Structure Functions and the Issue of Nucleon Shape

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Abstract. Azimuthal single-spin asymmetries in semi-inclusive deep-inelastic scattering from a transversely polarized target have been measured by the HERMES and COMPASS experiments. Such azimuthal asymmetries originate from the quark transversity distribution in conjunction with the Collins fragmentation function and the Sivers quark distribution function which involves correlations between the transverse polarization of the target nucleon and the transverse momentum of quarks. The Sivers asymmetry for positive pions and kaons, measured by HERMES with a proton target, is significantly different from zero. Consequently one has to conclude from this result that orbital angular momenta of quarks inside a transversely polarised nucleon are non-zero, leading to a non-spherical shape of the nucleon.

PACS: 13.60.-r, 13.88.+e, 14.20.Dh, 14.65.-q

INTRODUCTION

When the conference organizers confronted me with the title of my talk I needed some time until I realized that they wanted me to discuss the question: is there evidence from deep-inelastic scattering for non-zero orbital angular momenta of quarks in the nucleon and hence for a non-spherical nucleon shape?

Indeed, since recently there is such information available based on single-spin azimuthal asymmetries for hadrons measured by the HERMES experiment in semi-inclusive deep-inelastic scattering from a transversely polarized hydrogen target. One source for such an azimuthal asymmetry is the so-called "Sivers distribution function" $f_{1T}^\perp$, which is one of the many possible transverse momentum dependent distribution functions. [1]. This function has been invented more than 15 years ago by Sivers [2] to explain the large single-spin asymmetry A_N in proton-proton scattering, observed by the experiment E704 at FNAL [3] for neutral pions at a centre-of-mass energy of $\sqrt{s} = 20$ GeV. It is related to intrinsic transverse momenta and hence orbital angular momenta of quarks in the nucleon. _

INGREDIENTS

Several ingredients are required to qualitatively explain in a semi-classical picture the relation between orbital angular momenta of quarks and transverse single-spin asymmetries, namely quark distributions in impact parameter space and chromodynamic lensing. In my explanation I follow closely the argumentation by M. Burkardt [4]. As discussed in detail in the contribution by P. Kroll [5] generalized parton distributions (GPDs) [6] can provide us with a 3-dimensional picture (2 space dimensions and one dimension of longitudinal momentum) of the nucleon. They contain the information how partons carrying the fraction x of the nucleon's light cone momentum, are distributed in the transverse plane. The impact parameter $\mathbf{b}_\perp$ is defined as the distance from the center of longitudinal momentum. It can be shown that the impact parameter dependent parton distribution $q(x, \mathbf{b}_\perp)$ is the Fourier transform of the GPD $H(x, 0, -\Delta_\perp^2)$, where $\Delta_\perp$ is the transverse momentum transfer from the incoming to the outgoing nucleon. In this picture quarks with large light-cone momentum fraction x are concentrated near the center of longitudinal momentum. The width of $q(x, \mathbf{b}_\perp)$ increases with decreasing x as does the magnitude of the distribution since the quark number density $q(x)$ is falling with x . For an unpolarized nucleon or a longitudinally polarized nucleon the distribution $q(x, \mathbf{b}_\perp)$ is axially symmetric around the center of longitudinal momentum. Consider then a deep-inelastic process where the virtual photon hits a quark at a certain impact parameter $\mathbf{b}_\perp$. Upon leaving the nucleon the struck quark with colour c will be attracted by the anticolour $\bar{c}$ of the remnant. Due to this final state interaction the outgoing quark will receive a transverse momentum that is directed towards the center of the nucleon. This effect has been named 'chromodynamic

CP904, *Shapes of Hadrons*

edited by C. N. Papanicolas and A. M. Bernstein

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lensing'. For an unpolarized nucleon this lensing will not be visible in the final state due to the axially symmetric quark distributions and the stochastic distribution of interactions around the center of longitudinal momentum.

The situation changes, however, when the nucleon is polarized transversely to the direction of longitudinal momentum and if the quarks have an orbital angular momentum directed parallel or antiparallel to the polarisation axis. Let's look at the case, when both the polarisation axis and the direction of the orbital angular momentum vector are pointing upwards. If then the virtual photon hits a quark on the left hand side of the center of longitudinal nucleon momentum, the apparent x value x_{app} deduced from the lepton kinematics is given by the sum of the longitudinal momentum fraction x_{long} and the extra momentum due to the orbital movement x_{orb} : $x_{app} = x_{long} + x_{orb}$. Correspondingly, if the photon hits a quark on the right hand side of the center of longitudinal momentum, we have $x_{app} = x_{long} - x_{orb}$. At a fixed measured value of x_{app} the virtual photon probes on the left hand side quarks with lower longitudinal momentum fraction x_{long} than on the right hand side. Consequently the quark number density on the left hand side is larger than on the right hand side, since quark number densities fall with x . This leads to an impact parameter dependent quark distribution which is no longer symmetric around the center of momentum but shifted to the left. (In the framework of GPDs the difference between the impact parameter dependent quark distribution for an unpolarized nucleon and for a transversely polarized nucleon is related to the Fourier transform of the GPD $E(x, 0, -\Delta_T^2)$). The final state interaction translates this axial asymmetry in impact parameter space into an axial asymmetry in transverse momentum and hence into an azimuthal single spin asymmetry of the produced hadrons around the virtual photon direction.

TRANSVERSITY AND COLLINS EFFECT

The observation of an azimuthal single-spin asymmetry around the virtual photon direction is, however, not yet a prove of the existence of the Sivers effect and hence orbital angular momenta of quarks. There is another source of such an azimuthal asymmetry: the quark transversity distribution.

A complete description of the partonic structure of the nucleon in leading twist requires in addition to the unpolarized quark distributions $q(x)$ and the quark helicity distributions $\Delta q(x)$ a third quark distribution, named transversity $\delta q(x)$ [7], which survives integration over intrinsic transverse momenta. (For clarity we suppress here the dependence of these distributions on Q^2 , the negative square of the momentum transfer from the incident electron to the virtual photon). The corresponding structure function is denoted as $h_1(x)$. Physically, one may think of transversity as the distribution of quarks with spin parallel to the nucleon spin minus the distribution of quarks polarized anti-parallel to the nucleon spin for a transversely polarized nucleon, in analogy to the helicity distribution $\Delta q(x)$ for a longitudinally polarized nucleon. While $\delta q(x)$ and $\Delta q(x)$ should be identical in the non-relativistic quark model, they are different for quarks moving relativistically since in this case rotations and boosts do not commute.

Very little experimental information about transversity exists up to know. It is a chiral-odd quantity and cannot be probed in inclusive DIS since hard interactions conserve chirality. Its measurement requires processes involving some additional chiral-odd structure like, e.g., another transversity distribution in transversely polarized Drell-Yan production of lepton pairs, or a chiral-odd fragmentation function in semi-inclusive DIS. One of the possibilities to study transversity [7, 8] is via the azimuthal angular asymmetry in the distribution of hadrons produced in semi-inclusive DIS. Such an asymmetry can arise if the transverse polarization of the struck quark influences the transverse momentum of the produced hadron and thereby its distribution in the azimuthal angle ϕ about the virtual photon direction relative to the lepton scattering plane. The corresponding chiral-odd fragmentation function $H_1^\perp$, which is also odd under naive time reversal, is known as the "Collins fragmentation function" [9, 10]. It arises from the interference of two amplitudes with different imaginary parts, generating a nontrivial phase in the DIS amplitude [11, 1, 12].

AZIMUTHAL SINGLE-SPIN ASYMMETRIES, RESULTS FROM HERMES AND COMPASS

Measurements with a transversely polarized target allow to distinguish between the Collins mechanism and the Sivers mechanism [13, 14, 15]. The Collins mechanism will cause a $\sin(\phi + \phi_S)$ moment proportional to $\delta q(x) \cdot H_1^\perp(z)$, while the Sivers mechanism will cause a $\sin(\phi - \phi_S)$ moment proportional to $f_{1T}^\perp(x) \cdot D(z)$. Here ϕ_S is the angle between the electron scattering plane and the target spin axis, as shown in Fig. 1, and $D(z)$ is the familiar unpolarized fragmentation function, where $z = E_h/\nu$ is the ratio of the energies of the observed hadron and the virtual photon.

FIGURE 1. Definition of angles ϕ and ϕ_S .

In the years 2002-05 HERMES has taken data with a transversely polarized proton target and COMPASS has taken some fraction of the data with a transversely polarised LiD (deuteron) target. HERMES has evaluated the corresponding azimuthal asymmetry in two dimensions and extracted the Collins and Sivers virtual-photon asymmetries by a simultaneous fit to $\sin(\phi + \phi_S)$ and $\sin(\phi - \phi_S)$.

First results for charged pion asymmetries based on the data taken in 2002, which constitute about 10% of the available statistics, have already been published [16, 17]. Preliminary results for the "Collins moments" for charged pions and kaons, based on the data taken in the years 2002-04 [18], which correspond to about 30% of the total statistics, are shown in Fig. 2 as a function of x and z and the transverse momentum of the observed hadron $p_{h\perp}$. The measured asymmetries are small but different from zero providing evidence for the existence of both the transversity distribution and the Collins fragmentation function. The π^+ asymmetry is positive and seems to be slightly rising with x and z . The π^- asymmetry is negative with higher magnitude than the amplitude for π^+ . Because of the up-quark dominance in DIS from the proton one would expect the amplitudes of the positive pions and kaons to be similar. The amplitudes for the K^+ are, however, systematically lower than those for π^+ . In contrast to the positive pions and kaons the amplitudes of the negative ones are not expected to be similar, since the K^- contains only sea-quark flavors of the proton. The kaon asymmetries have substantially larger error bars than those of the pions and the full statistics is required to judge, how much they are different from zero.

The large amplitude for negative pions is quite unexpected. Assuming a similar behaviour for the transversity distributions as for the helicity distributions, $|\delta(u(x))| > |\delta(d(x))|$, and for the Collins function a similar behaviour as for the unpolarised fragmentation function, i.e. a suppression of the disfavoured fragmentation function, $H_{1,disfav}^\perp$ for the fragmentation ($u \rightarrow \pi^-$), compared to the favoured one, $H_{1,fav}^\perp$ for ($d \rightarrow \pi^-$), one would, due to up-quark dominance in the proton, expect a much larger magnitude of the asymmetry for π^+ than for π^- . One possible explanation for the different behavior observed experimentally could be a substantial magnitude with opposite sign for the disfavoured Collins function $H_{1,disfav}^\perp \approx -H_{1,fav}^\perp$ [17, 18].

In Fig. 3 the preliminary HERMES results from the 2002-04 data sample for the "Sivers moments" are shown. These are the key results for the topic of this paper. The π^+ and K^+ asymmetries are significantly positive, providing the first evidence for a T-odd parton distribution function appearing in leptonproduction. The π^- asymmetry is consistent with zero. Since the π^+ asymmetry is dominated by up-quarks, its positive value with the definition of azimuthal angles used by HERMES implies a negative value for the Sivers function of this flavour. The positive kaon amplitudes are about twice as large as the pion amplitudes, which might point to a large Sivers function for sea-quarks. Like the Collins amplitudes also the Sivers amplitudes are consistent with zero for negative kaons. The improved statistical accuracy of the total data sample should allow HERMES to extract the Sivers functions for up- and down-quarks in a procedure similar to the one used for the extraction of the quark helicity distributions. This work is underway and results can be expected in the near future.

COMPASS extracted the Collins and Sivers asymmetries for both positive and negative hadrons from the combined 2002-04 deuteron data set in an 1-dimensional analysis. Statistical errors have been reduced by at least a factor of two compared to the previously published results [19]. In Fig. 4 preliminary results for the Collins asymmetries and in Fig. 5 for the Sivers asymmetries for positive and negative hadrons are shown as a function of x_{Bj} , z and p_t together with theoretical predictions [20, 21]. Note that COMPASS and HERMES use a different convention for the definition of the angle ϕ which differs by π and therefore the sign of one of the data sets should be inverted for a direct comparison.

FIGURE 2. HERMES results for the "Collins moments" for charged pions and kaons obtained with a transversely polarized hydrogen target.

FIGURE 3. HERMES results for the "Sivers moments" for charged pions and kaons obtained with a transversely polarized hydrogen target.

FIGURE 4. COMPASS results for the "Collins moments" of positive and negative hadrons obtained with a transversely polarized LiD (deuteron) target.

FIGURE 5. COMPASS results for the "Sivers moments" of positive and negative hadrons obtained with a transversely polarized LiD (deuteron) target.

The COMPASS data are compatible with zero within errors. Very likely this can be traced back to cancellations of up- and down-quark distributions arising due to the use of a deuteron target. Together with proton data the results can be used to constrain the relative magnitude of up-quark and down-quark transversity distributions and Sivers functions at low values of x . Therefore COMPASS has scheduled a run with a transversely polarized hydrogen target.

From the observed non-zero Sivers asymmetries of positive pions and kaons one has to conclude that orbital angular momenta of quarks inside a transversely polarized nucleon are non-zero. This is equivalent to a distorted quark distribution in impact parameter space and consequently to a non-spherical shape of the nucleon. At present it is, however, not yet possible to quantitatively relate the magnitude of this asymmetry to the fraction of nucleon spin which can be attributed to orbital angular momenta of quarks.

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