International Journal of Modern Physics: Conference Series

Recent key measurements for accessing the transverse spin and momentum structure of the nucleon

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Received Day Month Year
Revised Day Month Year
Published Day Month Year

A selection of recent key results obtained in semi-inclusive deeply inelastic scattering (SIDIS) experiments is presented. The observations strongly support the description of the nucleon structure in terms of transverse momentum dependent parton distribution functions, which represent the various correlations between the quarks spins, the quarks transverse momenta and the nucleon spin which give rise to specific spin-dependent azimuthal asymmetries.

Keywords: nucleon structure; transverse spin; transverse momentum

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

1. Introduction

The study of the structure of the nucleon is one of the main research fields of hadron physics. During the last decade considerable theoretical and experimental progress has been made in the description of the transverse spin and momentum structure leading to a rigorous theoretical framework in which new objects, the transverse momentum dependent parton distribution functions (TMD PDFs), have been introduced. They give the joint distribution of partons as function of their longitudinal momentum fraction x and of their transverse momentum $\vec{k}_T$. Eight independent TMD PDFs are required at leading order for each quark flavor to describe the possible correlations between the transverse momentum and spin of the quarks and the spin of the nucleon. After integration over the transverse momentum three of them give the well-known "collinear" PDFs, namely the number, the helicity and the transversity distributions. Transversity is the analogous of helicity in the case of transversely polarized nucleon and is the least known of the three. It is related to the tensor charge, a fundamental property of the nucleon, and only recently has been accessed experimentally. The other five TMD PDFs are sensitive to the direction of the quark transverse momentum, they vanish when integrating over $\vec{k}_T$, and their measurement provides important information on the dynamics of the partons in the transverse plane in momentum space. In particular the T-odd Sivers and the Boer-Mulders functions are related to the correlations between the transverse momentum and the nucleon transverse spin of quarks, and between the transverse momentum and the transverse spin of quarks in unpolarised nucleons respectively.

Experimentally the TMD PDFs are difficult to be measured and are studied in several different processes, like Drell-Yan, semi-inclusive deeply inelastic scattering (SIDIS), and hadron and jet production in pp scattering. Interesting results are coming from this last process [1] but today SIDIS is their most powerful probe [2]. When using unpolarised, longitudinally and transversely polarized targets, and unpolarised and polarized beams, SIDIS allows to access all the different TMD PDFs by means of high statistics measurements of the azimuthal asymmetries. They are the amplitudes of different azimuthal modulations and can be written as convolutions over transverse momenta of TMD PDFs and fragmentation functions (FFs). Also, using different (p, d, or n) targets and identifying the final state hadrons, one can separate the contributions of the quarks of different flavor. As a matter of fact, the first evidence for non-vanishing transversity and TMD PDFs came from this process, ten years ago. Recent key measurements in SIDIS on unpolarised and transversely polarised target will be shortly presented in the following. For lack of space, the interesting results on TMD observable obtained with longitudinally polarised targets are not included here.

2. Transversity distribution

The transversity PDF h_1 is difficult to access experimentally because of its chiral-odd nature. It can be studied in SIDIS on transversely polarized targets by measuring the Collins asymmetry $A_{UT}^{\sin(\phi_h+\phi_S)}$, where transversity appears in the convolution with the chiral-odd Collins FF. Independent information on this new transverse spin dependent FF comes from the measurements of azimuthal asymmetries in two hadron production in e^+e^- annihilations which depend on the product of two Collins FFs.

A decisive step forward occurred exactly ten years ago, when the results of their first measurements of the Collins asymmetries were announced by the HERMES and the COMPASS collaborations. Using a transversely polarised proton target and a 27 GeV electron beam HERMES observed non zero asymmetries with opposite sign for positive and negative pions. Using a transversely polarised deuteron target and a 160 GeV muon beam COMPASS found asymmetries compatible with zero. Almost at the same time, the azimuthal asymmetries in e^+e^- annihilation were measured to be different from zero by the Belle collaborations. These results were interpreted as the first evidence that both the Collins FF and the transversity PDF are different

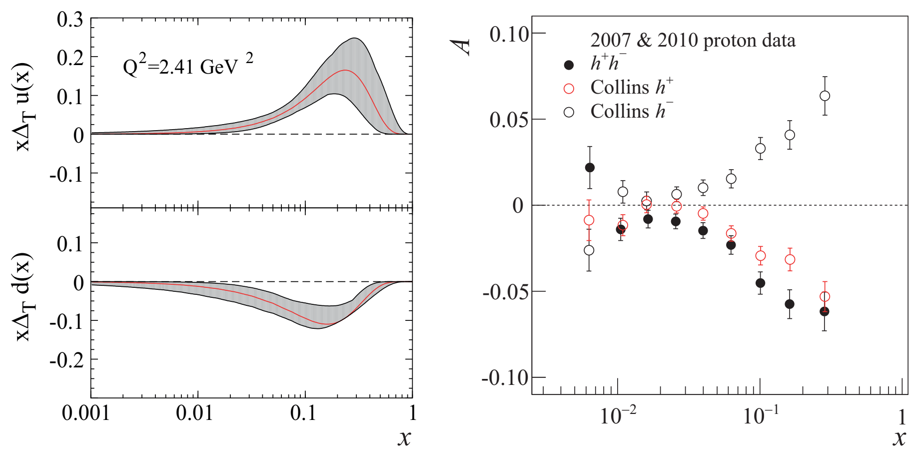


Fig. 1. Left: the transversity distribution functions $xh_1(x)$ for u (top) and d (bottom) quarks from the Collins asymmetries [11]. Right: dihadron (closed points) asymmetry and Collins asymmetries (open points) from COMPASS proton data [5].

from zero. All the data could be well described with favored and unflavored Collins FF as well as a u- and d-quark transversity of opposite sign and simultaneous fits of the data allowed for the first time the extraction of these functions.

Following those first measurements, many more have been performed to further explore the Collins asymmetries in SIDIS by HERMES [3], COMPASS [4,5,6] and JLab Hall A experiments [7,8], and by Belle [9] and BaBar [10] in e^+e^- annihilation. The statistical significance of the first measurements could be considerably improved in particular for what concerns the data collected with a proton target. The Collins asymmetries on proton for charged hadrons (pions) measured by COMPASS turned out to be in very good agreement with the HERMES results, in spite of the different Q^2 values (about 23 GeV^2 at the highest x in COMPASS, i.e. about 3 times the value in HERMES at the same x). This fact made very unlikely the possibility that the observed asymmetries were due to higher twist effects and confirmed the interpretation of the Collins asymmetry in terms of a convolution between the transversity PDF and the Collins FF. All the new SIDIS and e^+e^- data have already been used for more precise extractions of the transversity distribution, with more refined treatments of the Q^2 evolution, and of the tensor charge [11,12]. The u- and d-quark transversity PDFs from Ref. 11 are shown in the left panel of Fig. 1

The data analysis is still ongoing both in HERMES and in COMPASS. In particular new preliminary results from 3- and 4-dimensional analysis have been shown at this Symposium [13,14]. Presently no strong unexpected effects are seen, but these data will be very useful to further study the properties of the transversity and Collins functions.

Hadron pair production in SIDIS is, in principle, an independent channel to access transversity. In this case the transverse spin asymmetry (the dihadron asymmetry) is given by the product of the transversity PDF and the dihadron FF, and is not sensitive to the intrinsic transverse momentum. Again, the corresponding azimuthal asymmetry in e^+e^- annihilation allows to obtain the product of two dihadron FFs and the transversity PDF.

The dihadron asymmetry in SIDIS was measured for the first time with a proton target by the HERMES experiment, and turned out to be different from zero and with the same sign as the Collins asymmetry for positive pions. The dihadron asymmetry has also been measured in SIDIS on d and p by COMPASS [15,16,17] and in e^+e^- by Belle [18]. From all these data the parametrisations of the transversity distributions of u and d valence quark have been recently obtained for the first time [19], with results in substantial agreement with those obtained from the Collins asymmetries in Ref. 11. A point by point extraction of the transversity PDFs has also been performed [20] using both the Collins and the dihadron asymmetries measured by COMPASS on deuteron and proton at the same energy and with the same x binning and the corresponding e^+e^- data to get the analysing power.

Further studies on the dihadron asymmetries are ongoing. Preliminary results from a new analysis of the HERMES data which is based on the expansion of the fragmentation functions in partial waves on the basis of spherical harmonics have been recently produced [21]. In COMPASS, the high statistics measurement of the dihadron asymmetry on p allowed to investigate the striking similarities between the Collins asymmetries for positive and for negative hadrons and the dihadron asymmetry, shown in the right panel of Fig. 1. New specific measurements of these asymmetries which make the similarities even more impressive have been performed and described in terms of simple expressions, giving further evidence for a common origin of the Collins and the dihadron FFs [22].

3. Sivers and other transverse spin asymmetries

The Sivers function is today the best known of the TMD PDFs. In SIDIS it can be accessed trough the Sivers asymmetry $A_{UT}^{\sin(\phi_h-\phi_S)}$ where it appears in the convolution with the unpolarised and well known FFs. The first measurements of this asymmetry were performed 10 years ago when HERMES, with the p target, measured clearly positive values for positive pions, and compatible with zero values for negative pions, while COMPASS, with the deuteron target measured all the asymmetries to be compatible with zero. The results allowed the first extractions of the u- and d-quark Sivers functions, which turned out to be both different from zero and of opposite sign. As in the transversity case much more has been learned in the following years thanks to more precise and new measurements by HERMES [23], COMPASS [4,24,6] and JLab Hall A [7,8] experiments. An important milestones was the measurement on proton performed at COMPASS. In agreement with the HERMES results, the Sivers asymmetry was measured to be positive for positive hadrons. At variance with the Collins asymmetry, however, the values of the Sivers asymmetry turned out to be somewhat smaller in COMPASS, a fact which could be explained in

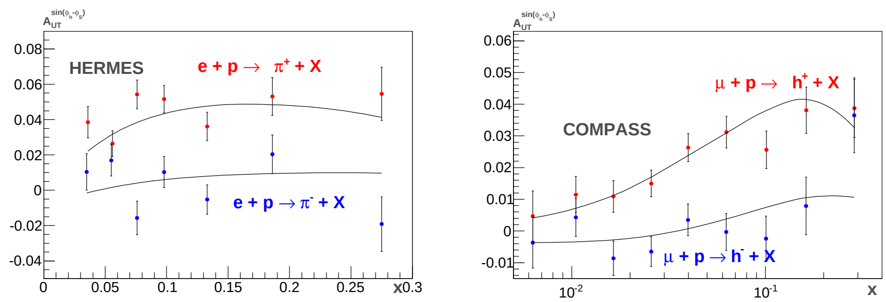


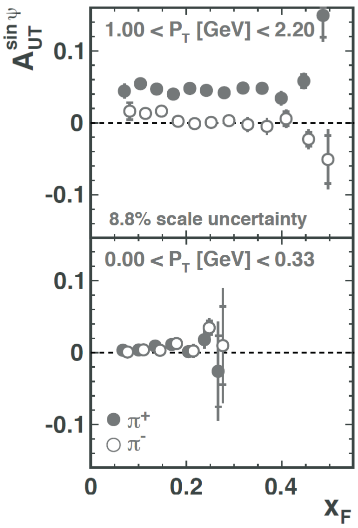
Fig. 2. Comparison of the fits of Ref. 25 with the experimental data for the Sivers asymmetries measured at HERMES [23] (left) and at COMPASS [24] (right).

terms of the still unknown Q^2 evolution of the TMD PDFs, and which stimulated one of the most interesting and debated lines of theoretical research in the field. Several calculations and fits can satisfactory reproduce the present SIDIS data set, as can be seen f.i. in Fig. 2 from Ref. 25, but the corresponding predictions for the Sivers function at higher Q^2 are quite different. If the Q^2 evolution of the Sivers function is strong, its size might be so reduced to spoil the statistical significance of the test of the change of sign between SIDIS and the Drell-Yan process. This test is generally regarded as very important for the present theoretical framework, and it is the aim of the Drell-Yan measurement planned in COMPASS in 2015. To check if this could be the case a dedicated multidimensional analysis of the COMPASS SIDIS proton data has been performed. The results [26] show that the Sivers asymmetry is clearly positive also at the Drell-Yan scale, namely for $Q^2 > 16$ GeV^2.

Further information on the Sivers asymmetry is expected from the full multi-dimensional analysis undertaken by the HERMES and COMPASS collaborations, for which interesting preliminary results are already available [13,14]. Unfortunately the statistics of the available data is limited and detailed studies of some specific effects (like the K^+ Sivers asymmetries, found to be unexpectedly larger than those for pions both by the HERMES and the COMPASS experiments) will not be possible. Quite interesting is also the novel COMPASS analysis aiming to access the gluon Sivers distribution through the spin asymmetry of high p_T^h hadron pair lepto-production on transversely polarised nucleons [27]. The results on the deuteron target suggest a non zero value, but the statistics is marginal. The analysis of the proton data is ongoing.

Finally, one has to quote the measurements of the left-right transverse-spin asymmetries in inclusive electroproduction of charged hadrons by the HERMES [28] and the JLab Hall A [29] collaborations, expected to be sensitive to the Sivers effect and a possible bridge from SIDIS to inclusive hadron production in *pp* transverse spin asymmetries. Large asymmetries have been measured (see Fig. 3) but presently the interpretation is not as easy as had been hoped originally.

All the other transverse spin asymmetries which are expected in SIDIS and



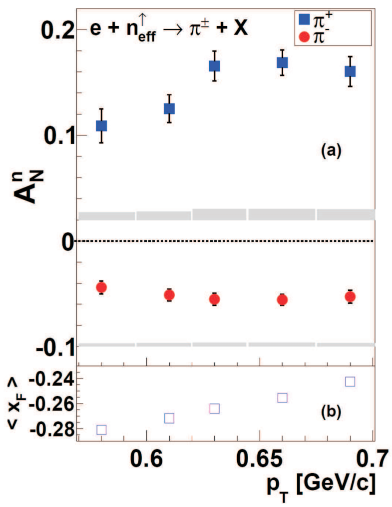


Fig. 3. Left: HERMES results [28] for the inclusive transverse-spin asymmetries for charged pions on p vs x_F in two slices in p_T^h. Right: JLab Hall A [29] results for the same asymmetry on n. The mean x_F values are given in the lower plot.

which give access to different TMD PDFs have also been recently measured. Here the picture is less clear than for the Collins and Sivers asymmetries. One of the difficulties is that in some cases the y-dependent kinematic factors which appear in the cross-section are such that the sensitivity to the TMD PDFs is very low. This is f.i. the case for the $A_{LT}^{\cos(\phi_h-\phi_S)}$ asymmetry which is due to the worm-gear distribution function. Other problems are given by the possible contributions of the longitudinal spin asymmetries and of higher twist effects which are different in the different experiments, as demonstrated f.i. by the $A_{UT}^{\sin\phi_S}$ asymmetry, a twist-3 object, measured to be almost a factor 5 larger in HERMES than in COMPASS [30].

4. Unpolarised SIDIS

To address TMD evolution and to get more insight on the role of transverse momentum, recently it turned out that a better understanding of unpolarised SIDIS is needed and a lot of theoretical and experimental work is going on in that field.

New results have been recently produced for the hadron multiplicities measured as function of p_T and for the azimuthal asymmetries $A_{UU}^{\cos\phi_h}$ and $A_{UU}^{\cos 2\phi_h}$ which are proportional to the amplitudes of the $\cos\phi_h$ and $\cos 2\phi_h$ modulations in unpolarised SIDIS [31,32,33].

The first set of measurements could give access both to the intrinsic transverse momentum $k_\perp$ and to the momentum $p_\perp$ acquired by the hadron in the quark fragmentation. Apart from normalization problems, these data alone are satisfactorily reproduced [34,35] by assuming the simple relation between the mean values of the squared momenta which is valid in case of Gaussian dependence of the TMD PDFs and FFs and which however is not supported by data.

The measurements of $A_{UU}^{\cos\phi_h}$ are aimed to extract $< k_\perp^2 >$ since a clean and simple dependence is expected thanks to the dominant Cahn effect. The interest for $A_{UU}^{\cos 2\phi_h}$ is due to the fact that here the dominant contribution should be the structure function containing the convolution on transverse momenta of the Collins FF (the same appearing in the Collins asymmetry) and of the still unknown Boer-Mulders TMD PDF. The phenomenological analysis of these measurements is made difficult by the strong kinematical dependence observed both in HERMES and in COMPASS results, and by the possible contributions of both the Cahn effect and the Boer-Mulders function to the two asymmetries. The most recent works go into the direction of analysing the two azimuthal asymmetries and the multiplicities together, in a simultaneous fit, in order to separate the different contributions, and new results are expected soon.

Today it is clear that new more precise data on unpolarised SIDIS are needed. Good opportunities will be provided in the near future by the measurements on a liquid hydrogen target foreseen in COMPASS and by the new measurements planned at JLab12.

5. Conclusions

In the last few years more precise and new measurements of TMD observables in SIDIS off unpolarised and polarised nucleons have been performed. They have been crucial in assessing the correlation between quark intrinsic momentum, quark spin and nucleon spin, and in probing the new effects predicted in the last 25 years and coded in the present picture of the nucleon which is based on the TMD PDFs.

Much has been understood from the existing experimental results, and more can come from their combined analyses, which already started. Also, specific new analysis of existing data, to be identified thanks to a more strict collaboration between experimentalists and theoreticians, could allow for further progress.

What has been done and will be done in the near future in SIDIS will hopefully provide the key to understand the intriguing transverse spin effects which since many decades have been observed in hadronic reactions. Undoubtedly it is an excellent starting point for the already approved or proposed experiments at the future facilities like JLab12 and EIC, where definitive answers are expected.

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