Three–Dimensional parton structure of light nuclei

Sergio Scopetta\textsuperscript{1}, Alessio Del Dotto\textsuperscript{2,3}, Leonid Kaptari\textsuperscript{4}, Emanuele Pace\textsuperscript{5}, Matteo Rinaldi\textsuperscript{6} and Giovanni Salm\textparagraphe\textsuperscript{2}

\textsuperscript{1} Dipartimento di Fisica e Geologia, Universit\`a di Perugia and INFN, Sezione di Perugia, Italy
\textsuperscript{2} INFN, Sezione di Roma, Italy
\textsuperscript{3} University of South Carolina, Columbia, SC 29208, USA
\textsuperscript{4} Bogoliubov Lab. Theor. Phys., 141980, JINR, Dubna, Russia
\textsuperscript{5} Dipartimento di Fisica, Universit\`a di Roma Tor Vergata and INFN, Sezione di Roma Tor Vergata, Italy
\textsuperscript{6} Departamento de F \` ısica Te\` orica, Universidad de Valencia and IFIC, CSIC, Valencia, Spain

Abstract. Two promising directions beyond inclusive deep inelastic scattering experiments, aimed at unveiling the three dimensional structure of the bound nucleon, are reviewed, considering in particular the $^3$He nuclear target. The 3D structure in coordinate space can be accessed through deep exclusive processes, whose non-perturbative part is encoded in generalized parton distributions. In this way, the distribution of partons in the transverse plane can be obtained. As an example of a deep exclusive process, coherent deeply virtual Compton scattering (DVCS) off $^3$He nuclei, important to access the neutron generalized parton distributions (GPDs), will be discussed. In Impulse Approximation (IA), the sum of the two leading twist, quark helicity conserving GPDs of $^3$He, $H$ and $E$, at low momentum transfer, turns out to be dominated by the neutron contribution. Besides, a technique, able to take into account the nuclear effects included in the Impulse Approximation analysis, has been developed. The spin dependent GPD $\tilde{H}$ of $^3$He is also found to be largely dominated, at low momentum transfer, by the neutron contribution. The knowledge of the GPDs $H, E$ and $\tilde{H}$ of $^3$He is relevant for the planning of coherent DVCS off $^3$He measurements. Semi-inclusive deep inelastic scattering processes access the momentum space 3D structure parameterized through transverse momentum dependent parton distributions. A distorted spin-dependent spectral function has been recently introduced for $^3$He, in a non-relativistic framework, to take care of the final state interaction between the observed pion and the remnant in semi-inclusive deep inelastic electron scattering off transversely polarized $^3$He. The calculation of the Sivers and Collins single spin asymmetries for $^3$He, and a straightforward procedure to effectively take into account nuclear dynamics and final state interactions, will be reviewed. The Light-front dynamics generalization of the analysis is also addressed.

1. Introduction

The nucleus is a unique laboratory for studies of the QCD hadron structure. Indeed, nuclear targets are required, e.g., for the extraction of the neutron information from light nuclei and a precise flavor separation of parton distributions (PDFs), for the measurement of nuclear PDFs, relevant for the analysis of heavy ions collisions aimed at producing quark-gluon plasma, or to study in-medium fragmentation, mandatory to clarify the dynamics of hadronization. Unfortunately, inclusive Deep Inelastic Scattering (DIS) off nuclei has proven to be unable to answer fundamental questions, such as the quantitative microscopic explanation of the European Muon Collaboration (EMC) effect [1], i.e., the medium modification of PDFs, the quantitative
understanding of the parton structure of the neutron, the study in-medium of the distribution of parton transverse momentum, relevant for studies of hadronization as well as of chiral-odd quantities, such as the transversity PDFs or the Sivers and Collins functions and asymmetries. Thanks to novel coincidence measurements, possible at high luminosity facilities such as Jefferson Laboratory (JLab), a new era in the knowledge of the parton structure of nuclei has started [2].

In particular, two promising directions beyond inclusive measurements, aimed at accessing the three dimensional (3D) structure of the bound nucleon, are deep exclusive processes off nuclei, and semi-inclusive deep inelastic scattering (SIDIS) involving nuclear targets. In deep exclusive processes, such as deeply virtual Compton Scattering (DVCS), one accesses the 3D structure in coordinate space in terms of generalized parton distributions (GPDs) [3]; in SIDIS, the momentum space 3D structure is obtained by studying transverse momentum dependent parton distributions (TMDs) [3]. In the following, we summarize relevant results obtained by our group, for the $^3$He target, in the last few years, mainly with the aim of extracting the neutron information. The next section is devoted to the analysis of $^3$He GPDs, entering the DVCS cross sections of experiments which could be planned at the high-luminosity facilities; in the third section, an analysis of SIDIS off $^3$He, taking into account final state interactions between the produced meson and the remnants, will be reviewed. In the last section, perspectives are addressed and conclusions are drawn.

2. Deeply virtual Compton Scattering off $^3$He
Initially introduced in Ref. [4], GPDs are a crucial source of unique information. They represent in particular a tool to shed light on the so called “Spin Crisis” problem. GPDs measurements will allow indeed to access the parton total angular momentum [5]. Then, by subtracting from the latter the helicity quark contribution, measured in other independent processes, the parton orbital angular momentum (OAM) could be estimated.

Deeply Virtual Compton Scattering, i.e. the process $eH \rightarrow e'H'\gamma$ when $Q^2 \gg M^2$ ($Q^2 = -q \cdot q$ is the transferred momentum between the leptons $e$ and $e'$, $\Delta^2$ the one between hadrons $H$ and $H'$ with momenta $P$ and $P'$, and $M$ is the nucleon mass), is one of the cleanest

Figure 1. The $q = u$ flavor GPD $x_3 \hat{H}^{3,u}(x, \Delta^2, \xi)$, where $x_3 = (M_3/M)x$ and $\xi_3 = (M_3/M)\xi$, shown in the forward limit (left panel) and at $\Delta^2 = -0.1$ GeV$^2$ and $\xi_3 = 0.1$ (right panel), together with the neutron and the proton contribution. Solid lines correspond to the full IA result, Eq. (2), while the dashed ones represent the approximation Eq. (6).
between the nuclei structure (see, e.g., Refs. [9, 10]). This is valid also for GPD studies. Indeed, among the light quantities has been derived. Later, the treatment has been extended to the Hamiltonian of the system of two nucleons with relative momentum, which requires nuclear targets, is important. It permits in facts, together with the proton measurement, a flavor decomposition of GPDs. In studying observables related to the neutron polarization, He plays a special role, due to its spin structure (see, e.g., Refs. [9]10). This is valid also for GPD studies. Indeed, among the light nuclei He is the only one for which the quantity $\tilde{G}_M^{3,q}(x, \Delta^2, \xi) = H_3^q(x, \Delta^2, \xi) + E_3^q(x, \Delta^2, \xi)$, i.e., the sum of its quark-helicity independent GPDs $\tilde{H}_q$ and $E_q$, could be dominated by the neutron: in facts, the isoscalar targets $^2\text{H}$ and $^3\text{He}$ are not suitable to this aim. In Refs. [11], it has been also shown to what extent this fact can be used to extract the neutron information.

The analysis of $^3\text{He}$ GPDs in Impulse Approximation (IA) can be found in Refs. [12], where, for the GPD $H_3$ of $^3\text{He}$, convolution-like formulas in terms of the corresponding nucleon quantities has been derived. Later, the treatment has been extended to $\tilde{G}_M^{3,q}$ (see Ref. [11] for details), and to the quark helicity flip GPD $\tilde{H}_q$ [13], yielding

$$\tilde{G}_M^{3,q}(x, \Delta^2, \xi) = \sum_N \int dE \int d\tilde{p} \left[ P^N_{+,-,+} - P^N_{+,-,-} \right] (\tilde{p}, \tilde{p}', E) \frac{\xi^2}{\xi} \tilde{G}_M^{3,q}(x', \Delta^2, \xi'),$$

and

$$\tilde{H}_q^3(x, \Delta^2, \xi) = \sum_N \int dE \int d\tilde{p} \left[ P^N_{++,+++} - P^N_{++,--} \right] (\tilde{p}, \tilde{p}', E) \frac{\xi^2}{\xi} \tilde{H}_q^3(x', \Delta^2, \xi'),$$

respectively.

In the last two equations, $x'$ and $\xi'$ are the variables for the GPDs of the bound nucleons, $p (p' = p + \Delta)$ is its 4-momentum in the initial (final) state and, eventually, proper components appear of the one body, off diagonal, spin dependent spectral function:

$$P^N_{SS', ss}(\tilde{p}, \tilde{p}', E) = \frac{1}{(2\pi)^6} \frac{M \sqrt{ME}}{2} \int d\Omega_4 \sum_{s_4} \langle \tilde{P}S' | \tilde{p}' s', \tilde{s}_4 s_4 | N \rangle \langle \tilde{p} s, \tilde{s}_4 s_4 | \tilde{P}S \rangle_N,$$

where $S, S'$ are respectively the nuclear (nucleon) spin projections in the initial (final) state, and $E = E_{min} + E_{\scriptscriptstyle R}$, being $E_{\scriptscriptstyle R}$ the excitation energy of the interacting two-body recoiling system. The main ingredient in the definition Eq. (3) is the intrinsic overlap integral

$$\langle \tilde{p} s, \tilde{s}_4 s_4 | \tilde{P}S \rangle_N = \int d\gamma e^{i\tilde{p} \cdot \gamma} \langle \chi_N | N(\gamma) | \Psi_{\scriptscriptstyle R}^S(\tilde{x}, \gamma) \rangle$$

between the $^3\text{He}$ wave function, $\Psi_3^S$, and the final state, described by two different wave functions: i) the eigenfunction $\Psi_{\scriptscriptstyle R}^S$, with eigenvalue $E = E_{min} + E_{\scriptscriptstyle R}$, of the state $s_4$ of the intrinsic Hamiltonian of the system of two interacting nucleons with relative momentum $\tilde{t}$, which can be either a deuteron nucleus or a scattering state, and ii) the plane wave describing the nucleon $N$ in IA. For a numerical evaluation of Eqs. (1) and (2), we used the overlaps Eq. (4) appearing in Eq. (3) and corresponding to the analysis presented in Ref. [14] in terms of wave functions [15] evaluated using the AV18 interaction [16].

1 In this paper, $a^\pm = (a^0 \pm a^3)/\sqrt{2}$.
For the nucleonic $\tilde{G}_M^{N,q}$ and $\tilde{H}_q^N$, use has been made of a simple model \cite{17}, extended to evaluate also spin dependent GPDs (see Ref. \cite{11,13} for details). Since $^3$He data are not yet available, one can verify only a few general GPDs properties, i.e., the forward limit and the first moments. In particular the calculation of $H_q^3(x, \Delta^2, \xi)$ fulfills these constraints \cite{12}. Since there is no observable forward limit for $E_q^3(x, \Delta^2, \xi)$, for the $G_M^{3,q}(x, \Delta^2, \xi)$ calculation the only possible check is the first moment: $\int dA \tilde{G}_M^{3,q}(x, \Delta^2, \xi) = G_M^3(\Delta^2)$; where $G_M^3(\Delta^2)$ is the magnetic form factor (ff) of $^3$He. The obtained result was found to be in agreement with previous calculations (in particular, with the one-body part of the AV18 calculation presented in Ref. \cite{18}) and, for the low values of $\Delta^2$ which are relevant for the coherent process described here, i.e., $-\Delta^2 \leq 0.15$ GeV$^2$, our results compare well also with the data.

As an example, let us discuss now, in a little more detail, our calculation of $\tilde{H}_q^3$ \cite{13}. We checked first of all that the forward limit of our expression, Eq. (2), reproduces formally and quantitatively the results of Ref. \cite{9} for polarized DIS off $^3$He. On the other hand, the first moment of $\tilde{H}_q^3$ is related to the axial form factor of $^3$He, a poorly known observable which does not permit therefore a direct check. Having fulfilled at least the forward limit constraint, we proceed now to analyze the proton and neutron contributions to the $^3$He observable. The GPD $\tilde{H}_q^3$ is measured using a polarized target and, as a consequence, it should be dominated by the neutron contribution. Let us show now to what extent this property is obtained and how, thanks to this, the neutron information could be extracted.

Results of the numerical evaluation of Eq. (4) are shown in Fig. 1. In the forward limit, the neutron contribution strongly dominates the $^3$He quantity but, increasing $\Delta^2$, the proton contribution grows up, in particular for the $u$ flavor (see solid lines in Fig. 1). A procedure to safely extract the neutron information from $^3$He data is therefore necessary. This can be obtained by observing that Eq. (2) can be cast in the form

$$\tilde{H}_q^3(x, \Delta^2, \xi) \simeq \sum_N \int_{x_3}^{M_A} \frac{dz}{z} h_N^3(z, \Delta^2, \xi) \tilde{H}_q^N \left( \frac{x}{z}, \Delta^2, \frac{\xi}{z} \right),$$

where $h_N^3(z, \Delta^2, \xi)$ is a “light-cone spin dependent off-forward momentum distribution”, which turns out to be strongly peaked around $z = 1$, close to the forward limit. Therefore, in this region, for $x_3 = (M_A/M)x \leq 0.7$ one has:

$$\tilde{H}_q^3(x, \Delta^2, \xi) \simeq \sum_N \tilde{H}_q^N \left( \frac{x}{z}, \Delta^2, \xi \right) \int_0^{M_A} dz h_N^3(z, \Delta^2, \xi) \tilde{H}_q^N \left( \frac{x}{z}, \Delta^2, \frac{\xi}{z} \right),$$

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where $h_N^3(z, \Delta^2, \xi) \simeq \sum_N \tilde{H}_q^N \left( \frac{x}{z}, \Delta^2, \xi \right) \int_0^{M_A} dz h_N^3(z, \Delta^2, \xi) \tilde{H}_q^N \left( \frac{x}{z}, \Delta^2, \frac{\xi}{z} \right),$ which would give the nuclear axial ff if the proton and the neutron were point-like particles. These objects, at small values of $\Delta^2$, depend slowly on the potential used in the calculation, so that theoretical errors in their computation are small. This can be realized observing that, in the forward limit, they reproduce the “effective polarizations” of the protons ($p_p$) and the neutron ($p_n$) in $^3$He, whose values are rather similar if evaluated within different nucleon nucleon potentials (see Refs. \cite{11,14} for a comprehensive discussion). In particular, within the AV18 potential used here, the values $p_n = 0.878$ and $p_p = -0.024$ are obtained. Then, Eq. (6) can be used to extract the neutron contribution from possible sets of data for the proton and for $^3$He:

$$\tilde{H}_q^{n,extr} \left( \frac{x}{z}, \Delta^2, \xi \right) \simeq \frac{1}{G_A^{3,n,point}(\Delta^2)} \left\{ \tilde{H}_q^3 \left( \frac{x}{z}, \Delta^2, \xi \right) - G_A^{3,p,point}(\Delta^2) \tilde{H}_q^p \left( \frac{x}{z}, \Delta^2, \xi \right) \right\}.$$
This comparison between the free neutron GPDs, used as input in the calculation, and the ones extracted using our calculation for $^3\text{He}$ and the proton model for $^4\text{He}$, shows that the procedure works nicely even beyond the forward limit. The only theoretical input are axial point like ffs, which, as discussed above, are under good theoretical control. The procedure works for $x \leq 0.7$, the region where possible data could be gathered. Analogous extraction procedures have been demonstrated to hold for $^5\text{He}$ in ref. [11].

In closing this section, we have shown that coherent DVCS off $^3\text{He}$ at low momentum transfer $\Delta^2$ as an ideal process to access the neutron GPDs; if data were taken at higher $\Delta^2$, a relativistic treatment [19] and/or the inclusion of many body currents, beyond the present IA scheme, should be implemented. The next step of this investigation will be the evaluation of cross section asymmetries relevant to DVCS experiments at JLab kinematics, using the obtained GPDs $H, E$ and $\tilde{H}$ of $^3\text{He}$ as a theoretical input. At the beginning, the leading twist analysis of DVCS for a spin 1/2 target, presented in Ref. [20], will be performed.

3. Extraction of neutron asymmetries from SIDIS experiments off $^3\text{He}$

As discussed in the Introduction, information on the three-dimensional structure of the nucleon in momentum space can be obtained studying TMDs and transverse momentum dependent fragmentation functions (TMFFs) in SIDIS processes. The Sivers TMD [21] and the Collins TMFF [22], describing correlations between the spin and the momentum of a parton, are due to leading-twist state final interactions at the parton level and have therefore a very interesting dynamical content [23]. The Sivers and Collins functions are extracted from single spin asymmetries (SSAs) built from differential cross sections of SIDIS of unpolarized electrons off transversely polarized targets. The present data for the processes $\overline{p}(e, e'\pi)x$ [24] and $D(e, e'\pi)x$ [25] show a strong flavor dependence and measurements with a $^3\text{He}$ target have been proposed and performed (see Ref. [26] for the first data at JLab with a 6 GeV electron beam). Further accurate experiments are planned at the 12-GeV upgrade of JLab [27]. As in the GPDs case discussed in the previous section, neutron data are important to achieve the flavor separation of the Sivers and Collins distributions [25], and polarized $^3\text{He}$ targets play a special role. To obtain a reliable information one has to take into account the nuclear structure of $^3\text{He}$ as carefully as possible. Initially, the process can be described using the Plane Wave Impulse Approximation (PWIA), leading to dynamical nuclear effects described by the spin-dependent spectral function of $^3\text{He}$, $P_{\sigma,\sigma'}(\tilde{p}, E)$, (see, e.g. [24]) that yields the probability distribution to find a nucleon with given removal energy (as a matter of facts, the spectator pair is interacting), three-momentum and polarization inside the nucleus. By using this formalism, it has been shown long time ago that, in spin dependent DIS, one can safely extract the neutron longitudinal asymmetry, $A_n$, from the corresponding $^3\text{He}$ observable, $A_3^{exp}$ [9]. One obtains

$$A_n \simeq \left( A_3^{exp} - 2p_p f_p A_p^{exp} \right) / (p_n f_n) \quad (8)$$

with $p_n(p_p)$ the neutron (proton) effective polarization inside the polarized $^3\text{He}$, and $f_n(p_p)$, the dilution factor. Values of $p_n$ and $p_p$ obtained using the AV18 interaction [16] are $p_p = -0.024$, $p_n = 0.878$ (see, e.g., [30]). In Ref. [30], an analogous extraction was demonstrated to work also in SIDIS, if the Bjorken limit and PWIA are assumed, and applied to the SSA of a transversely polarized $^3\text{He}$ target, obtained from the process $^3\text{He}(e, e'\pi)X$, in order to obtain the SSA of a transversely polarized neutron. In that approach, the SSAs of $^3\text{He}$ can be expressed as convolutions of $P_{\sigma,\sigma'}(\tilde{p}, E)$ and proper combinations of suitable TMDs and TMFFs. The same extraction procedure has been also applied in combination with a Monte Carlo simulating the kinematics of the experiment E12-09-018 [31]. Indeed Eq. (8) has been used by the JLab Hall A Collaboration to extract, for the first time, the Collins and Sivers moments from a transversely polarized $^3\text{He}$ target [26]. Since existing measurements are limited in statistical accuracy and
kinematics coverage, an extensive program of high precision measurements of SIDIS off $^3$He will be part of the JLab program at 12 GeV [27]. The expected statistical accuracy is of the order of percent in a wide range of multi-dimensional kinematical binning; for this reason the PWIA could be no longer sufficient and Final State Interactions (FSI) between the detected meson and the remnants of the process, not considered in PWIA, may have a relevant role. Let us discuss now a proper way to introduce this mechanism, leading to a distorted spin-dependent spectral function of the $^3$He. The JLab SIDIS experiments will exploit an electron beam at 8.8 and 11 GeV off $^3$He polarized gaseous target; the relative energy between the $(A-1)$ system and the system of the detected pion and the remnant (depicted in Fig. 2) is a few GeV and therefore FSI can be treated within a generalized eikonal approximation (GEA). This framework was already successfully applied to unpolarized SIDIS [32], and in a recent paper the distorted spin-dependent spectral function has been calculated for the so-called spectator SIDIS, where a slow $(A-1)$ nucleon system, acting as a spectator of the photon-nucleon interaction, is detected, while the produced fast hadron is not [33]. In the following we discuss standard SIDIS, where all the possible state of the two-nucleon spectator system have to be considered.

The distorted spin-dependent spectral function for a polarized $^3$He target can be written as

$$S_{SS}^N(E, p_{mis}) = \sum_{f_2} \sum_{\epsilon^*_2} \rho(\epsilon^*_2) \tilde{O}_{f_2}^{N f_2} \delta(E + M_3 - m_N - M_2^*)$$

with the product of distorted overlaps, given in terms of the intrinsic Jacobi coordinates $\mathbf{r}$ and $\mathbf{\rho}$, defined by

$$\tilde{O}_{f_2}^{N f_2}(\epsilon^*_2, p_{mis}) = \langle \lambda, \phi_{f_2}^{\epsilon^*_2}(\mathbf{r}) e^{-i p_{mis} \cdot \mathbf{\rho}} \mathcal{G}(\mathbf{r}, \mathbf{\rho}) \vert \Psi_{f_2}^{S_3} \rangle \langle \Psi_{f_2}^{S_3} \vert \lambda', \phi_{f_2}^{\epsilon^*_2}(\mathbf{r}) e^{-i p_{mis} \cdot \mathbf{\rho}} \rangle.$$

with $i)$ $\rho(\epsilon^*_2)$ is the density of the spectator pair with intrinsic energy $\epsilon^*_2$, $ii)$ $|\Psi_{f_2}^{S_3}(\mathbf{r}, \mathbf{\rho})\rangle$ is the ground state of the 3-nucleon system with polarization $S_3$, $iii)$ $E$ is the removal energy $E = \epsilon^*_2 + B_3$, $p_{mis}$ is the three momentum of the spectator pair.

The Glauber operator in Cartesian coordinates is given by

$$\mathcal{G}(\mathbf{r}, \mathbf{\rho}) = \prod_{i=2,3} \left[ 1 - \theta(\mathbf{r}_i - \mathbf{r}_1) \right] \Gamma \left( \mathbf{r}_{i\bot} - \mathbf{r}_{1\bot}, \mathbf{r}_i - \mathbf{r}_1 \right),$$

where $\Gamma(\mathbf{r}, \mathbf{\rho})$ is the density of the spectator pair with intrinsic energy $\epsilon^*_2$.
Figure 3. The $^3$He spectral function, for the neutron, in the unpolarized case, as a function of $p_{mis} = |p_{mis}|$ and of the removal energy $E$, in PWIA (full lines) and with FSI taken into account in the present GEA framework (dotted lines). The spectral functions are shown for the values of $E$ and $p_{mis}$ that contribute to the calculus of the SIDIS cross section when $A(p_N \cdot q)/(P_3 \cdot q) = 0.86$ at $\mathcal{E} = 11$ GeV and $Q^2 \simeq 7.6$ (GeV/c)$^2$ (see Ref. [34] for more details).

where $\hat{r}_i⊥$ and $\hat{r}_i||$ are the perpendicular and the parallel components of $r_i$ with respect to the direction of the debris. The profile function

$$\Gamma(r_i⊥ - r_i⊥, r_i|| - r_i||) = \frac{(1-i \eta) \sigma_{eff}(r_i|| - r_i||)}{4 \pi b_0^2} \exp \left[ -\frac{(r_i⊥ - r_i⊥)^2}{2 b_0^2} \right] ,$$



(12)

unlike that occurring in the standard Glauber approach, depends not only on the impact parameter but also on the longitudinal separation through an effective cross section, $\sigma_{eff}$. For the latter we used the model proposed and exploited in previous works (for details on the model see Ref. [32, 33]). To recover the PWIA formulation, one has simply to put $\mathcal{G} \equiv 1$ in Eq. (11). In Fig. 3 a plot of the $^3$He spectral function, evaluated within plane wave impulse approximation or taking FSI into account, is shown, for the neutron, in the unpolarized case.

The relevant part in the extraction of the transversely polarized neutron’s SSAs is the transverse spectral function, given by a proper combination of non-diagonal elements of the spin-dependent spectral function defined in Eq. (9). In general, the transverse spin-dependent SF evaluated in PWIA, $S^{\perp(PWIA)}$, and the corresponding distorted quantity, $S^{\perp(FSI)}$, can be
Figure 4. Neutron asymmetries extracted through Eq. (8) from the Sivers (Left panel) and Collins (Right panel) \(^3\)He asymmetries, with and without FSI taken into account in the actual kinematics of JLab at 12 GeV [27]. Preliminary results to appear in [34].

quite different and the corresponding effective polarizations can differ by 10-15%. Nevertheless, in Eq. (8) the effective polarizations occur in products with the dilution factors and to a large extent it turns out that, in the kinematical range explored at JLab, \(p_{PWIA}^p f_{PWIA}^p \approx p_{FSI}^p f_{FSI}^p\), \(p_{PWIA}^n f_{PWIA}^n \approx p_{FSI}^n f_{FSI}^n\) [43]. This allows one to safely adopt the usual extraction, as shown in Fig. 4 and therefore the goal of a sound flavor decomposition of TMDs seems definitely safe.

4. Conclusions and Perspectives

Let us summarize the status of our calculations of DVCS and SIDIS processes with \(^3\)He targets. In section 2, we have shown realistic calculations of GPDs of \(^3\)He, in plane wave impulse approximation, the essential ingredients for the evaluation of DVCS cross sections. Although DVCS off \(^3\)He turns out to be promising for the extraction of neutron GPDs and relevant to understand the \(A\)–dependence of the modification of the parton structure of bound nucleons, for technical reasons, the present experimental program of JLab at 12 GeV will collect data for DVCS off deuteron and \(^4\)He targets. Preliminary data of DVCS off \(^4\)He, gathered with JLab at 6 GeV, are already available and should be published soon [35]. They deserve the attention of our community, which could perform precise calculations. Anyway, as explained in section 2, isoscalar targets such as deuteron or \(^4\)He are not useful for a complete flavor separation of GPDs. Besides, a scalar nucleus as \(^4\)He cannot be used for the measurement of helicity dependent GPDs, and the same quantity is hardly extracted from deuteron data. At the planned Electron Ion Collider [36], where slow nuclear recoiling systems will be easily detected and polarized nuclear beams will be naturally available, the proposal of polarized DVCS off \(^3\)He and the measurement of the neutron helicity dependent GPD, \(\tilde{H}\), using the technique described in Section 2, should become feasible.

As described in this talk for both DVCS and SIDIS, the standard theoretical description of few-nucleon systems, where nucleon and pion degrees of freedom are taken into account, has achieved a very high degree of sophistication. Nonetheless, one should try to fulfill, as much as possible, the relativistic constraints, dictated by covariance with respect to the Poincaré group, if processes involving nucleons with large 3-momentum are considered and a high precision is needed. At least, one should carefully deal with the boosts of the nuclear states, \(|\Psi_{init}\rangle\) and...
In particular, a relativistic treatment is important to precisely describe the JLab program @ 12 GeV for few-body systems (see, e.g., Refs. [37], [38]). To this aim, in the last few years, we have developed a relativistic description of $^3\text{He}$ using a Poincaré covariant spectral function built up within the light-front Hamiltonian dynamics (LFHD) [39].

Indeed, the Relativistic Hamiltonian Dynamics (RHD) of an interacting system with a fixed number of on-mass-shell constituents (see, e.g., [40]), associated to the Bakamijan-Thomas construction of the Poincaré generators [41], permits a fully Poincaré covariant description of DIS, SIDIS and DVCS off $^3\text{He}$. The light-front (LF) form of RHD has been adopted [40], which has a subgroup structure of the LF boosts (with a separation of the intrinsic motion from the global one, which is very important for our aim) and a meaningful Fock expansion (see, e.g., Ref. [42]). Furthermore, within the LFHD, one can take advantage of the successful non-relativistic phenomenology that has been developed for the nuclear interaction.

The LF spin-dependent spectral function obtained from the LF wave functions for the two- and the three-nucleon systems has been defined in [39, 43]. With respect to previous attempts, the essential difference is the definition of the nucleon momentum: in our approach, it is the intrinsic momentum of the nucleon in the cluster formed by the nucleon and by the fully interacting (A-1) spectator system with given mass. This definition implements the macrocausality: if a system is separated into disjoint subsystems by a sufficiently large spacelike separation, then the subsystems behave as independent systems. The proposed formalism can find useful applications in deep inelastic scattering, since the LF momentum distribution fulfills both normalization and momentum sum rules, while the cluster separability introduces new binding effects with respect to previous approaches.

We are presently applying our relativistic spectral function to study the role of relativity in the EMC effect for $^3\text{He}$. Preliminary results have been presented in Ref. [44]. We plan now to complete the LF analysis of the EMC effect for $^3\text{He}$. As next steps, we will calculate a LF non-diagonal spectral function, to analyze DVCS cross sections, where relativity could play an essential role, if high transfer momentum is involved, as it happens for hadrons electromagnetic form factors (see, e.g., Ref. [45]). Eventually, FSI should be added to our LF relativistic description of $^3\text{He}$, to study SIDIS processes and calculate single spin asymmetries.

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