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The JLAB 3D program at 12 GeV (TMDs + GPDs)

Silvia Pisano[1,a]

[1] *Laboratori Nazionali di Frascati - INFN*

Abstract. The Jefferson Lab CEBAF accelerator is undergoing an upgrade that will increase the beam energy up to 12 GeV. The three experimental Halls operating in the 6-GeV era are upgrading their detectors to adapt their performances to the new available kinematics, and a new Hall (D) is being built. The investigation of the three-dimensional nucleon structure both in the coordinate and in the momentum space represents an essential part of the 12-GeV physics program, and several proposals aiming at the extraction of related observables have been already approved in Hall A, B and C. In this proceedings, the focus of the JLab 3D program will be described, and a selection of proposals will be discussed.

1 Introduction

The investigation of the nucleon structure is one of the most challenging fields of the hadronic physics. Despite many years of both theoretical and experimental studies, indeed, many open questions remain concerning the proton structure in terms of the QCD degrees of freedom, as how its spin and mass can be related to the dynamics of its miscoscopic constituents, or the nature of the confinement itself. The Jefferson Laboratory is currently undergoing an upgrade [1] of the CEBAF and of the equipment installed in the experimental halls. Such an upgrade will widen the phase-space accessible through JLab experiments, and will provide high-precision measurements of observables related to the nucleon structure in an enlarged kinematical region. All the three preexisting halls are upgrading their detectors, so to adapt their performances to the increased beam energy and luminosity while mantaining their specialization for high-precision, high-luminosity (Hall A and C) or large-acceptance measurements (Hall B). In addition to the three halls of the 6 GeV era, another experimental hall devoted to the meson spectroscopy, Hall D, will be installed at the CEBAF.

Hall A, B and C have a comprehensive program devoted to the nucleon structure study, with many already-approved experiments to be performed with different targets and polarization degrees of freedom. This common effort will allow to explore the nucleon in its three-dimensional structure both in the coordinate and in the momentum space, pushing forward the simple, one-dimensional description encoded in the longitudinal parton distribution functions (PDFs).

[a] e-mail: silvia.pisano@lnf.infn.it

2 Generalized Parton Distributions

Generalized Parton Distributions are three-dimensional functions describing the proton structure in the 1+2D space composed of the longitudinal fraction x of the proton momentum carried by the parton and by the tranverse position of the parton itself in the impact paramenter description [2–5]. GPDs generalize the electromagnetic form factors and the longitudinal PDFs, relating the parton x to their position in the transverse space. They can also give access to the quark total angular momentum through the Ji's sum rule [5]. GPDs are accessed through the so-called Deeply-Virtual Compton Scattering (Fig. 1), where an electron scatters off a proton producing a final state composed of the outgoing electron, the recoil proton and a real photon, this last being emitted by the struck quark after the interaction with the virtual photon exchanged with the electron. Another process, however, contribute to the same final state, the so-called Bethe-Heitler, where the final, real photon is emitted by the incoming or the outgoing electron and not from the struck quark. Since the two final states cannot be distinguished experimentally, their contributions sum up at the amplitude level. While the BH dominates the cross section at the JLab kinematics, information on the DVCS can anyhow be extracted from the interference term, where the factor arising from the BH contribution can be exactly calculable through QED. Details on the access to GPDs through the DVCS can be found in [6]. In the next years many new data on DVCS will get available. The COMPASS experiment at CERN forsees a full DVCS program, that will explore DVCS observables in the low-x region. On the other hand, JLab experiments will access the same observables in the high-x regime. Combined data from these two facilities will allow a map of the nuclear spatial structure in a wide x domain, allowing to understand how the valence and sea degrees of freedom contribute at the different regimes. DVCS constitutes an

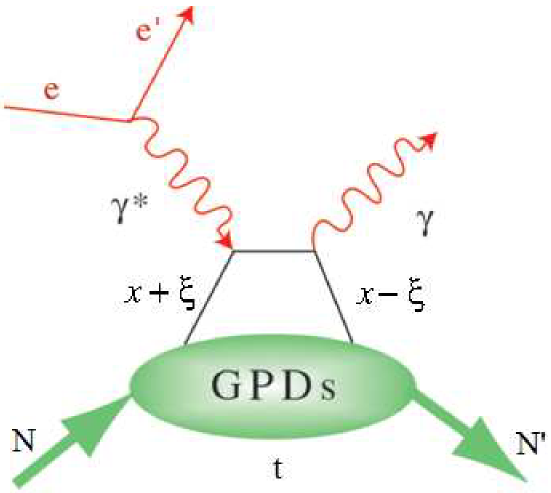

Figure 1. The "handbag" diagram for the DVCS process on the nucleon $eN \rightarrow e'N'\gamma'$. Here $x+\xi$ and $x-\xi$ are the longitudinal momentum fractions of the initial and final quark, respectively, and $t = (N - N')^2$ is the squared momentum transfer between the initial and final nucleons (or equivalently between the two photons). ξ is proportional to the Bjorken scaling variable x_B ($\xi \simeq \frac{x_B}{2-x_B}$, where $x_B = \frac{Q^2}{2M\nu}$, M is the nucleon mass and ν is the difference between the energies of the initial and final electron in the lab frame). x is not accessible experimentally.

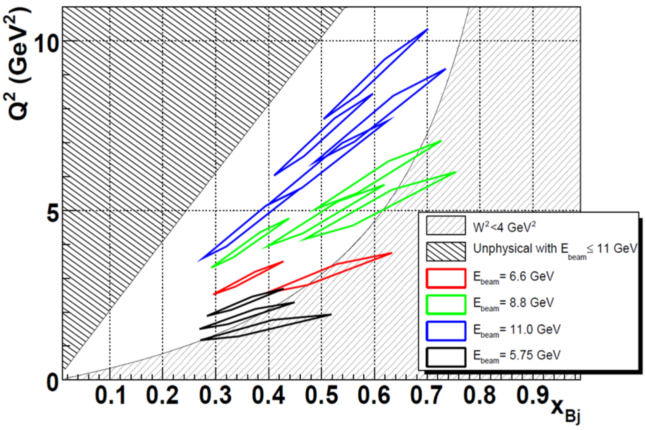

Figure 2. DVCS kinematics explored in the Hall A measurements proposed in [12] in correspondence of different beam energies, together with the region explored at 6 GeV [13] . Diamond shapes describe the acceptance of the spectrometer.

important part of the 12 GeV physics program of Jefferson Lab, and important measurements have already been performed during the 6-GeV operations, both in Hall A and Hall B. The exploratory observation of a non-zero DVCS Beam-Spin Asymmetry (Hall B, [7]) and the following observation of the scaling properties (Hall A, [13]) verified the validity of the handbag description and the possibility to access DVCS at the kinematics regime explored at JLab. High-statistics, wide kinematics extractions of Single and Double-Spin Asymmetries followed ([8], [9], [10], [11]). As to the 12-GeV program, Hall-A proposed an extension to a wider kinematics of the scaling measurements performed at 6 GeV [13], so to produce a precision measurement of the DVCS helicity-dependent and helicity-independent cross sections [12] in an extended Q^2 region. Goal of this proposal is to explore DVCS scaling in a Q^2 scan of the cross section for three values of x_B, whose kinematics is shown in Fig. 2. This experiment is considered a high-impact measurement and will be the first experiment to run after the 12 GeV upgrade. A similar measurement has been proposed in Hall C [14]. As to Hall-B, several measurements aiming at the extraction of DVCS observables have been approved, including different targets both unpolarized and longitudinally or transversely polarized. A big impact from Hall-B program is expected on the knowledge of quark orbital angular momentum. As already mentioned, GPDs provide an access to the total quark orbital angular momentum through the Ji's sum rule [5], where both the GPDs H and E appear. H has already constraints from existing data (e.g. [8]), but its knowledge will be dramatically improved through the measurement of the Beam-Spin Asymmetry on the proton proposed in Hall B [15]. GPD E, on the other hand, remains essentially unknown. The observables most sentitive to E are the Transverse Target-Spin Asymmetry for the proton and the longitudinal Beam-Spin Asymmetry for the neutron. The measurements of these two observables have been proposed in Hall B in [16, 17]. The extraction of E both on a proton and neutron target will allow to perform a flavor separation, eventually leading to the extraction of E for individual quark flavors. Projections from the mentioned proposals are reported in Fig. 3, together with the impact that they will have in constraining the total angular momentum carried by the u and d-quark flavors.

3 Transverse Momentum Distributions

Information complementary to the ones encoded in the GPDs come from the Transverse Momentum Dependent distributions (TMDs). TMDs describe the nucleon structure in terms of quark longitudinal and transverse momenta. At leading twist, eigth TMDs for each quark flavor describe the nucleon, categorized in terms of nucleon and parton spin information. TMDs can be accessed through Semi-Inclusive Deep-Inelastic Scattering (SIDIS), where at least one hadron is detected in the final state together with the outgoing electron. SIDIS cross section is parametrized in terms of Structure Functions (SF), where TMDs appear coupled to another non-perturbative object, the so-called Fragmentation Functions (FFs), that describe the hadronization of the struck quark to the final hadron. Different SFs can be accessed depending on the beam/target polarization degrees of freedom active in the process. JLab already approved several proposals by Hall

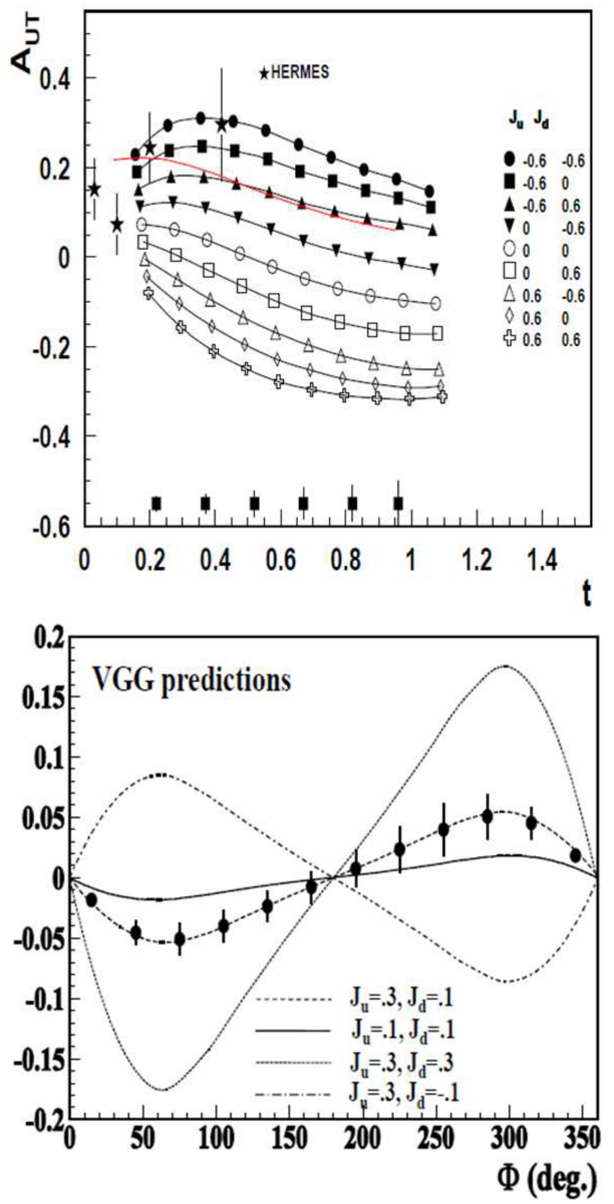

Figure 3. Impact of the measurement of A_{UT} on the proton (left plot, $-t$-dependence) [16] and of A_{UL} on the neutron (right plot, ϕ-dependence) [17] proposed in Hall B on the knowledge of the total angular momentum carried by individual flavors, as evaluated in the VGG model [18, 19].

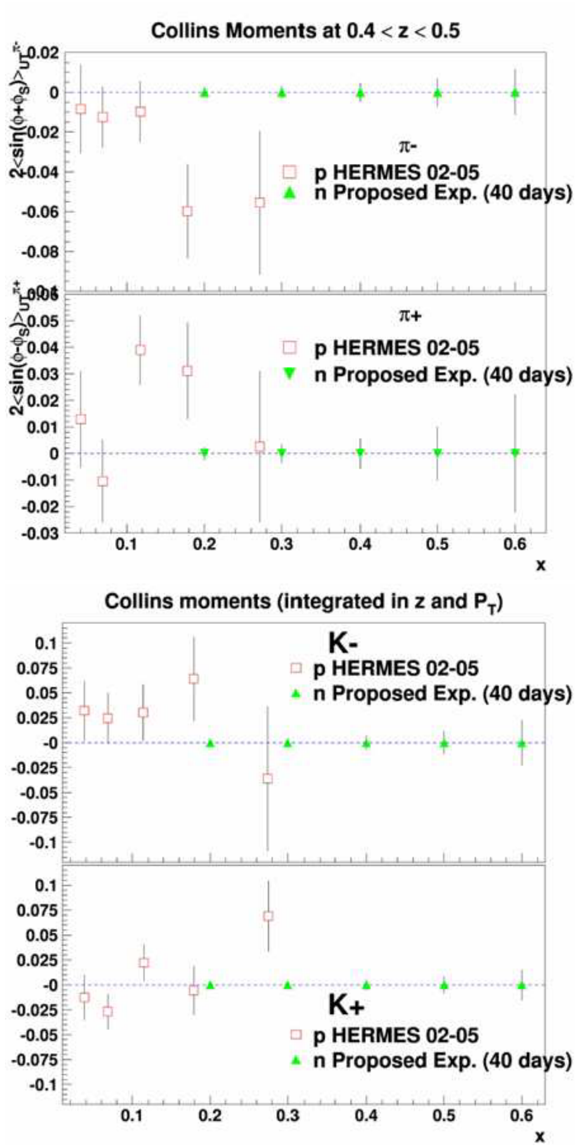

Figure 4. Projections for Collins functions on the neutron from Hall-A proposal [22], for pions and kaons. HERMES data on proton [23] are also shown.

A, B and C aiming at the extraction of SIDIS related observables. The joint efforts from the three halls involved, where the high-precision, high-statistics measurements in Hall A and C will be combined with the wide kinematics ones to be performed in Hall B, by using different targets and several target/beam polarization combinations, will allow a thorough exploration of the 3D structure of the nucleon in the momentum space and of its flavor structure (through the FFs). Hall-A proposed mesurements for the Collins and Sivers effects both on transversely-polarized NH_3 (proton) [21] and ^3He (neutron) [22] target. An analog measurement has been proposed by Hall-B on a tranversely-polarized proton target. Figs. 4, 5 show projections for both pions and kaons SIDIS on neutron [22], while Figs. 6, 7 reports projections from Hall-B measurements on proton [20]: it clearly emerges that a big impact on the knowledge of Sivers and Collins effects in the valence region and on the role played by the s-quark in the nucleon (in its relation to the u-quark dominance issue) can be expected from these measurements. Beyond the aformentioned measurements, other proposals devoted to the study of TMD-related effects (Boer-Mulders, Cahn effects, Kotzinian asymmetry etc) have been already approved for the JLab 12 GeV program in Hall A, B and C [26–28].

4 Conclusions

One of the most important challenge in hadronic physics is to reach the ultimate description of the nucleon in terms

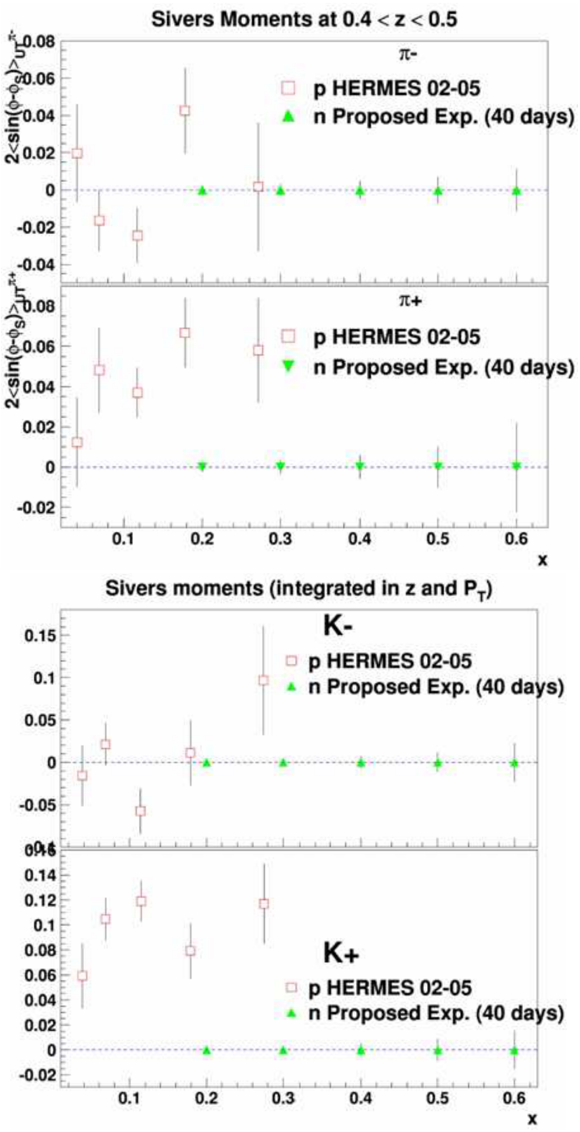

Figure 5. Projections for Sivers functions on the neutron from Hall-A proposal [22], for pions and kaons. HERMES data on proton [25] are also shown.

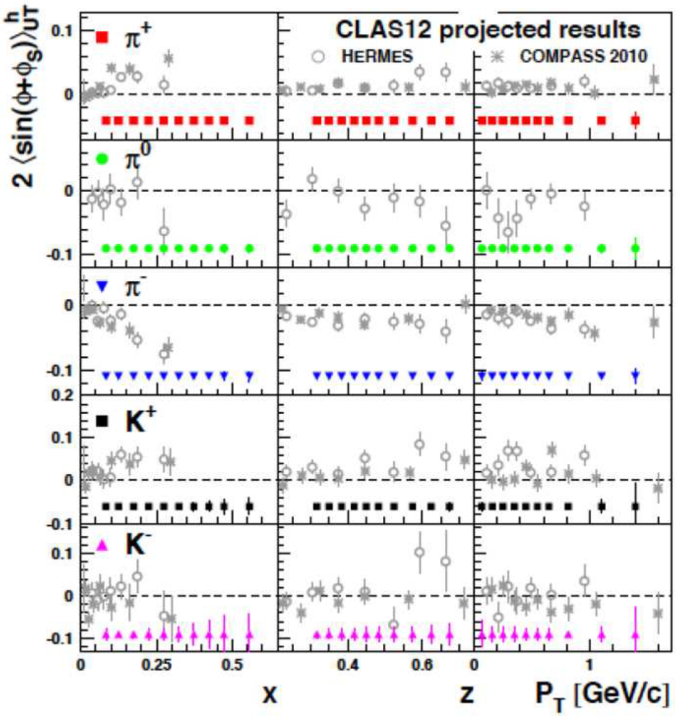

Figure 6. Projections for Collins functions on proton for SIDIS electro-production of pions and kaons from Hall-B proposals [20], together with HERMES [23] and COMPASS [24] measurements.

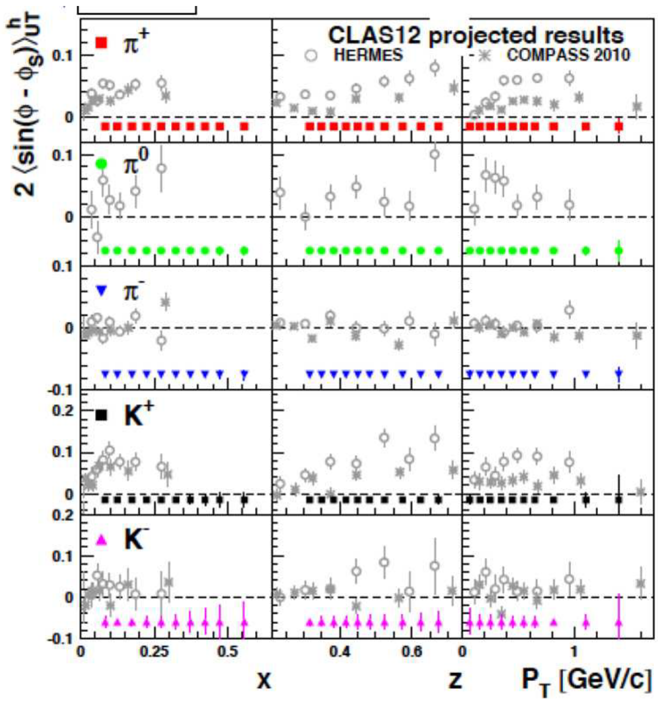

Figure 7. Projections for Sivers functions on proton for SIDIS electro-production of pions and kaons from Hall-B proposals [20], together with HERMES [25] and COMPASS [24] measurements.

of its elementary constituents, quarks and gluons. Parton behaviour is encoded in phase-space distributions $W(\vec{k},\vec{b})$ called Wigner functions, that, once integrated over tranverse space $\vec{b}$, lead to the TMDs, while if integrated over tranverse momentum $\vec{k}$ lead to the GPDs. The understanding of such a 5D description can be the central object of future studies on the nucleon structure. The Jefferson Lab 12-GeV program forsees a rich plethora of measurements aiming at the extraction of GPDs and TMDs observables. It will be realized through the joint efforts of three experimental halls, where different and complementary detectors will be installed, and whose excellent performances both in terms of luminosity and kinematics coverage will highly impact the knowledge of the nucleon structure in the valence region, eventually leading to a full mapping of the dynamics of its constituents in the 5D space.

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