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Transverse-spin physics: Highlights and news

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Summary. — We describe a few of the recent theory highlights in the field of transverse-spin physics.

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1. – Introduction

Single-transverse-spin asymmetries play an important role for our understanding of QCD and nucleon structure. They have a long history, starting from the 1970s and 1980s when surprisingly large asymmetries were observed in hadronic reactions such as $p^{\uparrow}p \rightarrow \pi X$ at forward angles of the produced pion [1]. The last few years have seen a renaissance in the experimental studies of single-spin asymmetries. HERMES and COMPASS, in particular, have investigated them in semi-inclusive hadron production $eN^{\uparrow} \rightarrow e\pi X$ in deep-inelastic scattering [2, 3]. The advent of the first polarized proton-proton collider, RHIC, has opened new possibilities for extending the studies of single-spin asymmetries in hadronic scattering into a regime where the use of QCD perturbation theory in the analysis of the data appears to be justified. The STAR [4], PHENIX [5] and BRAHMS [6] collaborations have presented data for single-inclusive hadron production, and large single-spin effects at forward rapidities were found to persist to RHIC energies.

The observed large size of single-spin asymmetries in hadronic scattering has presented a challenge for QCD theorists. Two mechanisms have been proposed and been extensively applied in phenomenological studies. The first relies on the use of transverse-momentum–dependent parton distributions for the transversely polarized proton. For these distributions, among them the Sivers functions [7], the parton transverse momentum is assumed to be correlated with the proton spin vector, so that spin asymmetries naturally arise from the directional preference expressed by that correlation. The other mechanism [8] is formulated in terms of the collinear factorization approach and twist-three transverse-spin–dependent quark-gluon correlation functions of the proton.

A concept common to both mechanisms is the factorization of the spin-dependent cross section into functions describing the distributions of quarks and gluons in the polarized proton, and partonic hard-scattering cross sections, calculated in QCD perturbation theory. The question of which mechanism should be used in the analysis of a single-spin asymmetry is therefore primarily tied to the factorization theorem that applies for the single-spin observable under consideration. For the single-inclusive process $p^\uparrow p \to \pi X$, there is only one hard scale, the transverse momentum p_T of the produced pion, and the spin asymmetry is power-suppressed ("higher-twist") by $1/p_T$. In this case, one can prove a *collinear* factorization theorem in terms of the quark-gluon correlation functions [8, 9]. On the other hand, the observables typically investigated in deep-inelastic lepton scattering are characterized by a large scale Q (the virtuality of the DIS photon) and by the much smaller, and also measured, transverse momentum q_T of the produced hadron. In this two-scale case, single-spin asymmetries may arise at leading twist, *i.e. not* suppressed by $1/Q$. The relevant factorization theorem is formulated in terms of *transverse-momentum–dependent* (TMD) functions, among them the Sivers function.

Theoretical studies have revealed a striking property of the Sivers functions [10-13]: the functions contributing to DIS and to the Drell-Yan process have opposite sign,

$$f^{\mathrm{Sivers}}(x, k_T)\Big|_{\text{Drell-Yan}} = -f^{\mathrm{Sivers}}(x, k_T)\Big|_{\text{DIS}}. \tag{1}$$

The non-universality of the Sivers functions is reflected in a process-dependence of the space-time direction of the gauge-link in the distribution. The crucial role played by the gauge link has given rise to intuitive model interpretations of single-spin asymmetries in terms of spatial deformations of parton distributions in a transversely polarized nucleon [14], and also to approximate relations between the Sivers functions and generalized parton distributions [15].

Much new theoretical progress has been made very recently. This talk describes a few of the highlights of what has been achieved. Most of the topics are discussed in more detail in other papers of these proceedings. Some of the recent progress originated in the course of a 10-week program "Gluons and the quark sea at high energies: Distributions, polarization, tomography" held at the INT in Seattle last fall. The goal of this program was to help develop the science case for a future Electron-Ion Collider (EIC). The results obtained there are summarized in [16].

2. – News

2˙1. *News item 1: No TMD factorization for general QCD hard scattering.* – It has been known for a few years now [17] that the process-dependence of the Sivers functions manifests itself in an even more striking way in more complicated QCD hard-scattering. An example is the single-spin asymmetry in dijet angular correlations [18, 19], to which to lowest order all 2 → 2 QCD partonic processes contribute. Tremendous progress has been made recently in our understanding of the gauge links for such more general QCD observables [17]. The more involved color structure of the hard-scattering functions has profound consequences. As a result, the Sivers functions for this reaction differ from those in DIS by more than just a sign. In fact, universality is lost completely: the u-quark distribution in, say, the process $ud \to ud$ will differ from that in $ug \to ug$. This feature has profound ramifications whenever transverse-momentum dependent parton distributions are relevant in hard-scattering reactions. It expresses the deep quantum-mechanical interplay between the structure of an object and the probe that is used to examine it.

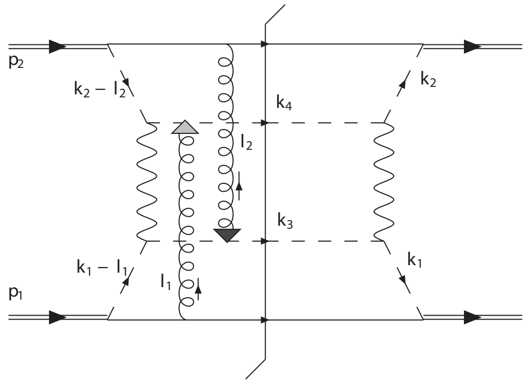

Fig. 1. – Diagram that contributes to a violation of generalized TMD-factorization. Taken from [20].

Until recently, there still seemed to be a logical possibility that despite the breakdown of universality there could still be a "generalized" factorization for hadronic single-spin asymmetries. By this one means that a factorized description of the observable can be achieved, albeit with non-universal distribution functions. Very recent work [20] has shown, however, that even such a generalized factorization does not appear to hold. The breakdown occurs at high order of perturbation theory. Figure 1 shows a sample diagram that contributes to a violation of generalized TMD-factorization.

2˙2. *News item 2: Most complete (to date) analysis of* $pp \to \pi X$ *data.* – Collinear factorization, on the other hand, is known to hold for the spin asymmetry in *single-inclusive* particle production in $pp \to \pi X$ [8, 9]. An extensive phenomenological study of the asymmetries measured in fixed-target scattering [1] and at RHIC [4-6] has first been performed in [21], based on the so-called soft-gluon-pole contributions to the twist-3 asymmetry. The framework and its phenomenological analysis has now been significantly improved by the recent work [22] through inclusion of the soft-fermion-pole contributions. These lead to a much better description of the data. In particular, the calculation in ref. [22] describes also the transverse-momentum (p_T)-dependence of the data well, as shown in fig. 2, whose explanation had remained elusive prior to the analysis. In addition, a quantitative description of the spin asymmetry in η-production is given, which comes out larger than the π^0 spin asymmetry, in accordance with measurements at RHIC [23].

2˙3. *News item 3: A sign puzzle?.* – An intriguing observation has recently been made that may impact our understanding of single-spin asymmetries [24]. It has been known for some time [25-27] that the k_T-moment of a quark's Sivers function is related to the corresponding twist-three quark-gluon correlation function $T_{q,F}(x,x)$:

$$gT_{q,F}(x,x) = -\int \mathrm{d}^2 k_T \frac{|k_T|^2}{M} f_{1T}^{\perp q}(x,k_T^2)|_{\mathrm{DIS}}. \tag{2}$$

Both functions have been extracted from data for single-spin asymmetries in semi-inclusive deep inelastic scattering and in single-inclusive hadron production in pp collisions, respectively. This opens the possibility for a test of the theoretical framework

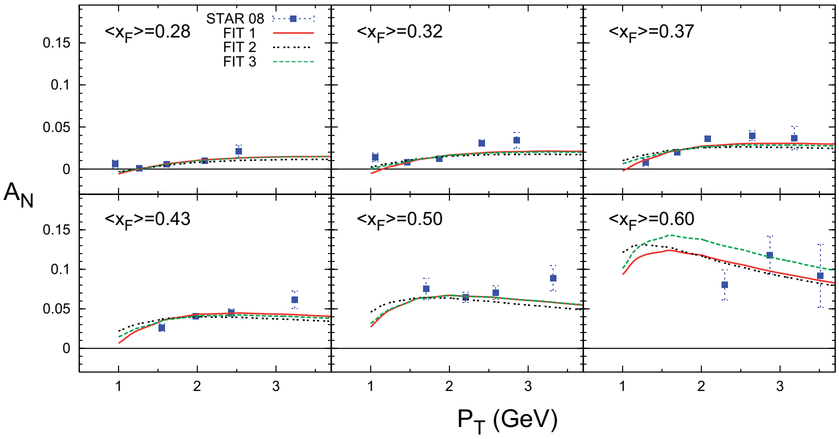

Fig. 2. – p_T-dependence of the spin asymmetry in $pp \to \pi^0 X$ as measured by STAR [4], compared to theoretical descriptions in the twist-3 formalism. Taken from [22].

by using the extracted phenomenological functions and inserting them into eq. (2). Surprisingly, one finds a “sign mismatch”: while the magnitude of the functions is roughly consistent, the k_T-moment of the Sivers function has opposite sign from that of $T_{q,F}(x,x)$, both for up and for down quarks. This is shown in fig. 3.

In fact, the basic problem is easy to see: the Sivers contributions to the single-spin asymmetries depend on initial- or final-state interactions in the scattering processes. The single-spin asymmetry in SIDIS comes from a final-state interaction. A negative up-quark Sivers function is known to generate a positive SIDIS spin asymmetry for π^+ production. In $p^\uparrow p \to \pi X$ at forward rapidities, however, the main partonic channel is $ug \to ug$, for which initial-state interactions play the dominant role, resulting in negative partonic hard-scattering functions. Therefore, if the Sivers mechanism (or its twist-3 variant) is primarily responsible for the single-spin asymmetry in this process, one would expect a negative asymmetry for π^+, contrary to what is observed. Thus the $T_{q,F}(x,x)$ functions needed to describe the RHIC single-spin asymmetries cannot have the signs suggested by eq. (2).

What are the implications of this finding? There are certainly some caveats. First, it could be that the Sivers effect in fact plays a relatively small role for the $p^\uparrow p \to \pi X$ spin asymmetries and that the Collins effect dominates. This is a logical possibility, even though the Collins effect would need to be strong enough to overcome the “wrong-sign” Sivers contribution.

Secondly, there could be a node in k_T in the integrand of eq. (2), such that the large-k_T tail of the distribution has a sign opposite from that of the distribution at $k_T \sim \Lambda_{\mathrm{QCD}}$ where it is mostly constrained by the SIDIS data. In other words, the current SIDIS data may not sufficiently constrain the k_T-moment of the quark Sivers functions. Such a possibility might be tested by a precise experimental mapping of the k_T-dependence of the Sivers functions, possible perhaps at an EIC [16]. It is also worth keeping in mind that the k_T-integral in (2) requires UV renormalization.

Finally, there could also be a node of $T_{q,F}(x,x)$ in x, as recently discussed in [30,31]. The SIDIS and RHIC data cover somewhat different regions in x, with the former mostly sitting at $x \leq 0.3$ and the latter extending to rater high values $x \geq 0.4$. It is thus

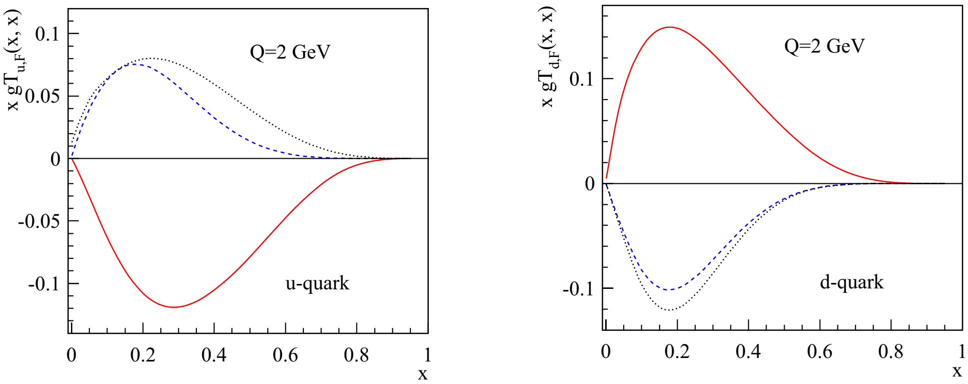

Fig. 3. – Illustration of the "sign puzzle": Quark-gluon correlation function $gT_{q,F}(x,x)$ as a function of momentum fraction x for u-quarks (left) and d-quarks (right). The dashed (dotted) lines are $gT_{q,F}(x,x)|_{\text{new Sivers}}$ [28] ($gT_{q,F}(x,x)|_{\text{old Sivers}}$ [29]) obtained by taking the k_T-moments of the corresponding quark Sivers functions according to the right-hand-side of eq. (2). The solid lines represent the correlation functions extracted directly from data on single-spin asymmetries for inclusive pion production in proton-proton collisions, $p^{\uparrow}p \to \pi + X$ [21] (after correcting for a sign convention; see [24] for details). Taken from [24].

conceivable that $T_{q,F}(x,x)$ has one sign at lower x, but the opposite sign at the higher x. Kang and Prokudin [31] have performed a fit to both sets of data, and they find indeed that a joint description is possible, at the expense of a $T_{u,F}(x,x)$ that has a node. Again, this possibility calls for extended measurements of the x-ranges of the distributions. It should be emphasized that, if $T_{u,F}(x,x)$ indeed has a node, there are important implications for the shape of the predicted Drell-Yan single-spin asymmetry, which in turn is important for the related efforts at COMPASS and RHIC to probe the predicted sign change of the Sivers functions between SIDIS and Drell-Yan.

Whatever the solution to the sign puzzle may be, it will likely teach us something new about the nucleon and QCD. If all of the above caveats can be ruled out, the observed sign puzzle would mean that we face an inconsistency in our QCD formalism for single-spin asymmetries. One would then have to wonder if we have sufficiently understood important issues such as the process dependence of the Sivers functions, the sign change between DIS and Drell-Yan, etc.

2˙4. *News item 4: QCD corrections to single-spin observables.* – Major progress has been made on the theoretical side by addressing the role of higher-order QCD corrections to single-spin observables, which will likely take this field to a new level and will be crucial at the EIC.

In refs. [32-34], the LO "DGLAP" evolution kernels (splitting functions) for the $T_{q,F}(x,x)$ were derived. These will be important in further phenomenological analyses of the RHIC $p^{\uparrow}p \to \pi X$ data. Reference [32, 34] performed a direct computation of the kernels, while in [33] actually a full NLO calculation of the inclusive (q_T-weighted) Drell-Yan spin asymmetry was carried out, which yields the kernels as a side product. It should be noted that the results given in [34] differ from those in [32, 33], which still needs to be understood.

The evolution of TMDs has also recently been addressed [35]. This is remarkable progress. By cleverly rearranging the Collins-Soper-Sterman formalism with particular

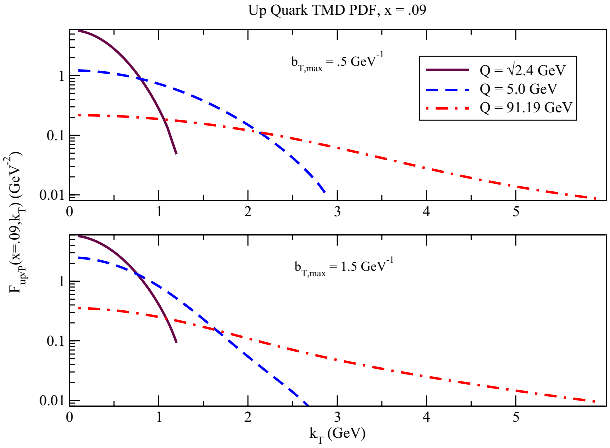

Fig. 4. – Up-quark TMD for $Q = \sqrt{2.4}$, 5.0 and 91.19 GeV and $x = 0.09$, for two different implementations of non-perturbative terms. Taken from [35].

attention to the role of soft factors, it has been possible to phrase the q_T-dependent SIDIS cross section in terms of a simple "parton-model–like" TMD formula with, however, evolved (Q-dependent) TMDs. At low q_T, the formalism is merged to phenomenologically determined non-perturbative terms. The evolution in Q turns out to be quite rapid, as shown in fig. 4. At low transverse momentum, the distributions can be fit to a Gaussian form. Recently, also the evolution of single-spin TMDs has been discussed [36, 37].

2·5. *News item 5: Study of gluon distributions.* – So far, the main focus of the field has been on quark TMDs, which is due to the fact that quark TMDs are primarily probed in semi-inclusive deep-inelastic scattering (SIDIS) and Drell-Yan dilepton production process, which have been accessible experimentally. Gluon TMDs [38] and processes sensitive to them have received closer attention only quite recently, at least for cases where nucleon or gluon polarization matter. Several processes for accessing the gluonic version of the Boer-Mulders function (more appropriately described as the TMD distribution of linearly polarized gluons in an unpolarized nucleon) [39-41], have been proposed for high-energy hadronic collisions, in particular, at RHIC, or for ep scattering at a future EIC. Among these, the double-photon production process $pp \to \gamma\gamma X$ appears particularly suited for studying spin-dependent gluonic TMDs in a theoretically clean way. First of all, since the final state is a color singlet, the diphoton process is expected to share many features with the Drell-Yan process, as far as factorization is concerned. Indeed, like the Drell-Yan process, its lowest-order contribution comes from $q\bar{q}$ annihilation, $q\bar{q} \to \gamma\gamma$, which can be shown to give rise to the same Wilson lines as the Drell-Yan subprocess $q\bar{q} \to \gamma^*$, and hence involves the same quark and antiquark TMDs. Second, it has been known for a long time that in the spin-averaged case [42] at colliders photon pair production is in fact dominated by the process $gg \to \gamma\gamma$, that is, gluon-gluon fusion to a photon pair via a quark box. Even though this process is formally down by two powers of the strong coupling constant α_s with respect to $q\bar{q} \to \gamma\gamma$, the suppression is compensated by the structure of the associated hard-scattering function, and by the size of the gluon distribution function. Hence, an experimental study of gluon TMDs should in principle be possible in this process. Finally, in order to study TMDs, precise measurement of the (small) transverse momentum of a final state is crucial. This should be relatively

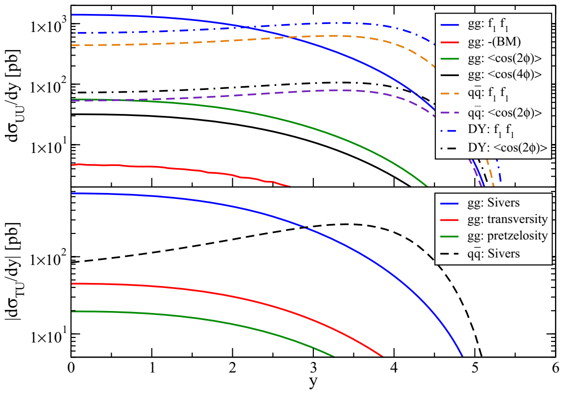

Fig. 5. – Pair rapidity dependence of angular terms in the $pp \to \gamma\gamma X$ cross section at RHIC, for the unpolarized [top] and single transversely polarized [bottom] cases. Taken from [41].

straightforward to achieve for a photon pair. Figure 5 shows predictions for the various azimuthal-angle dependencies in unpolarized and single-polarized $pp \to \gamma\gamma X$ at RHIC. The $\cos(4\phi)$ modulation can be used to extract the gluon Boer-Mulders function. Even a small effect can be significant since this modulation is absent in the $q\bar{q}$ channel. The $\cos(2\phi)$ modulation ultimately gives information on the sign of $h_1^{\perp g}$. Such measurements may also be performed at the LHC where the production rate from gluon fusion is much larger. Another unique feature of the diphoton process is its sensitivity to the gluon Sivers function in polarized proton collisions. Measurements at RHIC could hence provide important clues about the correlation between gluon motion and hadron spin. An additional very intriguing feature is that linearly polarized gluons generate a term in the cross section that is independent of azimuthal angle. In this way they can also contribute to production of a scalar particle, such as a scalar or pseudoscalar Higgs boson, when its transverse momentum q_T is measured. Even more, as was shown in [43], linearly polarized gluons may in fact provide a tool to uncover whether the Higgs boson is a scalar or a pseudoscalar particle, since the double helicity flip piece is opposite in the two cases.

Gluon distribution effects have also been studied for single-inclusive observables, where they contribute as twist-three three-gluon correlation functions to single-spin asymmetries. The most complete study has been performed in [44] for SIDIS processes.

2˙6. *Other recent highlights.* – Other important recent theory work that will not be discussed here in detail addresses the role of orbital angular momentum. The concept of Wigner distributions, in particular, appears to provide a very promising avenue here [45]. Also, the recent study [46] presents a phenomenological extraction of orbital angular momentum, using (model-dependent) relations between generalized parton distributions and the Sivers TMD. Progress on the question of orbital angular momentum is vital for achieving a complete understanding of the nucleon in QCD, and will likely continue to be a key focus in future years.

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