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Transverse Momentum Distributions: an experimental update

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Transverse-momentum-dependent parton distribution functions (TMDs) have been recognized as crucial ingredients for a complete understanding of the nucleon structure and, more generally, of the dynamics of confined partons in the nonperturbative regime of quantum-chromodynamics. Describing correlations between the quark transverse momentum and the quark or the nucleon spin (i.e. spin-orbit correlations), they allow for a 3-dimensional description of the nucleon (nucleon tomography) in momentum space, and could provide insights into the yet unmeasured quark orbital angular momentum. At leading twist eight TMDs enter the semi-inclusive DIS (SIDIS) cross section in conjunction with a fragmentation function. In the last years, many transverse-spin and transverse-momentum effects have been measured in SIDIS (essentially by the HERMES, COMPASS and JLab experiments), in pp collisions (e.g. experiments at RHIC), in unpolarized Drell-Yan processes (experiments at Fermilab and CERN), and in e^+e^- annihilation (BELLE and BABAR). An overview of the main experimental results concerning transverse phenomena in hard hadronic processes is presented, with particular emphasis on the SIDIS experiments.

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1. Accessing the nucleon structure

Most of our present understanding of the internal structure of nucleons derives from a variety of inclusive deep-inelastic-scattering (DIS) experiments performed over the past four decades in different kinematic regimes. Based on the large amount of precise data provided by these experiments in an overall kinematic domain that spans several orders of magnitudes in both the four-momentum transfer $Q^2 = -q^2$ and the *Bjorken variable* x, we have nowadays a good knowledge of the longitudinal-momentum and longitudinal-spin distributions of quarks in the nucleon, where "longitudinal" refers to the direction parallel to that of the exchanged virtual photon (the hard probe). These two distributions, described in the framework of the parton model by two collinear parton distribution functions (PDFs), $f_1(x)$ and $g_1(x)$, map the nucleon structure in a mono-dimensional space, as a function of the partonic longitudinal momentum.

For a long time transverse-spin effects in the nucleon were considered to be negligibly small. However, a complete description of the nucleon structure at leading-twist requires the knowledge of a third collinear PDF, the transversity distribution $h_1(x)$, describing the net quark transverse polarization in a transversely polarized nucleon. Being chiral-odd (i.e. requiring the spin-flip of the struck quark), it can only be measured in conjunction with another chiral-odd object, and therefore cannot be accessed in polarized inclusive DIS[1]. It took some time until it was realized that theory allows for unsuppressed transverse polarization effects in the nucleon. In particular, it was recognized that the transversity function can contribute substantially to transverse single-spin asymmetries (TSSAs) in semi-inclusive DIS (SIDIS) processes [1] as well as to double transverse-spin asymmetries in Drell-Yan (DY) production [2]. So far $h_1(x)$ has been experimentally probed in single-hadron and di-hadron electroproduction in SIDIS, where it can be accessed in TSSAs in conjunction with a chiral-odd fragmentation function, the Collins function and the di-hadron fragmentation function, respectively [3, 4, 5, 6, 7, 8, 9].

When the intrinsic transverse momentum p_T of the quarks is not integrated over, several new (transverse momentum dependent) parton distribution functions (TMDs) arise, each with a specific probabilistic interpretation in terms of parton densities. Describing correlations between the quark transverse momentum and the quark or the nucleon spin (i.e. *spin-orbit correlations*), they allow for a 3-dimensional description of the nucleon in momentum space, and in this sense they represent the natural extension of the standard (i.e. collinear) PDFs. Their knowledge will eventually allow us to build tomographic images of the inner structure of the nucleon in momentum space, complementary to the impact-parameter space tomography achievable from the study of generalized parton distribution functions (GPDs). Furthermore, they could provide insights into the yet unmeasured quark orbital angular momentum. Noteworthy, the interpretation of hard processes in terms of TMDs has been put on a solid basis by the proof of a non-collinear factorization theorem for SIDIS and DY [10].

At leading twist eight TMDs contribute to the SIDIS cross section in conjunction with a fragmentation function [11]. Three of them are the transverse-momentum-dependent versions of f_1, g_1 and h_1. The other five are the Sivers function $f_{1T}^{\perp}$, the Boer-Mulders function $h_1^{\perp}$, the *pretzelosity* function $h_{1T}^{\perp}$ and the so-called *worm-gear* functions $h_{1L}^{\perp}$ and $g_{1T}^{\perp}$.

[1]This is the reason why the transversity function remained unmeasured until very recently and is the least known among the three leading-twist collinear PDFs.

2. Transversity and Collins functions

The first evidence for a non-zero transversity function was reported by the HERMES Collaboration in 2005 [3]. HERMES measured significant *Collins amplitudes* in the production of π^+ and π^- in SIDIS, using an unpolarized 27.5 GeV electron beam and a transversely polarized hydrogen target. These amplitudes are sensitive to the convolution (integral over quark transverse momenta) between the transversity and the chiral-odd Collins fragmentation function $H_1^\perp$, describing the correlation between the quark transverse spin and the transverse momentum of the produced hadron:

$$A_{UT}^{\sin(\phi+\phi_S)} \propto \sum_q e_q^2\, h_1^q(x,p_T^2) \otimes H_1^{\perp,q}(z,k_T^2)\ . \tag{2.1}$$

Here ϕ and ϕ_S are, respectively, the azimuthal angle of the detected hadron and of the target transverse polarization with respect to the lepton scattering plane and about the virtual-photon direction, and z and k_T denote the fraction of the energy of the exchanged virtual photon carried by the produced hadron (pion) and the transverse momentum of the fragmenting quark with respect to the outgoing hadron direction, respectively. In particular, HERMES observed amplitudes of similar magnitude and opposite sign for π^+ and π^-. This unexpected result can be interpreted assuming that the scattering process involves predominantly the u-quarks (*u-quark dominance*) and that the unfavored Collins function is approximately the same size and opposite in sign with respect to the favored one: $H_{1,unfav}^{u\to\pi^-} \approx -H_{1,fav}^{u\to\pi^+}$. The latter assumption is consistent with the recent measurements of the Collins function at the BELLE [12] and BABAR [13] experiments. The final results recently published by the HERMES Collaboration [4], based on the full statistics available, confirm the main features of the early results for charged pions and include neutral pions and charged kaons. The amplitudes for K^+ are large and positive whereas those for π^0 and K^- are consistent with zero. Assuming that the scattering off u-quarks provides the dominant contribution to the production of both π^+ and K^+, one would naively expect similar amplitudes for these two mesons. The observed differences (the K^+ amplitudes are larger than the π^+ ones) can be ascribed, for instance, to the different Collins functions involved. On the other hand, the amplitudes for π^- and K^-, which also exhibit a very different behavior, are not expected to be similar not only because of the different fragmentation functions involved, but also because, in contrast to π^-, K^- have no valence quarks in common with the target proton. The COMPASS experiment, which uses a 160 GeV muon beam, has reported analogous results for both transversely polarized deuteron [6] and proton [7] targets. The deuteron results show amplitudes consistent with zero in the full kinematic range for both positive and negative pions whereas the proton ones show sizeable amplitudes of opposite sign for π^+ and π^- consistent, in the overlapping kinematic range, with the HERMES results. The kaons amplitudes are not fully consistent between the two experiments, though the statistical precision of both kaons data sets is relatively limited. Recently the Hall-A Collaboration at JLab has reported the first measurement of the Collins amplitudes for charged pions obtained using a neutron (^3He) target [9]. The results are consistent with zero for both π^+ and π^-. The first (model-dependent) joint extraction of the transversity and the Collins function was obtained through a global fit of the SIDIS data from HERMES and COMPASS (on deuterium target) and the BELLE data from e^+e^- annihilation [14]. The results show a positive (negative) transversity for the u (d) quark, similar to the helicity g_1, and favored and unfavored Collins functions of opposite sign.

An alternative and independent way to access the transversity function in SIDIS is through the di-hadron (e.g. a $\pi^+\pi^-$ pair) production mechanism. In this case the transversity appears in TSSAs in combination with the chiral-odd *di-hadron* fragmentation function $H_1^{\measuredangle,q}$:

$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta} \propto \sum_q e_q^2\, h_1^q(x,Q^2)\cdot H_1^{\measuredangle,q}(z,M_{hh}^2,Q^2)\;. \tag{2.2}$$

Here ϕ_R and M_{hh} indicate the azimuthal orientation of the relative transverse momentum and the invariant mass of the hadron pairs, respectively. The underlying mechanism differs from the Collins mechanism in that the transverse spin of the fragmenting quark is transferred to the relative orbital angular momentum of the hadron pair, i.e. it does not require transverse momentum of the hadron pair. Consequently, transversity and di-hadron functions appear in a simple product and the standard (collinear) factorization and QCD evolution can be applied. Both the HERMES and COMPASS experiments measured significant amplitudes (which are compatible in the overlapping region) as a function of x, z and M_{hh} [5, 8]. Very recently a first attempt to extract the transversity function through a global fit of the di-hadron TSSAs measured by HERMES and COMPASS and of the recent results from BELLE on the di-hadron fragmentation function [15] was carried out, obtaining results consistent with those extracted earlier from the Collins mechanism [16].

3. The Sivers function

Among the TMDs, particularly interesting is the Sivers function. It describes the correlation between the quark transverse momentum and the transverse spin of the nucleon. The existence of this TMD was proposed more than 20 years ago [17] in an effort to explain then-mysterious SSAs observed in pion production in the collision of unpolarized with transversely polarized nucleons [18]. The interest on the Sivers function suddenly increased after it was demonstrated [19] to be linked to the quark orbital angular momentum, the main still unmeasured contribution to the nucleon spin. Furthermore, it is naive-T-odd, i.e. it requires final-state interactions (FSIs) of the ejected quark with the color field of the nucleon remnant. These FSIs are formally introduced in the definition itself of the Sivers function in terms of a gauge link. In general gauge links are process-dependent and this leads to the remarkable fact that naive-T-odd TMDs are not universal. In particular, the difference of the gauge links between SIDIS and DY consists in a simple direction reversal and leads to a sign reversal for all naive-T-odd TMDs. The experimental verification of this direct QCD prediction is eagerly awaited. The first evidence for a non-zero Sivers function was reported by the HERMES Collaboration in 2005 [3]. HERMES measured significant *Sivers amplitudes* in the production of π^+ and π^- in SIDIS, using an unpolarized 27.5 GeV electron beam and a transversely polarized hydrogen target. These amplitudes are sensitive to the convolution between the Sivers function and the unpolarized fragmentation function D_1:

$$A_{UT}^{\sin(\phi-\phi_S)} \propto \sum_q e_q^2\, f_{1T}^{\perp,q}(x,p_T^2)\otimes D_1^q(z,k_T^2)\;. \tag{3.1}$$

In particular, HERMES observed large positive amplitudes for π^+ and amplitudes consistent with zero for π^-. The vanishing amplitudes for π^- require cancellation effects, e.g., from a d-quark Sivers function opposite in sign to the u-quark Sivers function. This conjecture is consistent with the vanishing amplitudes measured for both positive and negative pions by the COMPASS experiment using a transversely polarized deuterium target [6]. The final HERMES results [20], based on the full statistics available, confirm the main features of the early results for charged pions and include neutral pions and charged kaons. The amplitudes for K^+ are large and positive whereas those for π^0 and K^- are slightly positive. The K^+ amplitudes are larger than the π^+ ones. This observation can be ascribed, for instance, to a significant role of the sea quarks or to possible higher-twist contributions in kaon production. The COMPASS experiment has more recently reported analogous results obtained with the use of a transversely polarized proton target [7]. Differently from the case of the Collins amplitudes, the HERMES and COMPASS Sivers amplitudes for π^+ (and K^+) are not compatible, the COMPASS amplitudes being significantly smaller. Recent studies show that this difference substantially reduces when the COMPASS data are restricted to the low y region ($0.05 < y < 0.10$), where y is the fraction of the beam energy carried by the exchanged virtual photon. Furthermore, it has been recently shown that this apparent discrepancy can be well reproduced by applying the transverse-momentum-dependent QCD evolution between the different scales of the two experiments [21]. Recently the Hall-A Collaboration at JLab has reported the first measurements of Sivers amplitudes for charged pions obtained using a neutron (^3He) target [9]. The amplitudes are slightly negative for π^+ and consistent with zero for π^-. Finally, the Sivers effect is one of the main candidates (together with the Collins effect and twist-three effects) to explain the large left-right (A_N) asymmetries observed since decades in inclusive pion production in pp scattering experiments. These data show large and positive (negative) amplitudes for π^+ (π^-), almost linearly increasing with x_F (*Faynman x*), and no strong energy dependence: the basic pattern of the asymmetries doesn't change much from $\sqrt{s} \approx 5-10$ GeV (experiments at ANL and BNL) to $\sqrt{s} \approx 200$ GeV (experiments at RHIC). Recently, the STAR and PHENIX experiments reported large asymmetries in inclusive π^0 production as a function of the hadronic transverse momentum in bins of x_F. The data are in good agreement with predictions for the Sivers effect [22, 23]. There have been several attempts to extract the Sivers function from the measured SSAs, all consistently resulting in a positive (negative) Sivers function for the d (u) quarks (see e.g. [24]). Two very recent attempts, based on innovative approaches, are particularly interesting: one makes use for the first time of the TMD evolution [25] and the other uses the spectator model to link the Sivers function to the GPD E [26]. The latter approach provides in addition a parametrization for the unknown GPD E and estimates for the total angular momentum of quarks and anti-quarks.

4. The Boer-Mulders function

Another very intriguing TMD is the naive-T-odd Boer-Mulders function [27], describing the correlation between transverse polarization and transverse momentum of quarks in an unpolarized nucleon. The Boer-Mulders effects offers an explanation for the strong violation of the Lam-Tung relation [28] observed a long time ago in DY data from CERN and Fermilab experiments. In SIDIS the Boer-Mulders function in combination with the Collins function generates at leading twist a $\cos 2\phi$ azimuthal modulation of the unpolarized cross section:

$$d\sigma_{UU}(\phi) \propto \cos 2\phi \cdot \sum_q e_q^2 \, h_1^{\perp,q}(x, p_T^2) \otimes H_1^{\perp,q}(z, k_T^2) + \dots \, . \tag{4.1}$$

At twist-three it also contributes to a cosϕ modulation together with the *Cahn effect*, a pure kinematic effect due to the transverse motion of partons in the nucleon. Only a few measurements of cos2ϕ and cosϕ amplitudes in SIDIS have been published over the past 30 years. Recently the CLAS Collaboration reported non-zero cosine modulations for positive pions [29]. The HERMES Collaboration has very recently published results based on the use of unpolarized hydrogen and deuterium targets showing evidences for large cos2ϕ and cosϕ amplitudes for semi-inclusively produced charged pions and kaons [31]. In particular, concerning the cos2ϕ modulation, the data show amplitudes of opposite sing for π^+ and π^- and of the same sign for K^+ and K^-, the latter being significantly larger in magnitude than the former. The results obtained with the hydrogen and the deuterium targets are very similar, suggesting a Boer-Mulders function of the same sign for u and d quarks (the opposite sign of the pion amplitudes can be ascribed from the opposite sign of the favored and unfavored Collins functions). The preliminary COMPASS results [30] also show large cos2ϕ amplitudes, though with the same sign for positive and negative unidentified hadrons (mainly pions). The discrepancy between data and theoretical predictions (see e.g. [32]) is largely due to the uncertainty on the Cahn effect and on higher-twist contributions.

5. The other leading-twist TMDs

One of the remaining leading-twist TMDs is the so-called *pretzelosity*. It describes the correlation between the quark transverse momentum and transverse polarization in a transversely polarized nucleon and is linked to the non-spherical shape of the nucleon. In SIDIS it contributes, in conjunction with the Collins function, to $\sin(3\phi - \phi_S)_{UT}$ modulations. Both HERMES and COMPASS reported preliminary results consistent with zero. The other two TMDs are the intriguing *worm-gear* functions $g_{1T}^{\perp}$ and $h_{1L}^{\perp}$. The former (latter) describes the probability of finding a longitudinally (transversely) polarized quark inside a transversely (longitudinally) polarized nucleon. Interestingly, they are found to be opposite of each other in various quark models. Despite their similarities, these two TMDs have a different behavior under chiral transformations: $h_{1L}^{\perp}$ is chiral-odd and can be probed in SIDIS in combination with the Collins function, while $g_{1T}^{\perp}$ is chiral-even and can thus be accessed in SIDIS combined with the unpolarized fragmentation function D_1. Another important difference, especially from the experimental point of view, is that $h_{1L}^{\perp}$ can be accessed in longitudinal target A_{UL} single-spin asymmetries, whereas in the case of $g_{1T}^{\perp}$ the longitudinal polarization of the active quark leads to A_{LT} double-spin asymmetries, requiring both a longitudinally polarized beam and a transversely polarized target [11]:

$$A_{UL}^{\sin 2\phi} \propto \sum_q e_q^2\, h_{1L}^{\perp,q}(x,p_T^2) \otimes H_1^{\perp,q}(z,k_T^2)\,, \qquad A_{LT}^{\cos(\phi-\phi_S)} \propto \sum_q e_q^2\, g_{1T}^{\perp,q}(x,p_T^2) \otimes D_1^q(z,k_T^2)\,. \quad (5.1)$$

Concerning the worm-gear $h_{1L}^{\perp}$, both the HERMES and COMPASS experiments observed vanishing amplitudes. In contrast, the CLAS Collaboration reported non-zero (negative) amplitudes for charged pions [33], though with limited statistical precision. Preliminary results for the $\cos(\phi - \phi_S)_{LT}$ amplitude were presented by HERMES (on hydrogen target) and COMPASS (on proton target), whereas the Hall-A Collaboration at JLab has recently published final results on neutron (^3He) target [34]. While the COMPASS results are consistent with zero for both positive and negative hadrons, HERMES and Hall-A observed a positive amplitudes for the π^-.

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6. Future measurements

In the forthcoming future, ongoing analyses on HERMES and COMPASS existing SIDIS data will be finalized and new results on TMDs related observables will be published. In the meanwhile, the upgrade of the actual (6 GeV) JLab accelerator facility will be accomplished. In the 12 GeV era of JLab high precision SIDIS data will be collected allowing the study of TMDs in the valence region, i.e. in a kinematic domain (large-x) complementary to that exploited by HERMES and COMPASS. The main contributions to this study will be provided by two conceptually different experimental equipments: SOLID, a solenoid spectrometer to be constructed in Hall-A, and CLAS12, a large acceptance toroid spectrometer, evolution of the CLAS spectrometer in Hall-B. Several TMDs-related measurements were already approved for both experiments. For the long term range, large collaborations at BNL and JLab, encouraged by the USA agencies, are elaborating proposals for a high-luminosity ($L \approx 10^{34} cm^{-2} s^{-1}$, i.e. two orders of magnitudes larger than that of the HERA collider), high-energy polarized Electron Ion Collider (EIC). To carry out a rich and diversified physics program the recommended energies for the electrons are between 3 and 10 GeV, for the protons between 25 and 250 GeV, and for the heavy ions between 25 and 100 GeV. Two are the main proposals under investigation: eRHIC at BNL and MEIC/ELIC at JLab. The BNL project foresees the use of the existing RHIC highly polarized proton and nuclear beams in conjunction with a new storage ring for polarized electron or positron beams. The JLab project, on the other hand, foresees the injection of the already available 12 GeV electron beam from the upgraded CEBAF accelerator into a new concept eight-shaped electron-ion collider. Quite recently, preliminary ideas for a low-cost low-energy polarized electron-nucleon collider (ENC) at GSI, have also been considered. For the far future, a very-high energy electron-ion collider (LHeC) is being considered at CERN. The idea foresees the construction of an electron storage ring within the LHC tunnel. Though SIDIS is currently the most exploited process to study TMDs, extremely interesting results are expected from the yet experimentally unexplored polarized Drell-Yan production. In particular, doubly polarized DY can provide a very clean access to the transversity distribution as the cross-section asymmetries can be interpreted in terms of simple products of the transversity functions of the colliding hadrons (e.g. a proton and an antiproton). This is the idea at the basis of the PAX project at FAIR (GSI). If approved, PAX will make use of an asymmetric collider consisting of HERS (the antiproton storage ring for the PANDA experiment), where polarized protons will be stored, and of a new storage ring for the polarized antiprotons. Asymmetries of the order of $10-15\%$ are predicted. Also the Sivers effect can be probed in DY processes with a transversely polarized proton. Such a measurement is particularly interesting as it is expected to demonstrate the sign change of the Sivers function with respect to the SIDIS case, as predicted on the basis of QCD. In 2014 the COMPASS experiment will provide the first measurements of π^- induced DY on a transversely polarized proton target. Polarized DY measurements are also foreseen at Fermilab (E906), RHIC (PHENIX and STAR), J-PARC (P24) and NICA. Finally, concerning the e^+e^- experiments, new results on the fragmentation function will be released by the BELLE and BABAR collaborations in the forthcoming future. Particularly awaited, e.g. for a clearer interpretation of the HERMES and COMPASS Collins and Sivers amplitudes, are results for the Collins fragmentation function into charged kaons. In the medium range term, high precision results could come from the next generation B-factories: BELLE-II ($L \approx 8 \cdot 10^{35} cm^{-2} s{-}2$) and SuperB ($L \geq 10^{36} cm^{-2} s{-}2$).

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