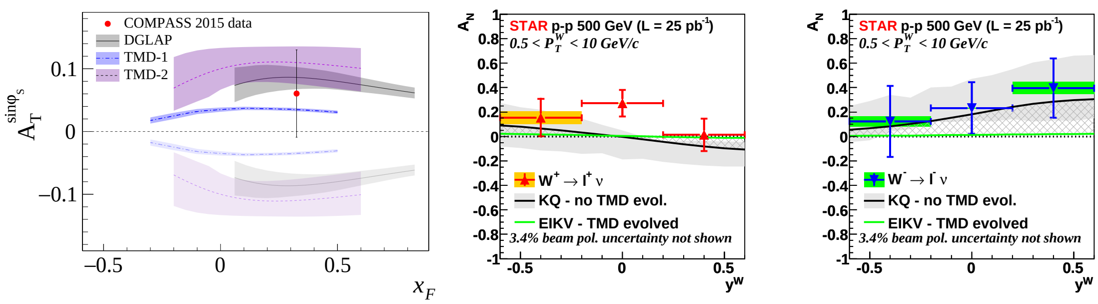


Figure 3: Left: COMPASS Sivers asymmetry amplitude from pion-induced DY on an $NH_3$ transversely polarized target [21]. The solid curves (DGLAP [22], TMD-1 [23], TMD-2 [24]) are fits to SIDIS world data that include the Sivers sign switch. Right: left-right asymmetry $A_N$ in $W$-boson production from $p^\uparrow p$ collisions at STAR [25].

apparatus and in overlapping kinematic domains. STAR measured left-right asymmetries in $W$- and $Z$-boson production from $p^\uparrow p$ collisions at $\sqrt{s} = 500$ GeV RHIC energies [25]. Both

[2] DY comprises the process $h_1 h_2 \to \ell^+\ell^- X$ as well as the generalized DY process, $h_1 h_2 \to W^\mp X$, with $W^\mp \to \ell^\mp \overset{(-)}{\nu}$.
[3] Final-state SIDIS interactions translate into DY initial-state i.a., changing the direction of gauge link integrals.

collaborations are working on the analysis of more data for the same channels. STAR also analyzes flavor-tagged di-jet Sivers asymmetries that flip with charge sign [26]. COMPASS also extracts other TMD-related observables such as the transversity and pretzelosity asymmetries from the spin-dependent DY data and has also recently made available first pion-induced DY results on a tungsten target indicating a violation of the Lam-Tung relation, which may be explained by the Boer-Mulders TMD [27].

### Common origin of transverse single-spin asymmetries and gluon Sivers TMD

While fixed-target experimenters often choose to simultaneously extract the various amplitudes of the harmonic modulations appearing in the cross section via a maximum-likelihood fit (Fig. 3 left), the typical collider spin observable is $A_{\mathrm{N}}$, a left-right asymmetry of normalized counts with respect to the proton-spin orientation (Fig. 3 middle/right). The two observables are related and can both be represented in first order by the simplified spin asymmetry in Eq. 1.

The finding that it is possible to simultaneously describe left-right asymmetries across multiple collision species [28] indicates that all $A_{\mathrm{N}}$ have a common origin that is related to multi-parton correlations. Different but related factorization schemes come into play at different scales [29]: TMD factorization applies to processes with one hard (e.g., $Q^2$) and one soft (e.g., $p_{\mathrm{T}}$) scale - SIDIS, DY, $W/Z$ production, di-jets, hadrons in jets, ... -, with $p_{\mathrm{T}} \ll Q$, while for single-scale ($p_{\mathrm{T}} \sim Q$) hard processes in $pp$ such as single inclusive particle production (particle or jet $p_{\mathrm{T}}$), collinear twist-3 factorization applies. In the latter case, $A_{\mathrm{N}}$ is thought not to arise from the TMD mechanism but from spin-momentum correlations ($qgq$ or tri-gluon $ggg$). The two factorization schemes are equivalent in the overlapping kinematic region.

PHENIX published new results on $p^{\uparrow}p$ mid-rapidity measurements sensitive to tri-gluon twist-3 correlation functions, which are related to the gluon Sivers TMD as outlined in the previous paragraph. For both the isolated direct-photon $A_{\mathrm{N}}$ [30] and the $A_{\mathrm{N}}$ in $\pi^0$ and $\eta$ production [31], no signals were found at high precision, see Fig. 4 left. On the other hand,

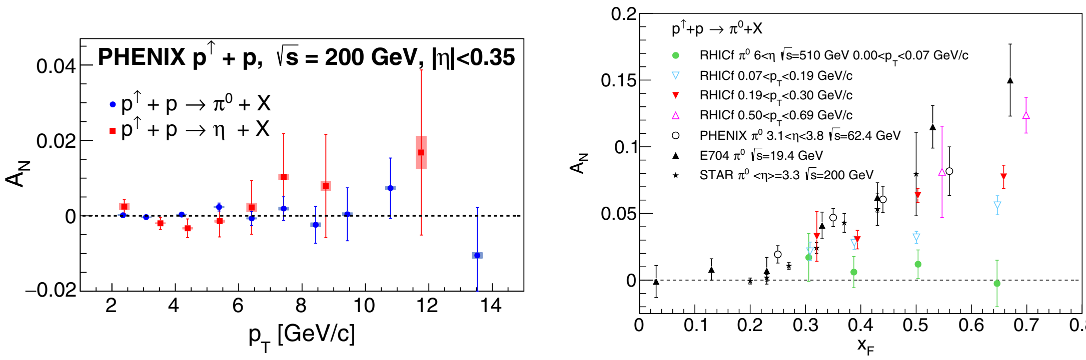


Figure 4: $A_{\mathrm{N}}$ in $p^{\uparrow}p$ collisions. Left: PHENIX mid-rapidity $\pi^0$ and $\eta$ production [31]. Right: RHICf $\pi^0$ in the very forward in comparison to other experiments [34].

COMPASS found a non-zero result at the 2.5-sigma level for the Sivers asymmetry in photon-gluon fusion from SIDIS data [32]. Collecting more experimental information about the gluon Sivers TMD from other experimental channels is therefore important and analysis is currently in progress of heavy-flavor production at PHENIX [33] and of $J/\psi$ production in pion-proton collisions at COMPASS.

## Left-right asymmetries in the forward

While transverse single-spin asymmetries are measured to be extremely small at mid-rapidity, they grow substantially at forward rapidity for various observables. A plethora of new RHIC results in $p^{\uparrow}p$ has recently become available. Using a calorimeter 18 m away from the STAR interaction region, the RHICf collaboration measured $A_{\mathrm{N}}$ from $\pi^0$ in electromagnetic jets [34] for very forward rapidity $2.4 < \eta < 4$ (see Fig. 4 right). PHENIX measured $A_{\mathrm{N}}$ from $\pi^0$ by detecting very forward neutrons [35], and STAR by detecting $\pi^0$ and electromagnetic jets [36]. The left-right asymmetry increases with $p_{\mathrm{T}}$, forwardness, $\pi^0$ isolation, and $\gamma$ multiplicity (STAR), suggesting it may in this domain arise from soft processes such as diffractive scattering.

## Transversity TMD and spin-dependent fragmentation

The Collins effect is the fragmentation of a transversely polarized parton into a final-state hadron. The Collins FF, $\sim \vec{s}_{\mathrm{T}} \cdot (\widehat{k} \times \vec{P}_{\mathrm{hT}})$, appears in the SIDIS cross section convoluted with the transversity TMD (which represents a spin-spin correlation). Both are chiral-odd. The coupling of the transversity TMD and the Collins FF in $p^{\uparrow}p$ leads to azimuthal modulations of charged-hadron yields around the jet axis, and the involvement of two momentum scales (jet and hadron transverse momenta) allows for an interpretation within the TMD framework. STAR measured Collins asymmetries for charged pions in jets [37] to be different from zero above the 5-sigma level at higher jet transverse momenta and with different signs for the two pion charges. Figure 5 shows the results together with model curves [38] [39], which are based on calculations using SIDIS and *ee* data. The good comparison between model and data confirms the universality of the Collins FFs. STAR also reported the first constraint on

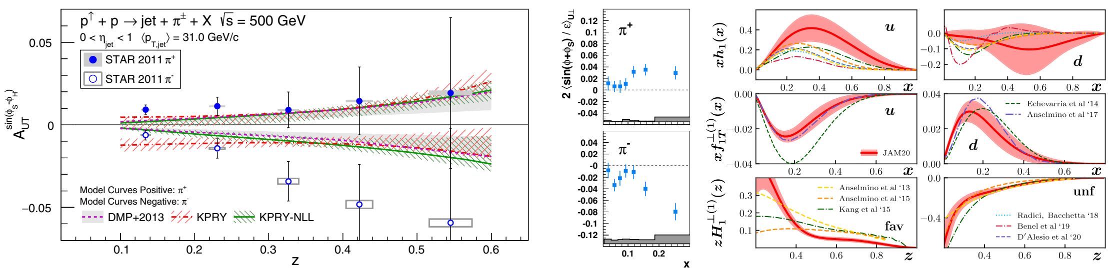

Figure 5: Left: STAR Collins asymmetries from charged pions in jets in $p^{\uparrow}p$ [37]. Middle: HERMES Collins asymmetries for charged pions in SIDIS [15]. Right: JAM global fits for transversity TMD (top), Sivers TMD (middle), Collins FF (bottom) [28].

the Collins-like asymmetry [37], which is sensitive to linear gluon polarization. STAR has also measured a significant Collins-dihadron interference-fragmentation asymmetry [40] with the expected prominent enhancement at the $\rho$-meson mass. More STAR data are being analyzed including kaons and protons in jets [41].

The final results of the HERMES SIDIS Collins asymmetries [15] are shown in the middle panel of Fig. 5. The HERMES and COMPASS SIDIS Collins asymmetries agree well for the common kinematics [18] (not shown). There is a mirror symmetry for $\pi^+$ and $\pi^-$, which indicates that $u$- ($\delta_u$) and $d$-quark transversity ($\delta_d$) have approximately equal magnitude but opposite signs. Also shown in Fig. 5 are universal fits by the JAM collaboration [28], which demonstrate that $\delta_d$ is poorer constrained than $\delta_u$, given the $u$-quark dominance of many of the processes used in the global fits. It is therefore important to collect more data sensitive to $\delta_d$. The just started COMPASS transversity run on the deuteron will double the experimental precision on the proton's tensor charge $g_T = \delta_u - \delta_d$ [42]. Already with existing data, it will be possible to test the predicted genuine universality for the transversity and pretzelosity TMDs by comparing extractions from SIDIS data and the new COMPASS DY data. An alternative method of accessing transversity, as recently made available by COMPASS [43] and STAR [44], is the measurement of hyperon transverse polarization, which may have been transferred from the struck quark in the transversely polarized proton.

Novel spin-dependent fragmentation effects are studied by COMPASS for $\rho$-meson production on the transversely polarized proton [45], investigating the difference in the Collins mechanism of spin-1 vector mesons versus that for pseudoscalar mesons (ordinary Collins FF). CLAS12 published a higher-twist di-hadron beam-spin asymmetry [46]. The measurement establishes the first empirical evidence of a non-zero helicity-dependent di-pion fragmentation function, which encodes spin-momentum correlations in hadronization and is equivalent to the Collins FF for two pions. CLAS published a non-zero higher-twist di-hadron beam-spin asymmetry [47]. Sizeable higher-twist beam-spin asymmetries in SIDIS were reported by CLAS12 [48] and HERMES [49]. These asymmetries provide access to so-far poorly known sub-leading twist-3 TMD PDFs and FFs containing information about quark-gluon correlations in the proton and in the hadronization process.

## 4 Hard exclusive reactions

Measurements providing access to GPD-related observables via the standard hard-exclusive channels of deeply virtual Compton scattering (DVCS $\ell N \to \ell N \gamma$) and deeply virtual meson production (DVMP $\ell N \to \ell N M$) were launched more than 20 years ago at HERMES, JLab and HERA and are to date continued by the JLab12 experiments and by COMPASS.

The DVCS $t$-slope $b$ from the COMPASS differential DVCS cross section $\mathrm{d}\sigma/\mathrm{d}t \propto \exp(-b|t|)$ [50] is shown in Fig. 6 for about 10% of the available muon-proton data with recoil-proton detection.[4] These data allow determination of the transverse extension of partons in the $x$ domain between valence quarks and gluons, with a value $\sqrt{\langle r_\perp^2 \rangle} = (0.58 \pm 0.04_{\mathrm{stat}}{}^{+0.01}_{-0.02}|_{\mathrm{sys}}$ $\pm 0.04_{\mathrm{model}})$ fm. More COMPASS DVCS data are currently analyzed. Experimental access to

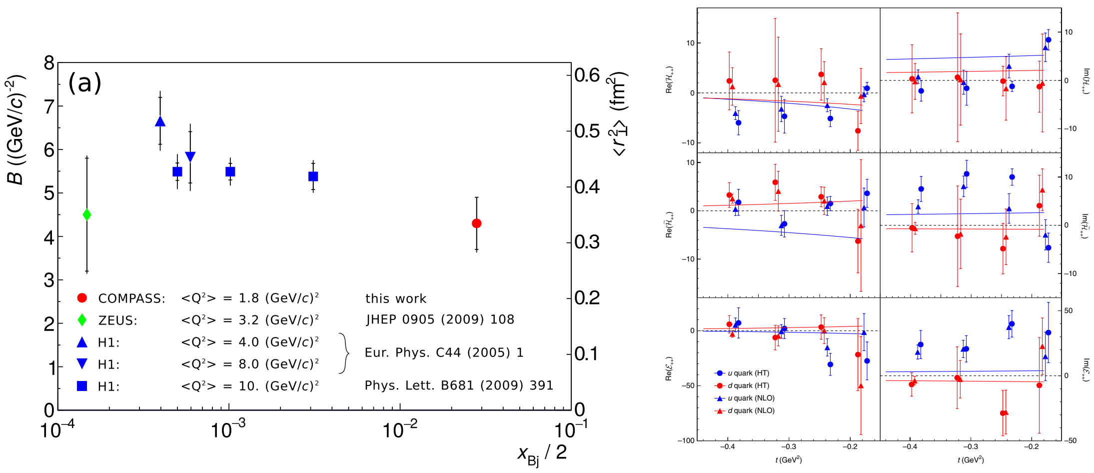


Figure 6: Left: COMPASS DVCS $t$-slope and comparison to HERA $ep$-collider (H1 and ZEUS) data [50]. Right: JLab Hall A - real and imaginary parts of various Compton form factors for $u$- and $d$-quarks [52].

[4] $t$ is the squared 4-momentum transfer to the target.

GPDs, which depend on 3 kinematic variables $(t, x, \xi)$[5], is usually achieved by measuring observables that are sensitive to the real or imaginary part of Compton form factors (CFFs), which are related to GPDs [51]. To explore the 3-dimensional GPD phase space, it is advantageous to have as many as possible different experimental combinations available: proton polarization (both longitudinal and transverse), longitudinal lepton-beam polarization, both lepton-beam charges, effective neutron targets in addition to proton targets, and several combinations. Figure 6 shows several flavor-separated CFFs extracted from JLab Hall-A data [52]. The DVCS dispersion relation for CFFs contains the so-called $D$-term, which is related to shear forces and the radial distribution of pressure inside the nucleon. There is a first extraction of the radial pressure distribution from CLAS data [51]. Several complementary DVCS-data analyses on proton targets are in progress: at CLAS12 on standard DVCS (GPD $H$) and on time-like Compton scattering (TCS), which is the time-reversal conjugate process of DVCS and sensitive to the real part of CFF $\mathcal{H}$ [53], and at COMPASS with higher lepton-beam energies and thus lower Bjørken-$x$ on DVCS beam-spin and -charge asymmetries (real and imaginary parts of CFF $\mathcal{H}$).

The experimental access to GPD $E$, which is linked to parton orbital angular momentum via the Ji sum rule [54], requires either transversely polarized protons or a neutron target. The analysis on CLAS12 DVCS beam-spin asymmetries on the neutron is in progress and CLAS12 data on a transversely polarized proton target are yet to be taken. All so-far discussed GPDs are quark GPDs. For the first time, data sensitive to the gluon GPD $E$ were collected by STAR in exclusive $J/\psi$ production in ultra-peripheral $pp$ collisions at RHIC. Significant improvements in precision for that channel are expected with the future STAR data to be taken with the just finished instrumentation upgrades.

All so-far discussed GPDs are chiral-even. In recent years, there have been multiple experimental campaigns to access the chiral-odd GPDs $H_\mathrm{T}$ and $E_\mathrm{T}$. COMPASS extracted the cross section for exclusive neutral pions [55] and the analyses on beam-spin asymmetries for neutral and positively charged pions at CLAS12 are in progress. COMPASS determined spin density matrix elements (SDMEs), which describe how the spin components of the virtual photon are transferred to the created vector meson, for exclusive $\omega$-mesons [56] and $\rho$-mesons [57].

For the first time, a DVCS beam-spin asymmetry was measured to be larger in the coherent (nucleus) channel than in the incoherent (proton) channel through detecting helium recoils using a radial TPC in CLAS [58]. Coherent DVCS allows studying if the DVCS amplitude rises with atomic mass number and if there is a "generalized" EMC effect. CLAS extracted exclusive $\pi^+$ beam-spin asymmetries for backward scattering angles [59], which allows studying nucleon-to-pion baryonic transition distribution amplitudes (TDAs), a further generalization of the GPD concept.

## 5 Conclusion and outlook

The experiments at CERN, DESY, Fermilab, JLab, and RHIC with their advanced and delicate technologies of spin-polarized lepton or hadron beams and/or spin-polarized fixed targets continue to produce rewarding and respectively complementary results about the proton's spin and multi-dimensional structure in transverse-momentum and position space. Careful examination of data from different facilities allows to put TMD universality (and restricted universality) to the test. The variety of experimental configurations allows to explore a wide portion of GPD kinematic space and types. Rich future experimental programs related to nucleon spin structure are planned prior to the EIC: until 2025, these are on the fixed-target side the just started final COMPASS $d$-quark transversity run [42], the continuation of the JLab12 program [60] [61], the SpinQuest / E1039 TMD campaigns with polarized targets [62]

[5] $x$ and $\xi$ are combinations of longitudinal parton momenta and $x$ is not identical to the Bjørken-$x$.

to access sea-quark TMDs, and AMBER [63] as COMPASS successor at the SPS M2 beamline in the CERN North Area, and on the RHIC-collider side STAR with several upgrades [64] and the new sPHENIX experiment [65], for which assembly has started in summer 2021.

## Acknowledgements

The author is funded in parts by *A Program of Medium Energy Nuclear Physics* NSF grant PHY 18-12377.

The author is grateful for the inputs from Elke Aschenauer, Harut Avakian, Marco Battaglieri, Alexander Bazilevsky, Pierre Chatagnon, Nicole D'Hose, Christopher Dilks, Oleg Eyser, Renee Fatemi, Carl Gagliardi, Andrey Kim, Jen-Chieh Peng, Matt Posik, Gunar Schnell, and others.

## References

[1] M. Diehl, *Introduction to GPDs and TMDs*, Eur. Phys. J. A **52**, 149 (2016), doi:10.1140/epja/i2016-16149-3.

[2] A. Moretti, *TMD observables in unpolarised Semi-Inclusive DIS at COMPASS*, talk given at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS21), Stony Brook (NY), USA, April 2021.

[3] H. Avakian, *Studies of transverse momentum distributions in SIDIS*, talk given at the 17th International Workshops on Hadron Structure and Spectroscopy (IWHSS 20), Trieste, Italy, November 2020.

[4] COMPASS Collaboration, *Transverse-momentum-dependent multiplicities of charged hadrons in muon-deuteron deep inelastic scattering*, Phys. Rev. D **97**, 032006 (2018), doi:10.1103/PhysRevD.97.032006.

[5] M. Boglione, A. Dotson, L. Gamberg, S. Gordon, J.O. Gonzalez-Hernandez, A. Prokudin, T.C. Rogers, N. Sato, *Mapping the kinematical regimes of semi-inclusive deep inelastic scattering*, J. High Energy Phys. **10**, 122 (2019), doi:10.1007/JHEP10(2019)122.

[6] J. Dove, B. Kerns, R.E. McClellan et al., *The asymmetry of antimatter in the proton*, Nature **590**, 561 (2021), doi:10.1038/s41586-021-03282-z.

[7] STAR Collaboration, *Measurements of $W$ and $Z/\gamma^*$ cross sections and their ratios in $p+p$ collisions at RHIC*, Phys. Rev. D **103**, 012001 (2021), doi:10.1103/PhysRevD.103.012001.

[8] HERMES Collaboration, *Longitudinal double-spin asymmetries in semi-inclusive deep-inelastic scattering of electrons and positrons by protons and deuterons*, Phys. Rev. D **99**, 112001 (2019), doi:10.1103/PhysRevD.99.112001.

[9] STAR Collaboration, *Measurement of the longitudinal spin asymmetries for weak boson production in proton-proton collisions at $\sqrt{s}$ = 510 GeV*, Phys. Rev. D **99**, 051102(R) (2019), doi:10.1103/PhysRevD.99.051102.

[10] PHENIX Collaboration, *Cross section and longitudinal single-spin asymmetry $A_L$ for forward $W^\pm \to \mu^\pm \nu$ production in polarized $p+p$ collisions at $\sqrt{s} = 510$ GeV*, Phys. Rev. D **98**, 032007 (2018), doi:10.1103/PhysRevD.98.032007.

[11] PHENIX Collaboration, *Measurement of charged pion double spin asymmetries at midrapidity in longitudinally polarized $p+p$ collisions at $\sqrt{s} = 510$ GeV*, Phys. Rev. D **102**, 032001 (2020), doi:10.1103/PhysRevD.102.032001.

[12] STAR Collaboration, *Longitudinal double-spin asymmetry for inclusive jet and dijet production in polarized proton collisions at $\sqrt{s} = 200$ GeV*, Phys. Rev. D **103**, L091103 (2021), doi:10.1103/PhysRevD.103.L091103.

[13] J. C. Collins, *Fragmentation of transversely polarized quarks probed in transverse momentum distributions*, Nucl. Phys. B **396**, 161 (1993). doi:10.1016/0550-3213(93)90262-N.

[14] S. J. Brodsky, D. S. Hwang, I. Schmidt, *Final-state interactions and single-spin asymmetries in semi-inclusive deep inelastic scattering*, Phys. Lett. B 530, 99 (2002), doi:10.1016/S0370-2693(02)01320-5.

[15] HERMES Collaboration, *Azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic lepton scattering by transversely polarized protons*, J. High Energy Phys. **12**, 10 (2020), doi:10.1007/JHEP12(2020)010.

[16] COMPASS Collaboration, *Measurement of $P_T$-weighted Sivers asymmetries in leptoproduction of hadrons*, Nucl. Phys. B **940** 34-53, (2019), doi:10.1016/j.nuclphysb.2018.12.024.

[17] M. Anselmino, M. Boglione, and S. Melis, *Strategy towards the extraction of the Sivers function with transverse momentum dependent evolution*, Phys. Rev. D **86** 014028 (2012), doi:10.1103/PhysRevD.86.014028.

[18] COMPASS Collaboration, *Collins and Sivers asymmetries in muonproduction of pions and kaons off transversely polarised protons*, Phys. Lett. B **744** (2015) 250-259, doi:10.1016/j.physletb.2015.03.056.

[19] HERMES Collaboration, *Observation of the Naive- $T$-Odd Sivers Effect in Deep-Inelastic Scattering*, Phys. Rev. Lett. **103**, 152002 (2009), doi:10.1103/PhysRevLett.103.152002.

[20] COMPASS Collaboration, *Sivers asymmetry extracted in SIDIS at the hard scales of the Drell–Yan process at COMPASS*, Phys. Lett. B **770**, 138-145 (2017), doi:10.1016/j.physletb.2017.04.042.

[21] COMPASS Collaboration, *First Measurement of Transverse-Spin-Dependent Azimuthal Asymmetries in the Drell-Yan Process*, Phys. Rev. Lett. **119**, 112002 (2017), doi:10.1103/PhysRevLett.119.112002.

[22] M. Anselmino, M. Boglione, U. D'Alesio, F. Murgia, and A. Prokudin, *Study of the sign change of the Sivers function from STAR collaboration $W/Z$ production data*, J. High Energy Phys. **2017**, 46 (2017), doi:10.1007/JHEP04(2017)046.

[23] M.G. Echevarria, A. Idilbi, Z.-B. Kang, and I. Vitev, *QCD evolution of the Sivers asymmetry*, Phys. Rev. D **89**, 074013 (2014), doi:10.1103/PhysRevD.89.074013.

[24] P. Sun and F. Yuan, *Transverse momentum dependent evolution: Matching semi-inclusive deep inelastic scattering processes to Drell-Yan and $W/Z$ boson production*, Phys. Rev. D **88**, 114012 (2013), doi:10.1103/PhysRevD.88.114012.

[25] STAR Collaboration, *Measurement of the Transverse Single-Spin Asymmetry in $p^\uparrow + p \rightarrow W^\pm/Z^0$ at RHIC*, Phys. Rev. Lett. **116**, 132301 (2016), doi:10.1103/PhysRevLett.116.132301.

[26] H. Liu, *Measurement of transverse single-spin asymmetries for di-jet production in polarized $p+p$ collisions at $\sqrt{s}=200$ GeV at STAR*, talk given at the 2019 Fall Meeting of the APS Division of Nuclear Physics, Crystal City (VA), USA, October 2019.

[27] Y.-H. Lien and A. Chumakov, *Measurement of target spin (in)dependent asymmetries in dimuon production in pion-nucleon collisions at COMPASS*, talk given at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS21), Stony Brook (NY), USA, April 2021.

[28] J. Cammarota, L. Gamberg, Z.-B. Kang, J. A. Miller, D. Pitonyak, A. Prokudin, T. C. Rogers, and N. Sato (JAM Collaboration), *Origin of single transverse-spin asymmetries in high-energy collisions*, Phys. Rev. D **102**, 054002 (2020), doi:10.1103/PhysRevD.102.054002.

[29] X. Ji, J.-W. Qiu, W. Vogelsang, and F. Yuan, *Unified Picture for Single Transverse-Spin Asymmetries in Hard-Scattering Processes*, Phys. Rev. Lett. **97**, 082002 (2006), doi:10.1103/PhysRevLett.97.082002.

[30] PHENIX Collaboration, *Probing gluon spin-momentum correlations in transversely polarized protons through midrapidity isolated direct photons in $p^{\uparrow}+p$ collisions at $\sqrt{s}=200$ GeV*, arXiv:2102.13585.

[31] PHENIX Collaboration, *Transverse single-spin asymmetries of midrapidity $\pi^0$ and $\eta$ mesons in polarized $p+p$ collisions at $\sqrt{s}=200$ GeV*, Phys. Rev. D **103**, 052009 (2021), doi:10.1103/PhysRevD.103.052009.

[32] COMPASS Collaboration, *First measurement of the Sivers asymmetry for gluons using SIDIS data*, Phys. Lett. B **772**, 854 (2017), doi:10.1016/j.physletb.2017.07.018.

[33] D. Fitzgerald, *Transverse Single Spin Asymmetries of Heavy Flavor Electrons and Charged Pions in 200 GeV $p+p^{\uparrow}$ Collisions at Midrapidity*, talk given at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS21), Stony Brook (NY), USA, April 2021.

[34] M.H. Kim et al., *Transverse Single-Spin Asymmetry for Very Forward Neutral Pion Production in Polarized pp Collisions at $\sqrt{s}=500$ GeV*, Phys. Rev. Lett. **124**, 252501 (2020), doi:10.1103/PhysRevLett.124.252501.

[35] PHENIX Collaboration, *Transverse momentum dependent forward neutron single spin asymmetries in transversely polarized $p+p$ collisions at $\sqrt{s}=200$ GeV*, Phys. Rev. D **103** 032007 (2021), doi:10.1103/PhysRevD.103.032007.

[36] STAR Collaboration, *Measurement of transverse single-spin asymmetries of $\pi^0$ and electromagnetic jets at forward rapidity in 200 and 500 GeV transversely polarized proton-proton collisions*, Phys. Rev. D **103**, 092009 (2021), doi:10.1103/PhysRevD.103.092009.

[37] STAR Collaboration, *Azimuthal transverse single-spin asymmetries of inclusive jets and charged pions within jets from polarized-proton collisions at $\sqrt{s}=500$ GeV*, Phys. Rev. D **97**, 032004 (2018), doi:10.1103/PhysRevD.97.032004.

[38] U. D'Alesio, F. Murgia, and C. Pisano, *Testing the universality of the Collins function in pion-jet production at RHIC*, Phys. Lett. **B** 773, 300-306 (2017), doi:10.1016/j.physletb.2017.08.023.

[39] Z.-B. Kang, A. Prokudin, F. Ringer, and F. Yuan, *Collins azimuthal asymmetries of hadron production inside jets*, Phys. Lett. **B** 774, 635-642 (2017), doi:10.1016/j.physletb.2017.10.031.

[40] STAR Collaboration, *Transverse spin-dependent azimuthal correlations of charged pion pairs measured in $p^{\uparrow}+p$ collisions at $\sqrt{s}=500$ GeV*, Phys. Lett. B **780**, 332 (2018), doi:10.1016/j.physletb.2018.02.069.

[41] B. Pokhrel, *Transverse Spin Dependent Azimuthal Correlations of Charged hadrons(s) in $p^{\uparrow}p$ Collisions at $\sqrt{s}=200$ GeV*, talk given at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS21), Stony Brook (NY), USA, April 2021.

[42] COMPASS Collaboration, *Addendum to the COMPASS-II Proposal*, CERN–SPSC–2017–034 (2017).

[43] COMPASS Collaboration, *Probing transversity by measuring $\Lambda$ polarisation in SIDIS*, Phys. Lett .B **824**, 136834 (2022).

[44] Y. Xu, *Longitudinal and Transverse Spin Transfer of $\Lambda$ and $\overline{\Lambda}$ Hyperons in Polarized $p+p$ Collisions at $\sqrt{s}=200$ GeV at RHIC-STAR*, talk given at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS21), Stony Brook (NY), USA, April 2021.

[45] A. Kerbizi, *Transverse spin asymmetries for inclusive $\rho^0$ production in SIDIS at COMPASS*, talk given at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS21), Stony Brook (NY), USA, April 2021.

[46] CLAS12 Collaboration, *Observation of Beam Spin Asymmetries in the Process $ep \rightarrow e'\pi^+\pi^-X$ with CLAS12*, Phys. Rev. Lett. **126**, 152501 (2021), doi:10.1103/PhysRevLett.126.152501.

[47] CLAS Collaboration, *Beam Spin Asymmetry in Semi-Inclusive Electroproduction of Hadron Pairs*, Phys. Rev. Lett. **126**, 062002 (2021), doi:10.1103/PhysRevLett.126.062002.

[48] CLAS12 Collaboration, *First multidimensional, high precision measurements of semi-inclusive $\pi^+$ beam single spin asymmetries from the proton over a wide range of kinematics*, arXiv:2101.03544.

[49] HERMES Collaboration, *Beam-helicity asymmetries for single-hadron production in semi-inclusive deep-inelastic scattering from unpolarized hydrogen and deuterium targets*, Phys. Lett. B **797**, 134886 (2019), doi:10.1016/j.physletb.2019.134886.

[50] COMPASS Collaboration, *Transverse extension of partons in the proton probed in the sea-quark range by measuring the DVCS cross section*, Phys. Lett. B **793**, 188 (2019), doi:10.1016/j.physletb.2019.04.038.

[51] V.D. Burkert, L. Elouadrhiri, and F.X. Girod, *The pressure distribution inside the proton*, Nature 557, 396 (2018), doi:10.1038/s41586-018-0060-z.

[52] M. Benali, C. Desnault, M. Mazouz, et al., *Deeply virtual Compton scattering off the neutron*, Nat. Phys. **16**, 191 (2020), doi:10.1038/s41567-019-0774-3.

[53] P. Chatagnon and CLAS Collaboration, *Timelike Compton Scattering with CLAS12 at Jefferson Lab*, J. Phys.: Conf. Ser. **1643** 012185 (2020), doi:10.1088/1742-6596/1643/1/012185.

[54] X. Ji, *Gauge-Invariant Decomposition of Nucleon Spin*, Phys. Rev. Lett. **78**, 610 (1997), doi:10.1103/PhysRevLett.78.610.

[55] COMPASS Collaboration, *Measurement of the cross section for hard exclusive $\pi^0$ muoproduction on the proton*, Phys. Lett. B **805**, 135454 (2020), doi:10.1016/j.physletb.2020.135454.

[56] COMPASS Collaboration, *Spin density matrix elements in exclusive $\omega$ meson muoproduction*, Eur. Phys. J. C **81**, 126 (2021), doi:10.1140/epjc/s10052-020-08740-y.

[57] W. Augustyniak, *Spin Density Matrix Elements in Exclusive $\rho^0$ Meson Muoproduction at COMPASS*, talk given at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS21), Stony Brook (NY), USA, April 2021.

[58] CLAS Collaboration, *Measurement of deeply virtual Compton scattering off Helium-4 with CLAS at Jefferson Lab*, arxiv:2102.07419.

[59] CLAS Collaboration, *Extraction of Beam-Spin Asymmetries from the Hard Exclusive $\pi^+$ Channel off Protons in a Wide Range of Kinematics*, Phys. Rev. Lett. **125**, 182001 (2020), doi:10.1103/PhysRevLett.125.182001.

[60] M. Battaglieri, *Present and future of JLab CLAS12 physics program*, talk given at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS21), Stony Brook (NY), USA, April 2021, and CLAS12 webpage.

[61] J.-P. Chen, *Overview of SoLID*, talk given at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS21), Stony Brook (NY), USA, April 2021, and SoLID webpage.

[62] M.Yurov, *Light anti-quarks Sivers function at Fermilab SpinQuest*, talk given at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS21), Stony Brook (NY), USA, April 2021, and SpinQuest webpage.

[63] D. Banerjee, *Studies performed for the EHN2 Beamline at CERN for next generation muon beam experiments*, talk given at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS21), Stony Brook (NY), USA, April 2021, and AMBER webpage.

[64] O. Tsai, *The STAR Forward Upgrade – An Overview*, talk given at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS21), Stony Brook (NY), USA, April 2021, STAR upgrade webpage.

[65] A. Bazilevsky, *Cold QCD physics program with sPHENIX*, talk given at the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS21), Stony Brook (NY), USA, April 2021, and sPHENIX webpage.