The spin structure of the nucleon in light-cone quark models

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The quark spin densities related to generalized parton distributions in impact-parameter space and to transverse-momentum dependent parton distributions are reviewed within a light-cone quark model, with focus on the role of the different spin-spin and spin-orbit correlations of quarks. Results for azimuthal spin asymmetries in semi-inclusive deep-inelastic scattering due to T-even transverse-momentum dependent parton distributions are also discussed.

Keywords: parton correlation functions, light-cone quantization, semi-inclusive deep inelastic scattering

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1. Introduction

One of the most challenging tasks for unravelling the partonic structure of hadrons is mapping the distribution of the spin of the proton onto its constituents. To this aim, generalized parton distributions (GPDs) 1-6 and transverse-momentum dependent parton distributions (TMDs) 7,8 have proved to be among the most useful tools. GPDs provide a new method of spatial imaging of the nucleon 9-10, through the definition of impact-parameter dependent spin densities which reveal the correlations between the quark distributions in transverse-coordinate space and longitudinal momentum for different quark and target polarizations. On the other hand, TMDs contain novel and direct three-dimensional information about the strength of different spin-spin and spin-orbit correlations in the momentum space. Although GPDs and TMDs can be seen as two different limiting cases of the same general-
ized parton-correlation functions, no-model independent relations between the two classes of objects has been obtained so far. A convenient way to make explicit which kind of information on hadron structure is contained in these quantities is the representation in terms of overlap of light-cone wave functions (LCWFs) which are the probability amplitudes to find a given $N$-parton configuration in the Fock-space expansion of the hadron state. In the following, we will confine our analysis to the three-quark sector, by truncating the light-cone expansion of the nucleon state to the minimal Fock-space configuration. The three-quark component of the nucleon has been studied extensively in the literature in terms of quark distribution amplitudes defined as hadron-to-vacuum transition matrix elements of non-local gauge-invariant light-cone operators. Unlike these works, the authors of Refs. considered the wave-function amplitudes keeping full transverse-momentum dependence of partons and proposed a systematic way to enumerate independent amplitudes of a LCWF which parametrize the different orbital angular momentum components of the nucleon state. In particular, the three-quark LCWF involves six independent amplitudes corresponding to different combinations of quark orbital angular momentum and helicity. With such amplitudes one can obtain a model-independent representation for the quark contribution to TMDs and GPDs which emphasizes the role of the different orbital angular momentum components. One could then choose a phenomenological approach parametrizing the light-cone amplitudes and fitting observables related to TMDs and GPDs to data. Here we will adopt a light-cone constituent quark model (CQM) which has been successfully applied in the calculation of the electroweak properties of the nucleon. As outlined in Ref. the starting point is the three-quark wave function obtained as solution of the Schrödinger-like eigenvalue equation in the instant-form dynamics. The corresponding solution in light-cone dynamics is obtained through the unitary transformation represented by product of Melosh rotations acting on the spin of the individual quarks. In particular, the instant-form wave function is constructed as a product of a momentum wave function which is spherically symmetric and invariant under permutations, and a spin-isospin wave function which is uniquely determined by SU(6) symmetry requirements. By applying the Melosh rotations, the Pauli spinors of the quarks in the nucleon rest frame are converted to light-cone spinors. The relativistic spin effects are evident in the presence of spin-flip terms in the Melosh rotations which generate non-zero orbital angular momentum components and non-trivial correlations between spin and transverse momentum of the quarks. On the other hand, the momentum-dependent wave function keeps the original functional form, with instant-form coordinates rewritten in terms of light-cone coordinates. The explicit expressions of the light-cone amplitudes within this CQM can be found in Ref., while the corresponding results for GPDs in impact-parameter space and for TMDs will be discussed in sect. 2 and 3, respectively. Finally, in sect. 4 we will show predictions for single spin asymmetries in semi-inclusive deep inelastic scattering (SIDIS) due to T-even TMDs.
2. Spin densities in the impact parameter space

In light cone gauge $A^+ = 0$, GPDs are obtained from the same quark correlation function entering the definition of the ordinary parton distributions, but now evaluated between hadron with different momentum in the initial and final state. They depend on the average longitudinal-momentum fraction $x$, the skewness parameter $\xi$ describing the longitudinal change of the nucleon momentum, and the momentum transfer $t = \Delta^2$. When $\xi = 0$ and $x > 0$, by a two-dimensional Fourier transform to impact-parameter space GPDs can be interpreted as densities of quarks with longitudinal momentum fraction $x$ and transverse location $b$ with respect to the nucleon center of momentum. Depending on the polarization of both the active quark and the parent nucleon, one defines three-dimensional densities $\rho(x, b, \lambda, (\Lambda, S_T))$ and $\rho(x, b, s_T, S_T)$ representing the probability to find a quark with longitudinal momentum fraction $x$ and transverse position $b$ either with light-cone helicity $\lambda$ ($= \pm 1$) or transverse spin $s_T$ in the nucleon with longitudinal polarization $\Lambda$ ($= \pm 1$) or transverse spin $S_T$. They read

$$
\rho(x, b, \lambda, (\Lambda, S_T)) = \frac{1}{2} \left[ H(x, b^2) + b^j \varepsilon^{ji} S_T^i \frac{1}{M} E'(x, b^2) + \lambda \Delta \tilde{H}(x, b^2) \right],
$$

$$
\rho(x, b, s_T, S_T) = \frac{1}{2} \left[ H(x, b^2) + s_T^j S_T^i \left( H_T(x, b^2) - \frac{1}{2M^2} \Delta b \tilde{H}_{T}(x, b^2) \right) + \frac{b^j \varepsilon^{ji}}{M} \left( S_T^i E'(x, b^2) + s_T^i \left[ E_T'(x, b^2) + 2 \tilde{H}_T'(x, b^2) \right] \right) + s_T^j (2b^j b^i - b^2 \delta_{ij}) S_T^i \frac{1}{M^2} \tilde{H}_{T}''(x, b^2) \right],
$$

where the derivatives are defined $f' = \frac{\partial}{\partial b^j} f$, and $\Delta b f = 4 \frac{\partial}{\partial b^j} \left( b^2 \frac{\partial}{\partial b^j} \right) f$. In Eqs. (1) and (2) enter the Fourier transforms of the GPDs for unpolarized quarks ($H$ and $E$), for longitudinally polarized quarks ($\tilde{H}$ and $\tilde{E}$) and transversely polarized quarks ($H_T$, $E_T$, $\tilde{H}_T$, and $\tilde{E}_T$).

In Eq. (1) the first term with $H$ describes the density of unpolarized quarks in the unpolarized proton. The term with $E'$ introduces a sideways shift in such a density when the proton is transversely polarized, and the term with $\tilde{H}$ reflects the difference in the density of quarks with helicity equal or opposite to the proton helicity. In the three lines of Eq. (2) one may distinguish the three contributions corresponding to monopole, dipole and quadrupole structures. The unpolarized quark density $\frac{1}{2} H$ in the monopole structure is modified by the chiral-odd terms with $H_T$ and $\Delta b \tilde{H}_T$ when both the quark and the proton are transversely polarized. Responsible for the dipole structure is either the same chiral-even contribution with $E'$ from the transversely polarized proton appearing in the spin distribution (1) or the chiral-odd contribution with $E_T' + 2 \tilde{H}_T'$ from the transversely polarized quarks or both. The quadrupole term with $\tilde{H}_T''$ is present only when both quark and proton are transversely polarized. In terms of overlap of light-cone amplitudes, the monopole distributions are associated to GPDs which are diagonal in the orbital angular mo-
Fig. 1. The spin-densities for (transversely) $\hat{x}$-polarized quarks in an unpolarized proton (left panels) and for unpolarized quarks in a (transversely) $\hat{x}$-polarized proton. The upper (lower) row corresponds to the results for up (down) quarks.

momentum space, while the dipole distributions describe spin flip either of the nucleon or of the quark, and accordingly are given by overlap of light-cone amplitudes which differ by one unit of orbital angular momentum in the initial and final state. In the case of the chiral-odd GPD $\tilde{H}_T$ the nucleon helicity flips in the direction opposite to the quark helicity, with a mismatch of orbital angular momentum of two units between the initial and final state.

In the following, we show some examples of spin densities using the model predictions for the GPDs from Refs. 21, 23, 24. In the case of transversely polarized quarks in an unpolarized proton the dipole contribution introduces a large distortion perpendicular to both the quark spin and the momentum of the proton, as shown in the left column of Fig. 1. This effect has been related to a non-vanishing Boer-Mulders function $h_1^T$ which describes the correlation between intrinsic transverse momentum and transverse spin of quarks. Such a distortion reflects the large value of the anomalous tensor magnetic moment $\kappa_T$ for both flavors. Here, $\kappa_T^u = 3.98$ and $\kappa_T^d = 2.60$, to be compared with the values $\kappa_T^u \approx 3.0$ and $\kappa_T^d \approx 1.9$ of Ref. 24 due to a positive combination $E_T + 2H_T$. Since $\kappa_T \sim -h_1^T$, the present results confirm the conjecture that $h_1^T$ is large and negative both for up and down quarks. As also noticed in Refs. 25, 27, the large anomalous magnetic moments $\kappa^{u,d}$ are responsible for the dipole distortion produced in the case of unpolarized quarks in transversely polarized nucleons (right column of Fig. 1). With the present model, $\kappa^u = 1.86$ and $\kappa^d = -1.57$, to be compared with the values $\kappa^u = 1.673$ and $\kappa^d = -2.033$ derived
from data. This effect can serve as a dynamical explanation of a non-vanishing Sivers function\(^{28}\) \(f_{1T}^\perp\) which measures the correlation between the intrinsic quark transverse momentum and the transverse nucleon spin. The present results, with the opposite shift of up and down quark spin distributions imply an opposite sign of \(f_{1T}^\perp\) for up and down quarks\(^{25}\) as confirmed by the recent observation of the HERMES collaboration\(^{29}\). The results in Fig. 1 are also in qualitative agreement with those obtained in lattice calculations\(^{27}\).

Finally, we refer to\(^{6,30}\) for the light-cone CQM results of the densities with more complex spin-configurations with transverse polarization of both the quark as well as the proton.

3. Transverse-momentum dependent distributions

The eight leading-twist TMDs, \(f_1\), \(f_{1T}^\perp\), \(g_1\), \(g_{1T}\), \(g_{1L}\), \(h_1\), \(h_{1T}\), \(h_{1L}\), and \(h_1^\perp\), are a natural extension of standard parton distribution from one to three dimensions in momentum space, being defined in terms of the same quark correlation functions but without integration over the transverse momentum. Among them, the Boer-Mulders \(h_1\)\(^{26}\) and the Sivers \(f_{1T}^\perp\)\(^{28}\) functions are T-odd, i.e. they change sign under “naive time reversal”, which is defined as usual time reversal, but without interchange of initial and final states. Since non-vanishing T-odd TMDs require gauge boson degrees of freedom which are not taken into account in our light-cone quark model, our model results will be discussed only for the T-even TMDs.

Projecting the correlator for quarks of definite longitudinal or transverse polarizations, one obtains the following spin densities in the momentum space

\[
\tilde{\rho}(x, k_T^2, \Lambda, \mathbf{S}_T) = \frac{1}{2} \left[ f_1 + S_T^i \epsilon^{ij} k_j^i \frac{1}{m} f_{1T}^\perp + \lambda \Lambda g_1 + \lambda S_T^i k_j^i \frac{1}{m} g_{1T} \right],
\]

\[
\tilde{\rho}(x, k_T^2, s_T, \mathbf{S}_T) = \frac{1}{2} \left[ f_1 + S_T^i \epsilon^{ij} k_j^i \frac{1}{m} f_{1T}^\perp + s_T^i \epsilon^{ij} k_j^i \frac{1}{m} h_1^\perp + s_T^i S_T^j h_1 + s_T^i (2k^j k^j - k^2 \delta^{ij}) S_T^i \frac{1}{2m^2} h_{1T} + \Lambda s_T^i k^i \frac{1}{m} h_{1L} \right],
\]

where the distribution functions depend on \(x\) and \(k_T^2\). As first outlined in Ref\(^{10}\) and further discussed in a more broad context in Ref\(^{12}\), the tensor structure in \((3)\) and \((4)\) are analogs of those in \((3)\) and \((4)\), respectively, with \(k_T\) playing the role of \(b\). However \(k_T\) and \(b\) are not conjugate variables, and therefore the distributions in the transverse momentum are not Fourier transform of the impact-parameter dependent distributions. The analogy between the distributions in the two spaces reads

\[
f_1 \leftrightarrow H,
\]

\[
f_{1T}^\perp \leftrightarrow -E',
\]

\[
g_1 \leftrightarrow \tilde{H},
\]

\[
h_1 \leftrightarrow H_T - \Delta_b \tilde{H}_T/(4m^2),
\]

\[
h_1^\perp \leftrightarrow -(E'_T + 2\tilde{H}_T'),
\]

\[
h_{1T}^\perp \leftrightarrow 2\tilde{H}_T'.
\]
The impact-parameter distributions which would correspond to $g_{1T}$ and $h_{1L}^T$ are absent because of time-reversal invariance. Therefore the dipole correlations related to these TMDs are a characteristic feature of intrinsic transverse momentum. The results in the light-cone quark model of Ref. [22] for the densities with longitudinally polarized quarks in a transversely polarized proton are shown in Fig. 2. The sideways shift in the positive (negative) $x$ direction for up (down) quark due to the dipole term $\propto S^i k^i \frac{1}{m} g_{1T}$ is sizeable, and corresponds to an average deformation $\langle k^u_x \rangle = 55.8$ MeV, and $\langle k^d_x \rangle = -27.9$ MeV. The dipole distortion $\propto \Lambda S^i k^i \frac{1}{m} h_{1L}^T$ in the case of transversely polarized quarks in a longitudinally polarized proton is equal but opposite in sign, since in our model $h_{1L}^T = -g_{1T}$. These model results are supported from a recent lattice calculation [31] which gives, for the density related to $g_{1T}$, $\langle k^u_x \rangle = 67(5)$ MeV, and $\langle k^d_x \rangle = -30(5)$ MeV. For the density related to $h_{1L}^T$, they also find shifts of similar magnitude but opposite sign: $\langle k^u_x \rangle = -60(5)$ MeV, and $\langle k^d_x \rangle = 15(5)$ MeV.

The LCWF overlap representation of the T-even TMDs in Eq. (5) are given in terms of the same combinations of light-cone amplitudes parametrizing the corresponding GPDs at $\xi = 0$, but taken for different values of the transverse momenta of the quarks. In particular, TMDs are diagonal in the momentum space of the three quarks and are unintegrated over the transverse momentum of the active quark. On the other side, GPDs are integrated over the transverse momenta of all the three quarks, but with a finite transverse-momentum transfer between the quarks in the initial and final state. Therefore, the possibility to establish a direct relationship between TMDs and GPDs exists only in the kinematical limits where the differences in the momentum dependence of the light-cone amplitudes vanish. This is trivially the case when both the TMDs and the GPDs reduce to the ordinary quark distribution functions, i.e.

$$\int d k_T^2 f_1(x, k_T^2) = f_1(x) = H(x, \xi = 0, t = 0),$$

$$\int d k_T^2 g_{1L}(x, k_T^2) = g_{1L}(x) = \tilde{H}(x, \xi = 0, t = 0),$$
\[
\int dk_T^2 h_1(x, k_T^2) = h_1(x) = H_T(x, \xi = 0, t = 0),
\]
where \(f_1(x)\), \(g_1(x)\) and \(h_1(x)\) are the unpolarized, helicity and transversity quark distributions, respectively.

Moreover, within the light-cone CQM we find the following non-trivial relation
\[
\int dk_T^2 h_{1\perp}(x, k_T^2) = 2(1 - x)H_T(x, 0, 0).
\]

A similar relation holds also within the diquark spectator model\cite{12}, with a factor 3 instead of 2. The difference in the two model calculations supports the conclusions of Ref.\cite{12} that the relationship between \(h_{1\perp}\) and \(H_T\) cannot be established in a model-independent way, even when we restrict ourselves to the simplest situation with only valence quark contribution.

Furthermore, in the present light-cone quark model one can write down relations also among TMDs. Although in QCD the various TMDs are all independent of each other and describe different aspects of the nucleon structure, it is quite natural to encounter such relations in simple models limited to the valence-quark contribution.

For a more detailed discussion on this point, we refer to \cite{32,33}.

Finally, in Fig. 3 is shown the interplay between the different partial-wave contributions to the transverse moments \(g^{(1)}_{1T}\), \(h^{(1)}_{1L}\) and \(h^{(1)}_{1T}\). They are defined as the integrals in \(k_T^2\) of the TMDs multiplied by \(k_T^2/2m^2\). While the functions \(g^{(1)}_{1T}\) and

![Graph of Fig. 3 showing transverse moments of TMDs as function of x for up (upper panels) and down (lower panels) quark. In all panels the solid curves show the total results, sum of the partial wave contributions. In the case of \(g^{(1)}_{1T}\) and \(h^{(1)}_{1L}\) the dashed and dotted curves give the results from the S-P and P-D interference terms, respectively. In the case of \(h^{(1)}_{1T}\), the dashed curve is the result from P-wave interference, and the dotted curve is due to the interference of S and D waves.](image-url)
are dominated by the contribution due to P-wave interference, in the case of the contribution from the D wave is amplified through the interference with the S wave. The total results for up and down quarks obey the SU(6) isospin relation, i.e. the functions for up quarks are four times larger than for down quark and with opposite sign. This does not apply to the partial-wave contributions, as it is evident in particular for the terms containing D-wave contributions.

4. Results for azimuthal SSAs

In Ref.[34] the present results for the T-even TMDs were applied to estimate azimuthal asymmetries in SIDIS, discussing the range of applicability of the model, especially with regard to the scale dependence of the observables and the transverse-momentum dependence of the distributions. Here we review the results for the Collins asymmetry $A_{UT}^{\sin(\phi_h+\phi_S)}$ and for $A_{UT}^{\sin(3\phi_h-\phi_S)}$, due to the Collins fragmentation function and to the chirally-odd TMDs $h_1$, and $h_{1T}^\perp$, respectively. In both cases, we use the results extracted in Ref.[35] for the Collins function. In the denominator of the asymmetries we take $f_1$ from Ref.[36] and the unpolarized fragmentation function from Ref.[37] both valid at the scale $Q^2 = 2.5$ GeV$^2$.

In Fig. 4 the results for the Collins asymmetry in DIS production of charged pions off proton and deuterium targets are shown as function of $x$. The model results for $h_1$ evolved from the low hadronic scale of the model to $Q^2 = 2.5$ GeV$^2$ ideally describe the HERMES data[38] for a proton target (panels (a) and (b) of Fig. 4). This is in line with the favourable comparison between our model predictions[24] and the phenomenological extraction of the transversity and the tensor charges in Ref.[39].

Our results are compatible also with the COMPASS data[40] for a deuterium target (panels (c) and (d) of Fig. 4) which extend down to much lower values of $x$.

In the case of the asymmetry $A_{UT}^{\sin(3\phi_h-\phi_S)}$ we face the question how to evolve $h_{1T}^\perp(1)$ from the low scale of the model to the relevant experimental scale. Since exact evolution equations are not available in this case, we “simulate” the evolution of

![Fig. 4](image_url)

Fig. 4. The single-spin asymmetry $A_{UT}^{\sin(\phi_h+\phi_S)} \equiv -A_{UT}^{\sin \phi_C}$ in DIS production of charged pions off proton and deuterium targets, as function of $x$. The theoretical curves are obtained on the basis of the light-cone CQM predictions for $h_1(x, Q^2)$ from Ref.[24]. The (preliminary) proton target data are from HERMES[38] the deuterium target data are from COMPASS[40].
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Fig. 5. The single-spin asymmetry $A^{\sin(3\phi_h-\phi_S)}_{LT}$ in DIS production of charged pions off proton and deuterium targets, as function of $x$. The theoretical curves are obtained by evolving the light-cone CQM predictions for $h_{1T}^{(1)}$ of Ref. [22] to $Q^2 = 2.5$ GeV$^2$, using the $h_1$ evolution pattern. The preliminary COMPASS data are from Ref. [42].

$h_{1T}^{(1)}$ by evolving it according to the transversity-evolution pattern. Although this is not the correct evolution pattern, it may give us a rough insight on the possible size of effects due to evolution (for a more detailed discussion we refer to [34]). The evolution effects give smaller asymmetries in absolute value and shift the peak at lower $x$ values in comparison with the results obtained without evolution. The results shown in Fig. 5 are also much smaller than the bounds allowed by positivity, $|h_{1T}^{(1)}| \leq \frac{1}{2}(f_1(x) - g_1(x))$, and constructed using parametrizations of the unpolarized and helicity distributions at $Q^2 = 2.5$ GeV$^2$. Measurements in range $0.1 \lesssim x \lesssim 0.6$ are planned with the CLAS 12 GeV upgrade[41] and will be able to discriminate between these scenarios. There exist also preliminary deuterium target data[42] which are compatible, within error bars, with the model predictions both at the hadronic and the evolved scale.

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