EPJ Web of Conferences 85, 01006 (2015)
DOI: 10.1051/epjconf/20158501006

TMDs and Unpolarized SIDIS

M. Contalbrigo[1,3,a]

[1] INFN Sezione di Ferrara, Via Saragat 1, 44122 Ferrara, Italy

Abstract. The investigation of the partonic degrees of freedom beyond collinear approximation (toward a 3D description of the hadron structure) has been gaining increasing interest in the last decade. SIDIS reactions offer a rich phenomenology convoluting TMD parton distribution and fragmentation functions. In the recent years, several first measurements have been made that provide new insights on peculiar aspects of the parton dynamics, i.e. orbital motion and spin-orbits effects. Beyond spin asymmetries, unpolarized measurements, with their high-statistics data samples and natural connections among different fields of investigation, challenge our comprehension of TMD phenomena and are crucial for the TMD formalism assessment.

1 TMDs and the 3D Hadron Structure

Since decades, few questions have challenged the interpretation of hadron structure and phenomena in Hadronic Physics in terms of perturbative QCD. Among the most compelling, there is the spin budget of the nucleon, where there are missing contributions not quantified yet, and the surprising single-spin asymmetries, which do not vanish as expected with increasing energy. The questions above relate to one of the fundamental degree of freedom of the elementary particles, the spin, and its correlation with the motion (i.e. transverse momentum) of the partons. As part of the most general mechanism of confinement, these correlations might manifest also in unpolarized reactions where particle polarization is not directly observed or controlled.

Most of our present understanding of the internal structure of nucleons derives from inclusive deep-inelastic-scattering (DIS) experiments performed over the past four decades in different kinematic regimes at fixed-target experiments and collider machines. Based on the large amount of precise data provided by these experiments we have reached a good knowledge of the parton longitudinal-momentum and longitudinal-spin distributions of quarks in the nucleon, where "longitudinal" refers to the direction parallel to that of the exchanged virtual boson (the hard probe).

In the recent years, new transverse-momentum-dependent (TMD) parton distributions, in this work abbreviate as TMDs for simplicity, have been introduced to describe the rich complexity of the hadron structure, taking into account the parton transverse degrees of freedom and moving toward the achievement of a 3D comprehension of the parton dynamics. At the same time new channels of investigation have been gaining importance as the study of semi-inclusive deep-inelastic-scattering (SIDIS) reactions where the hadron produced by the struck quark is observed in conjunction with the scattered lepton probe. Such measurements have become possible by the parallel evolution of the experimental apparatuses.

At the price of an unprecedented complexity, the novel paradigm of hadron structure TMD investigation may eventually shed new light on the phenomena of quark confinement as it connects with color-glass condensate and hadron formation in cold nuclear matter.

This work presents a selection of the available observations and the planned experiments to address the mysteries of the hadron structure from a modern point of view.

2 Semi-inclusive Physics

A complete collinear description of the nucleon structure at leading order in an expansion in M/Q (twist expansion), where Q is the photon virtuality and M the nucleon mass, requires the knowledge of three fundamental parton distributions (pdfs): the momentum distribution $f_1(x)$, the helicity distribution $g_1(x)$, and the presently poorly known transversity distribution $h_1(x)$. Here x denotes the longitudinal momentum fraction carried by the partons and the scale dependence (on Q^2) has been neglected for simplicity. The transversity distribution reflects the quark transverse polarization in a transversely polarized nucleon and is related to the tensor charge of the nucleon [1]. Transversity has long remained unmeasured due to its chiral-odd nature, which prevents its measurement in inclusive deep-inelastic-scattering: the transversity distribution can only be measured in conjunction with another chiral-odd object. One possibility is represented by SIDIS reactions, where at least one final state hadron is detected in coincidence with the scattered lepton, thus conjugating parton distribution with fragmentation functions.

Besides allowing to access transversity, SIDIS experiments open the way to the extraction of transverse-

[a] e-mail: contalbrigo@fe.infn.it

momentum-dependent pdfs [2], which are increasingly gaining theoretical and experimental interest. Describing correlations between the quark or the nucleon polarization and the quark transverse momentum, i.e. spin-orbit correlations, the TMD distribution functions encode information on the 3-dimensional parton dynamics. There are eight independent leading-twist quark TMDs, ordered as a function of the nucleon N and quark q polarization in the following table.

N/q	Unpolarized	Longitudinal	Transverse
Unpolarized	f_1		$h_1^\perp$
Longitudinal		g_1	$h_{1L}^\perp$
Transverse	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

The diagonal elements are the momentum, longitudinal and transverse spin distributions of partons above introduced. Off-diagonal elements require non-zero orbital angular momentum as they are related to the wave function overlap of Fock states of the nucleon with different angular momentum. The chiral-even distributions $f_{1T}^\perp$ and g_{1T} are the imaginary parts and the chiral-odd $h_1^\perp$ and $h_{1L}^\perp$ are the real parts of the interference terms between S and P wave components. The chiral-odd $h_{1T}^\perp$ function is sensitive to the D-wave component. The TMDs $f_{1T}^\perp$ and $h_1^\perp$ are known as the Sivers [3] and Boer-Mulders [4] functions. They require a non-trivial gauge link and therefore exhibit a peculiar process dependence: a sign change is expected moving from SIDIS to Drell-Yan processes. They describe unpolarized quarks in the transversely polarized nucleon and transversely polarized quarks in the unpolarized nucleon, respectively. The most simple mechanism that can lead to a Boer-Mulders (Sivers) function is a correlation between the spin of the quarks (nucleon) and the quark orbital angular momentum. In combination with a final state interaction that is on average attractive, such correlations manifest as azimuthal asymmetries of the produced hadron distribution.

An analogous table exists for the fragmentation functions. As the polarization in the final state is not accounted for in this work, only two fragmentation functions are considered in the following: the unpolarized D_1 and the Collins $H_1^\perp$ fragmentation function. The latter acts as a polarimeter being sensitive to the correlation between the transverse momentum gained during fragmentation and the transverse polarization of the fragmenting quark [5]. The measurements indicate a peculiar behavior of the Collins functions, with similar magnitude but opposite sign for favored (the fragmenting quark is a valence quark of the produced hadron) and unfavored fragmentation.

TMDs can be accessed in SIDIS being associated with specific azimuthal angle dependencies of the cross-section:

$$\begin{aligned} d\sigma_{UU} &= \frac{d^5_{UU}}{dx\,dy\,dz\,dP^2_{h\perp}\,d\phi} \qquad (1) \\ &\propto \{F_{UU,T} + \epsilon F_{UU,L} \\ &+ \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi}\cos\phi + \epsilon F_{UU}^{\cos 2\phi}\cos 2\phi\} \end{aligned}$$

In the target rest frame, y is the fraction of the beam energy carried by the virtual photon and z is the fraction of the virtual photon energy carried by the produced hadron. The hadron momentum component transverse to the virtual photon direction is denoted $P_{h\perp}$, and ϕ is the azimuthal angle of the hadron production plane around the virtual photon direction with respect to the lepton scattering plane. The structure functions $F^{\cdots}_{UU\ldots}$ depend on x, Q^2, z and $P_{h\perp}$; the subscript UU stands for unpolarized beam and target, while T (L) indicates transverse (longitudinal) polarization of the virtual photon, and ϵ is the ratio of longitudinal to transverse photon flux.

Semi-inclusive DIS can be described using TMD factorization when the transverse momentum of the produced hadron is small compared to the hard scale Q [6]. In this case, the semi-inclusive structure functions can be interpreted in terms of convolutions involving TMD parton distribution and fragmentation functions. In the kinematics here considered, at leading order in the expansion in powers of $1/Q$ (twist-expansion) the structure functions read [2]:

$$\begin{aligned} F_{UU,T} &= C[f_1 D_1] \qquad (2) \\ F_{UU,L} &= 0 \\ F_{UU}^{\cos\phi} &= 0 \\ F_{UU}^{\cos 2\phi} &= C[-\frac{2(\hat{\mathbf{h}}\cdot\mathbf{k}_T)(\hat{\mathbf{h}}\cdot\mathbf{k}_T) - \mathbf{k_T}\cdot\mathbf{p_T}}{MM_h}h_1^\perp H_1^\perp] \end{aligned}$$

whit $\hat{\mathbf{h}} = \mathbf{P}_{h\perp}/|\mathbf{P}_{h\perp}|$, M_h the observed hadron mass and

$$\begin{aligned} C[wfD] &= x\Sigma_a e_q^2 \int \delta^{(2)}(\mathbf{p}_T - \mathbf{k}_T - \mathbf{P}_{h\perp}/z) \qquad (3) \\ & w(\mathbf{p}_T, \mathbf{k}_T) f^a(x, p_T^2) D^a(z, k_T^2) d\mathbf{p}_T^2 d\mathbf{k}_T^2 \end{aligned}$$

a weighted convolution integral over the quark intrinsic momentum $\mathbf{k}_T$ and the hadron transverse momentum acquired during fragmentation $\mathbf{p}_T$. In the convolution, $w(\mathbf{p}_T, \mathbf{k}_T)$ is a given function and the summation runs over quarks and antiquarks. The structure function F_{UU} and $F_{UU}^{\cos 2\phi}$ get the leading contribution from unpolarized and novel chirally-odd TMD parton distribution and fragmentation functions, respectively. The structure function $F_{UU}^{\cos\phi}$ gets contributions of order $1/Q$, as discussed in Section 5, whereas the structure function $F_{UU,L}$ involves only longitudinally polarized photons and, in the kinematics here considered, gets contributions of order $1/Q^2$.

3 The SIDIS Facilities

The TMDs investigation via SIDIS reactions has opened the way to a very rich phenomenology as provide access to both parton distributions and fragmentation functions. The interpretation of the observables is however not trivial as requires to solve a convolution over transverse momenta, see Eq. 3. As it is impractical for the experimental apparatus to achieve a full coverage in transverse momenta, a very careful control of the acceptance effect is crucial for each measurement. In addition, a complete analysis requires both a flavor sensitivity to isolate the different quark contributions and a multi-dimensional information to disentangle all the kinematical correlations. This has become possible only with the second generation SIDIS experiments operating in the last decade complemented by related measurements done at e^+e^- colliders (sensitive to the fragmentation functions) and at Drell-Yan experiments (sensitive to the pdfs).

The HERA facility at DESY comprises a 920 GeV proton and a 27.5 GeV electron (positron) storage ring. The H1 [7] and ZEUS [8] experiments use the colliding beams to perform precise measurements of the unpolarized structure functions in a broad kinematic regime allowed by the high center-of-mass energy. The Hermes fixed-target experiment [9] investigates polarized DIS exploiting the natural growth of polarization in the lepton beam due to the Sokolov-Ternov mechanism [10]. Its pure target gas, fed polarized or unpolarized in the open-ended storage cell internal to the lepton ring, is free from unwanted nuclear effects from heavier contaminant that act as a dilution on the TMD measurements [11]. Despite the HERA operation stopped in 2007, the experimental collaborations are still analyzing the large amount of data collected.

At CERN, the Compass experiment exploits the secondary beams derived from the 450 GeV SPS proton beam [12] and employes solid state polarized targets of ammonia or ^{6}LiD [13]. After several years of investigation of DIS reactions with a 160 GeV polarized muon beam, the program will be soon complemented by a high-statistics DIS run with a liquid hydrogen target. The experiment is now moving towards Drell-Yan measurements with a pion beam [14].

At the Thomas Jefferson National Laboratory (JLab) in Virginia, USA, three experimental halls have pursued a program of DIS measurements with complementary approaches. The CLAS spectrometer in Hall-B [15] features a large acceptance and polarized proton and deuteron targets; the double-arm spectrometer in Hall-A [16] exploits high-luminosity with the world leading polarized ^{3}He target whereas the one in Hall-C [17] concentrates on precise measurements of the unpolarized SIDIS cross-section. The CEBAF accelerator provides a continuous highly-polarized electron beam. It was turned off in 2011 after about 15 years of operation at 6 GeV and is now undergoing an upgrade to double the beam energy to 12 GeV. At the same time an effort is ongoing to enhance the detector capabilities to sustain the foreseen an-order-of-magnitude increase in luminosity and the much extended physics program [18].

A strong effort is ongoing worldwide to promote the realization of a polarized electron-ion collider able to address the still open issues in the nucleon structure. In Europe, the Large Hadron Electron Collider (LHeC) at CERN plans to extend the unpolarized HERA data to an unprecedented energy domain [19], whereas the polarized Electron-Nucleon Collider (ENC) at FAIR proposes to update the measurements done at Compass at comparable center-of-mass energy and luminosity [20]. Promoted by the BNL and JLab laboratories, the project for a polarized Electron-Ion Collider (EIC) in the States [21], has a comprehensive physics program ranging from the multi-dimensional spin physics investigation to the low-x physics saturation searches and the potentiality to address all the questions mentioned in this work.

4 TMDs and Quark Distributions

The unpolarized parton density functions have been constrained over a wide range of the kinematic variables by the high-precision combined HERA data on proton's deep-inelastic-scattering structure functions. The experimental information is being further strengthened by the related studies ongoing at the Large Hadron Collider (LHC), i.e. on W-boson production. Despite this wealthy amount of data there are still lack of knowledge in interesting distributions in relevant kinematical regions. For example, there is still a large uncertainty on the gluon distribution at low values of $x < 10^{-3}$ (see Section 7) and on the strange quark distribution at medium values of x around 0.1, i.e. when its magnitude starts to become significant. In all the cases, only a poorly knowledge is available on the transverse momentum dependencies.

4.1 Flavor Decomposition

Measurements of the W- and Z-boson production cross sections in proton- (anti)proton collisions are sensitive to the light quark distributions in the kinematic range $10^{-3} \leq x \leq 10^{-1}$. In a recent analysis by the ATLAS Collaboration [22], the inclusive cross section measurements of W- and Z-boson production were used in conjunction with DIS inclusive data from HERA. The result supports the hypothesis of a symmetric composition of the light quark sea in the kinematic region probed, i.e. a strange fraction $r_s = 0.5(s + \bar{s})/\bar{d} = 1.03 \pm 0.19_{\text{exp}}$ is quoted at $x = 0.023$ and $Q^2 = 1.9$ GeV^2 from a NLO fit. This results comes at a variance from the indication of an almost factor two strange suppression derived from the previously available phenomenological fits [23].

The muon charge asymmetry measurements have indirect sensitivity to the strange quark distribution. At a variance, the measurements of the total and differential cross sections of W + charm production have the potential to access the strange quark distribution directly through the LO process $g + s \rightarrow W + c$. In a recent CMS combined analysis of the two channels [24], the down quark distribution is significantly constrained by the muon charge asymmetry data, while the strange quark distribution is directly probed by the associated W + charm production measurements. The resulting integrated strange quark fraction $k_s = 0.52 \pm 0.11_{\text{exp}}$ at $Q^2 = 20$ GeV^2 is in good agreement with the $k_s = 0.591 \pm 0.019_{\text{exp}}$ value determined at NNLO by using dimuon production in neutrino interactions by the NOMAD experiment [25]. The extracted strange fraction $R_s = (s + \bar{s})/(\bar{u} + \bar{d}) \sim 0.65 \pm 0.16_{\text{exp}}$ at $x = 0.023$ and $Q^2 = 1.9$ GeV^2 is significantly smaller than the prediction provided by the ATLAS Collaboration and supporting the presence of a strange suppression in the probed light sea. It should be noted that the two LHC results are anyway compatible due to the large experimental uncertainty above quoted.

In all the above cases, there is an underline uncertainty due to the assumptions made in input to the fits, i.e. in the parameterization form describing the parton distribution shape, which is difficult to be reliably quantified. The measurements of semi-inclusive hadron production on an isoscalar deuteron target at HERMES have been used to obtain the x dependence of the strange quark distribution at LO at an average $Q^2 = 2.5$ GeV^2 [26]. In that analysis the strange quark distribution is found to drop with increasing x much faster than the $\bar{u}$ and $\bar{d}$ distributions and vanish above $x = 0.1$. Such a behavior finds a possible interpretation in lattice QCD as related to the absence of connected diagram contributions in the strange sector [27].

The HERMES results have been recently reevaluated [28] using the final results on pion and kaon multiplicities [29]. In the extraction, the correction for acceptance, kinematic smearing, and radiative effects is accomplished by a multi-dimensional unfolding in x, z, and $P_{h\perp}$ of the experimental effects, which has been derived from the novel TMD investigation approach. The strange distribution results softer than the previously determined in agreement with a strange suppression in the light sea around $x \sim 10^{-2}$. Nevertheless, the peculiar shape of the strange distribution around $x \sim 0.1$ has been confirmed.

The upcoming high-statistics measurements at the COMPASS experiment [14] and JLab12 facility [30] would need to be supplemented with a multi-dimensional analysis in order to best address the still open issues related to the light quark, in particular strange, distributions.

4.2 Distribution Widths

Hadron multiplicities in SIDIS reactions have since long time been used to study quark fragmentation, complementing the measurements done at higher energies at the e^+e^- collider machines. In particular, SIDIS measurements with various targets and hadron identification capability allow the study of fragmentation functions with enhanced flavor sensitivity.

A recent comparison between measurements at HERMES [29] and LO calculations based on fragmentation [31] and distribution [32] phenomenological parameterizations shows substantial discrepancies for negative charged pions and kaons. For negatively charged mesons, fragmentation is less affected by the u quark contribution and uncertainties in the less abundant production by strange and anti-u quarks may have a larger impact on the predictions than for the positively charged hadrons. Alternatively, next-to-leading-order (NLO) processes may be more important for negatively charged mesons.

The hadron multiplicities study is now being extended to a multi-dimensional analysis, in particular looking to the transverse momentum dependence and its correlations with other kinematic variables. In principle, from the observed transverse momentum $P_{h\perp}$, information can be gathered on the intrinsic transverse momentum k_T and the one generated during fragmentation p_T. For example, within the assumption of Gaussian distributions, they are related as $\langle P_{h\perp}^2 \rangle = \langle p_T^2 \rangle + z^2 \langle k_T^2 \rangle$.

There is no reason the transverse momentum dependence should be the same for all the flavors. Within the framework of the chiral quark soliton model, the predicted average transverse momentum square $\langle k_\perp^2 \rangle$ of quarks and antiquarks depends strongly on their longitudinal momentum fraction x, which means that the frequently used assumption of factorization in x and $k_\perp$ is significantly violated. It is also found, somewhat unexpectedly, that the average transverse momentum square of antiquarks is considerably larger than that of quarks [33] which has later been linked to a more general consequence of the dynamical chiral symmetry breaking [34].

Using the model of Nambu and Jona-Lasinio to provide a microscopic description of both the structure of the nucleon and of the quark to hadron elementary fragmentation functions within a Monte Carlo framework, it is found that diquark correlations in the nucleon give rise to a nontrivial flavor dependence in the unpolarized transverse-momentum-dependent quark distribution functions and that the average transverse momentum $\langle k_\perp^2 \rangle$ has a sizable x dependence [35]. At the same time, the average transverse momentum $\langle p_\perp^2 \rangle$ in fragmentation has a sizeable z dependence and is larger for produced kaons than pions.

Semi-inclusive electroproduction of charged pions has been measured from both proton and deuteron targets, using a 5.5 GeV energy electron beam in Hall-C at Jefferson Lab [36]. In the limited $P_{h\perp}^2 < 0.2$ explored, the $P_{h\perp}$ dependence from the deuteron was found to be slightly weaker than from the proton. In the context of a simple model, it was shown this would imply the initial transverse momenta width is larger for d quarks than u quarks and, contrary to expectations, the transverse momentum width of the favored fragmentation function is larger than the unfavored one.

Recently, multiplicities of charged pion and kaon mesons have been measured by Hermes using the electron beam scattering off hydrogen and deuterium targets [29]. In addition, multiplicities of charged hadrons produced in deep inelastic muon scattering off a ^{6}LiD target have been measured at COMPASS [37]. These high-statistics data samples have been used in phenomenological analyses to extract information on the flavor dependence of unpolarized TMD distribution and fragmentation functions. The measurements are well described by a TMD Gaussian model with constant and flavour independent widths, $\langle k_T^2 \rangle$ and $\langle p_T^2 \rangle$ [38]. Nevertheless, indications were reported that favored fragmentation functions into pions have smaller average transverse momentum than unfavored functions and fragmentation functions into kaons [39].

A precise determination of the separate values of $\langle k_\perp^2 \rangle$ and $\langle p_\perp^2 \rangle$ would require the simultaneous analysis of other observables, like the azimuthal dependencies of the SIDIS cross-section discussed in Section 5, which are sensitive to the ratio $\langle k_\perp^2 \rangle / \langle p_\perp^2 \rangle$. An important complementary information should come from the extension of the fragmentation studies done at the e^+e^- collider machines to the transverse momentum dependence. Measurements of inclusive differential cross sections for charged pion and kaon production in e^+e^- annihilation, carried out at a center-of-mass energy of $\sqrt{s} = 10.52$ GeV and unprecedented luminosity, have recently shown the potentiality of the B-factories [40].

New SIDIS data will be soon collected on a liquid hydrogen target by the COMPASS experiment [14]. A broad program of measurements is planned in different experimental halls of JLab after the beam energy and detector upgrades. Among the various planned experiments, there is the precise measurements of the SIDIS cross sections for charged pions and kaons at low transverse momentum $P_{h\perp}$ from hydrogen and deuterium targets [41], which can be used in order to gather measures of the mean transverse momentum of up and down quarks in the nucleon, and a extended exploration from current to target fragmentation region [30].

As highlighted by phenomenological analyses relating results of different reaction channels [42], the TMD distribution widths change with the center-of-mass energy. This is connected with the non-trivial evolution properties of the TMD functions, now at the center of a strong activity [43]. The novel high-precision SIDIS measurements, in conjunction with e^+e^- annihilation and Drell-Yan data, will be crucial to validate the TMD evolution formalism under development.

A complete comprehension would require the study of the longitudinal to transverse SIDIS cross-section ratio $R = \sigma_L/\sigma_R$. Although R appears in the denominator of all the azimuthal asymmetries related to the TMDs investigation, it is up to date unknown. The phenomenological analyses have typically assumed either zero or the values determined from inclusive DIS. The precise measurement of R for charged pions and kaons [44], and neutral pions, will help to shed light on the nature of the SIDIS reaction mechanism, in particular regarding the higher-twists contributions, which could be particularly important at the rather modest energies of JLab.

5 Azimuthal Dependencies

Already in the early days of the parton model it was realized that the inclusion of quark intrinsic transverse momentum leads to modifications of the cross sections in lepton-nucleon deep-inelastic scattering. Cosine modulations in the azimuthal dependencies of the distribution of the produced hadrons about the direction of the virtual photon can be non-vanishing due to simple kinematic effects (Cahn effect) [45]. It was also later realized that the interplay between the parton transverse momentum and spin (Boer-Mulders effect [46]) can generate a leading twist (unsuppressed in $1/Q$) contribution to the $\cos 2\phi$ modulations, see Eq. 2. Perturbative-QCD effects, like gluon radiation, can also lead to azimuthal dependencies in the semi-inclusive DIS cross section. However, they contribute mainly at large values of $P_{h\perp}$, and are next-to-leading order in the strong coupling constant.

Among the various contributions suppressed as $1/Q$, several involve either a distribution or fragmentation function that relates to quark-gluon-quark correlations, and hence is interaction dependent and has no probabilistic interpretation. In the Wandzura-Wilczeck approximation [47] all these terms are neglected, and only two contributions are considered:

$$F_{UU}^{\cos\phi} \simeq -\frac{2M}{Q}\, C\left[\frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M} f_1 D_1 + \frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h} h_1^\perp H_1^\perp\right] \tag{4}$$

where the first (second) term is related to the Chan (Boer-Mulders) effect. There are no contributions to $F_{UU}^{\cos 2\phi}$ at a suppression $1/Q$. Not all contributions beyond a suppression of $1/Q$ have been calculated, however a contribution suppressed as $1/Q^2$ is expected from the Cahn effect to $F_{UU}^{\cos 2\phi}$.

In Drell-Yan experiments, non-zero azimuthal modulations have been measured [48] that violate the Lam-Tung relation [49]. Such a violation can be ascribed to the Boer-Mulders distribution function [50]. Sizable modulations have been extracted in pion-induced Drell-Yan reactions, where a valence quark and a valence antiquark annihilate. At a variance, when a sea parton is involved as in proton-induced Drell-Yan processes, the measured modulations become smaller. This behavior can be explained by a small Boer-Mulders function for the sea partons.

Only a few measurements of cosine modulations in semi-inclusive DIS experiments have been published in the past [51]. Most measurements averaged over any possible flavor dependence as they refer to hadrons without type nor charge distinction, and only to hydrogen target or hydrogen and deuterium targets combined together.

Recently several precise SIDIS measurements have become available. The CLAS collaboration measured non-zero cosine modulations for positive pions produced by 6 GeV/c electrons scattering off the proton [52]. The HERMES experiment have measured cosine modulations of hadrons produced in the scattering of 27.5 GeV/c electrons and positrons off pure hydrogen and deuterium targets, where the lepton beam scatters directly off neutrons and protons (with only negligible nuclear effects in case of deuterium) [53]. For the first time these modulations were determined in a four-dimensional kinematic space for positively and negatively charged pions and kaons separately, as well as for unidentified hadrons. At COMPASS, positive and negative hadrons produced by the 160 GeV/c muon beam scattering off a ^{6}LiD target have been measured in a three-dimensional grid of the relevant kinematic variables x, z and $P_{h\perp}$ [54].

In all the experiments, the new data confirm the existence of a sizeable $\cos\phi$ and a not-zero $\cos 2\phi$ modulations. However, the results published by different experiment appear not fully consistent. For example, positive $\cos 2\phi$ amplitudes for both positively and negatively charged hadrons were measured at COMPASS. At HERMES, positive $\cos 2\phi$ amplitudes are extracted for negatively charged pions, while for positively charged pions the moments are compatible with zero, but tend to be negative in some kinematic regions. In all the cases, the amplitudes of the cosine modulations show strong kinematical dependencies. In order to perform a fair comparison between experimental results and with theoretical models, a full differential analysis, using the complete multidimensional information provided by the experiments in public databases, is mandatory.

The large $\cos\phi$ amplitude implies that the contribution suppressed with powers of $1/Q$, as the ones discussed in Eq. 2 and in Eq. 4, are not negligible. This largely complicates the interpretation as there could be several additional contributions at subleading order which are not calculable [55]. Nevertheless some attempts have been made to explain the main features of the resulting modulations, i.e. the sizeable changes with hadron type and charge. The similarity between hydrogen and deuterium results seems to indicate that the Boer-Mulders distribution function has the same sign for up and down quarks, in agreement with expectations from theoretical considerations [56]. The difference between charged pion results may be ascribed to the Boer-Mulders term, due to the dominating contribution of the up quark in SIDIS reactions and the opposite sign of Collins fragmentation of up quark into positively and negatively charged pions. The striking difference between kaon and pion $\cos 2\phi$ modulations measured at HERMES does not find an explanation on the peculiar Collins fragmentation as the B-factories find similar asymmetries between the two meson types [57].

A step forward will be possible by new complementary measurements. New Drell-Yan experiments offer the opportunity to study azimuthal modulations and the Lam-Tung relation with unprecedented precision [58]. At JLab, several experiments are planned to study in detail the unpolarized SIDIS azimuthal modulations for different hadron types in a broad kinematic range [59].

6 TMDs and Hadron Formation

When a hard parton passes through a medium, either cold nuclear matter or quark-gluon plasma, it loses energy due to multiple scatterings and induced gluon bremsstrahlung. Its fragmentation function into final hadrons will be modified as compared to that in vacuum. The modification in general involves suppression of leading hadrons in deeply inelastic scattering (DIS) off nuclei or high transverse momentum hadron spectra in high-energy heavy-ion collisions, a phenomena referred to as jet quenching. As a consequence, measurements of medium modification of the observed hadron spectra allow to extract medium properties information.

The hadronization process in free space has been studied extensively in e^+e^- annihilation experiments [31]. As a result the spectra of particles produced and their kinematic dependencies are rather well known. However, little is known about the space-time evolution of the process. Semi-inclusive production of hadrons in deep-inelastic scattering of leptons from atomic nuclei provides a way to investigate this space-time development. Leptoproduction of hadrons has the virtue that the energy and the momentum of the struck parton are well determined, as they are tagged by the scattered lepton. By using nuclei of increasing size one can investigate the time development of hadronization. If hadronization occurs quickly, i.e., if the hadrons are produced at small distances compared to the size of atomic nuclei, the relevant interactions in the nuclear environment involve well-known hadronic cross sections such as the ones for pion-nucleon interactions. If, in contrast, hadronization occurs over large distances, the relevant interactions are partonic and involve the emission of gluons and quark-antiquark pairs. The two mechanisms lead to different predictions for the decrease in hadron yield, known as attenuation, on nuclei as compared to that on free nucleons.

A series of semi-inclusive deep-inelastic scattering measurements on helium, neon, krypton, and xenon targets has been performed at HERMES to be compared with a deuteron target in order to study hadronization. The extensive study presents hadron multiplicities on nuclei relative to those on the deuteron for various hadrons (pions, kaons and protons) as a function of the virtual-photon energy ν, the fraction z of this energy transferred to the hadron, the photon virtuality Q^2, and the hadron transverse momentum squared $P^2_{h\perp}$ [60]. A multi-dimensional analysis has been performed to help disentangling the various kinematical dependencies [61].

A complementary approach is to measure the broadening of the transverse momentum distribution of various hadrons in SIDIS. This observable should be mostly sensitive to the partonic stage of hadron production as transverse momentum broadening ceases at the point of color neutralization. Measurements were done for π^+ at a beam energy of 6 GeV by the CLAS experiment as a function of ν, Q^2, and z with carbon, iron and lead targets [62]. For the heaviest target a hint of a saturation behavior was found. This would be expected in the case that the quark evolves into a prehadron within the medium for the largest nucleus. At the higher 27 GeV beam energies of HERMES [63], there is no clear indication of such a saturation at large atomic mass numbers. This behavior suggests that the color neutralization happens near the surface of the nucleus or outside at the average HERMES kinematics. In this case the broadening is expected to be simply proportional to the medium thickness, i.e. proportional to the mass number to the 1/3 power.

The HERMES SIDIS data have been used to study medium properties such as the jet transport parameter $\hat{q}$, the average squared transverse momentum broadening per unit length, which can be related in a model dependent way to the gluon distribution density [64]. The approach has been to study parton energy loss through the use of medium modified fragmentation functions where the inclusion of multiple gluon emissions can be achieved through a set of modified Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations [65] From a fit of the HERMES data a value of $\hat{q} \equiv 0.020 \pm 0.005$ GeV^2/fm at the center of a large nucleus has been extracted.

The resulting $\hat{q}$ from SIDIS data can be compared to the higher ones derived from the suppression of large p_T

single inclusive hadrons in heavy-ion collisions. Model-dependent values for the jet transport parameter $\hat{q}$ at the center of the most central heavy-ion collisions have been extracted by a phenomenological study [66] of experimental data from both RHIC [67] and LHC [68]. For a quark with initial energy of 10 GeV and at an initial time $\tau_0 = 0.6$ fm/c, $\hat{q} \equiv 1.2 \pm 0.3$ GeV^2/fm in Au+Au collisions at $\sqrt{s} = 200$ GeV/n and $\hat{q} \equiv 1.9 \pm 0.7$ GeV^2/fm in Pb+Pb collisions at $sqrts = 2.76$ TeV/n.

There is a growing interest in the study of nuclear dependence of the TMD parton distribution functions. The above results on jet transport parameter and p_T-broadening has been used to get numerical estimates of the suppression of azimuthal asymmetries in SIDIS off unpolarized and polarized nuclear targets [69]. This has driven an experimental proposal at JLab12 [70].

7 Low-x Physics and Gluon TMDs

In the region of very low values of x, where transverse-momentum ordering does not apply, fixed-order perturbative approaches are theoretically disfavored, and cannot be expected to describe the physics of the scaling violation. In that kinematic region a specific factorization scheme leading to the Balitskii-Fadin-Kuraev-Lipatov (BFKL) evolution [71] has been introduced to sum small-x logarithmic corrections to all orders in the strong coupling constant. Such a scheme naturally incorporates transverse-momentum unintegrated (TMD) parton distributions.

The Catani-Ciafaloni-Fiorani-Marchesini (CCFM) high-energy factorization extends the BFKL formalisms to include finite-x contributions. It expresses the heavy quark leptoproduction cross section in terms of the TMD gluon density via calculable perturbative coefficients [72] and can be extended to describe DIS structure functions [73]. It has been used to perform fits to the HERA measurements of the F_2 structure function [74], in the range $x < 0.005$, $Q^2 > 5$ GeV^2, and to measurements of the charm F_2^{charm} structure function [75], in the range $Q^2 > 2.5$ GeV^2, in order to make a determination of the TMD gluon density including also the valence quark contribution [76].

The extracted TMD gluon distributions can be used to make predictions for hadron-hadron collider processes, i.e. W-boson Drell-Yan production [77]. The comparison with LHC data on W-boson production associated with jets [78] shows a reasonable agreement both for the jet transverse momentum distribution and angular correlations. However, a still significant uncertainty is derived from the extracted TMD parton distributions as the computed p-p cross sections are not dominated by very small values of x.

It is conceivable that combining p-p measurements on vector boson production with the DIS measurements may help to constrain TMD pdfs especially at medium to large values of x. Thanks to its high luminosity and the feasibility for an energy scan, an EIC would improve upon HERA data for example on measurements of the longitudinal structure function F_L. The structure function F_L is particularly sensitive to the gluon distribution and QCD dynamics at small x which makes it a promising candidate to study the transition to the high parton density regime, i.e., the phenomenon of saturation [21].

8 Conclusions

In a modern investigation of the parton dynamics, the transverse degrees of freedom can not be anymore neglected, as historically done in the collinear approach. Beyond the growing interest of dedicated studies, it is being realized that even non-TMD observables could get contributions from TMD phenomena.

Unpolarized reactions manifest large azimuthal asymmetries originating from the interplay of parton transverse momentum and spin. Examples are the $\cos\phi$ modulations in SIDIS, which reach amplitudes up to 20% at large z and $P_{h\perp}$, and the cosine modulations in Drell-Yan experiments, which can reach amplitudes greater than 30% with pion beams and violate the Lam-Tung relation. Any precise measurement should account for such cross-section modulations as they fold with the detector acceptance which can hardly be isotropic: the non trivial dependencies in the multi-dimensional kinematic space complicate the correction of the unwanted effects.

The study of the partonic transverse degrees of freedom is a step forward the complete comprehension of the complex parton dynamics. To exploit the full potentiality of TMD mechanisms, an effort will be crucial to complete the theoretical assessment grounds (i.e. TMD evolution) in parallel with the ongoing experimental activity.

SIDIS reactions offer a rich playground for TMDs investigation: access to both parton distribution and fragmentation functions, flavor separation from various hadron types and targets, disentanglement of initial and final state interactions, control of parton kinematics in medium via the scattered lepton observation. A lot of data have been recently released and new experiments are coming soon. Meanwhile a big effort is ongoing to make an electron-ion-collider facility a reality. Unpolarized reactions are basic experimental tools which naturally connects different fields of investigation. Their large and precise data sets will be crucial to validate and develop the TMD formalism; their general interest will serve as assessment of TMD generic applicability.

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