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Twist-3 spin observables for single-hadron production in DIS

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Recently, three twist-3 spin asymmetries for single-inclusive hadron production in deep-inelastic lepton-nucleon scattering have been computed using collinear factorization and the leading order approximation. Here we summarize the main findings of these studies.

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1. Introduction

In lepton-nucleon scattering it is common to detect the scattered lepton. This allows one to measure the momentum transfer Q^2 between the initial-state and final-state leptons. Provided that Q^2 is sufficiently large it can be used as the hard scale needed for applying perturbative quantum chromodynamics (pQCD). Here we rather focus on the situation that the final-state lepton goes unobserved, and a single hadron is detected, i.e. $\ell\, N \to h\, X$. For such a process the transverse momentum of the hadron $P_{h\perp}$ can serve as a hard scale.

Using collinear QCD factorization and the leading order (LO) approximation, recently three twist-3 spin asymmetries were studied for this process, namely (i) the transverse single-spin asymmetry (SSA) (typically denoted by A_N) in $\ell\, N^{\uparrow} \to h\, X$ [1], (ii) the transverse SSA A_N in $\ell\, N \to \Lambda^{\uparrow}\, X$ [2], and (iii) the longitudinal-transverse double-spin asymmetry A_{LT} in $\vec{\ell}\, N^{\uparrow} \to h\, X$ [3]. The motivation to investigate these observables is at least fourfold:

1. Data exist for all three spin asymmetries. The HERMES Collaboration [4] and the Hall A Collaboration at Jefferson Lab (JLab) [5] measured A_N for $\ell\, N^{\uparrow} \to h\, X$. Moreover, HERMES took data for the production of transversely polarized Λ hyperons [6], while A_{LT} was measured at JLab [7]. One should try to understand those data and explore what one can learn from them. It is important, however, to keep in mind that $P_{h\perp}$ for many of these data is rather low ($< 1\,\mathrm{GeV}$) such that a pQCD approach becomes questionable.

2. The corresponding spin asymmetries in hadronic collisions have been studied extensively, where so far A_N for polarization in both the initial state and the final state has played the most important role — see for instance [8] for more information. It is challenging to describe the available data in pQCD [9, 10, 11]. Therefore, the asymmetries in lepton-nucleon scattering can be very valuable as they may give new insights into the case of hadron-hadron scattering.

3. The number of LO Feynman diagrams contributing to the spin asymmetries in $\ell\, N \to h\, X$ is rather small. This allows one to “easily" scrutinize the twist-3 framework by checking the gauge invariance and the frame-independence of the results. Also, one can streamline the calculations which in particular would be beneficial for a potential future NLO treatment.

4. It is important to fully explore the physics potential of these spin asymmetries. Especially a next-generation electron-ion collider (EIC) [12, 13] may be ideal in that regard as it would allow measurements at large $P_{h\perp}$ where the pQCD expansion should converge best.

The three spin asymmetries are discussed in the following sections. For collinear twist-3 factorization usually three non-perturbative components have to be taken into account: (i) collinear twist-3 two-parton correlation functions, (ii) effects due to transverse parton momenta in two-parton correlators, and (iii) collinear three-parton correlators. Sometimes final results can be simplified thanks to relations among the non-perturbative correlators like those following from QCD equations of motion. This happens, for instance, in the case of the “classic" twist-3 (double-) spin asymmetry A_{LT} in inclusive deep inelastic lepton-nucleon scattering which at LO can be entirely expressed through the well-known twist-3 quark-quark correlation function g_T.

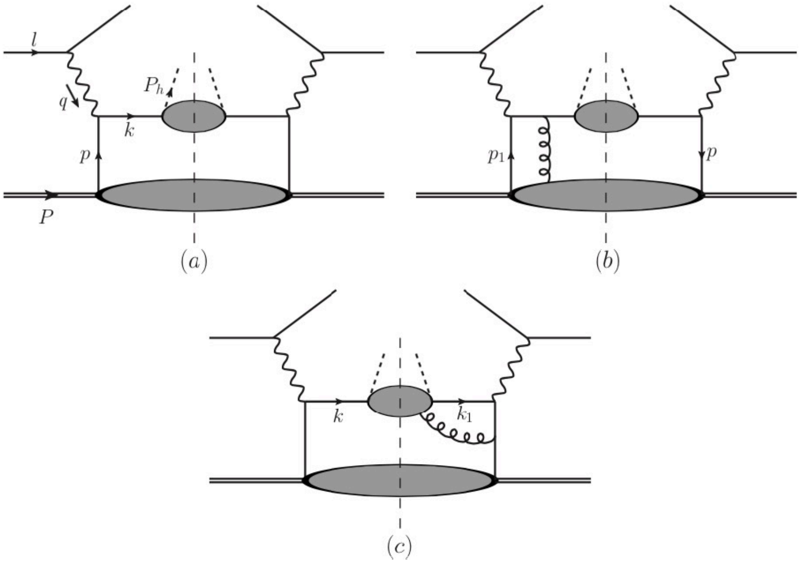

Figure 1: Leading order graphs contributing to twist-3 spin asymmetries in collinear factorization. The diagram (a) involves qq correlators (including transverse momentum effects), while diagrams (b), (c) (and their Hermitian conjugates) deal with qgq correlators.

2. Transverse single-spin asymmetry in $\ell\, N^{\uparrow} \to h\, X$

In Fig. 1, the LO diagrams for the spin-dependent cross section of the transverse SSA A_N in $\ell\, N^{\uparrow} \to h\, X$ are shown. (The same graphs contribute to the other two spin asymmetries.) The analytical result of the SSA $A_N^{\ell N^{\uparrow} \to h X}$ can be found in Ref. [1]. Generically it reads

$$A_N^{\ell N^{\uparrow} \to h X} \sim F_{FT} \otimes D_1 \otimes S_D + h_1 \otimes \left(\hat{H} \otimes S_F^{\hat{H}} + H \otimes S_F^{H} + \hat{H}_{FU}^{\Im} \otimes S_F^{\hat{H}_{FU}^{\Im}} \right), \qquad (2.1)$$

where only the structure of the numerator is given. The twist-3 effect of the asymmetry can arise from the distribution side (the transversely polarized nucleon), and the fragmentation side. The final result of the former is given by the twist-3 Qiu-Sterman (QS) function F_{FT} [14] which parameterizes a particular quark-gluon-quark (qgq) correlator of the nucleon. The QS function is convoluted with the ordinary twist-2 unpolarized fragmentation function D_1 and the hard scattering factor S_D. For the twist-3 fragmentation piece, a priori, three functions contribute that are convoluted with the twist-2 transversity distribution h_1 and the respective hard scattering factors: $\hat{H}$ (describing the transverse momentum dependence of the qq correlator), H (given by collinear twist-3 qq correlator), and $\hat{H}_{FU}^{\Im}$ (two-argument function, given by collinear twist-3 qgq correlator). Due to QCD equations of motion these functions are related according to [15, 1]

$$H(z) = -2z\hat{H}(z) + 2z^3 \int_z^{\infty} \frac{dz_1}{z_1^2} \frac{1}{\frac{1}{z} - \frac{1}{z_1}} \hat{H}_{FU}^{\Im}(z, z_1)\,. \qquad (2.2)$$

Now we briefly describe the input used in [1] for the various parton correlators in order to get an estimate of $A_N^{\ell N^{\uparrow} \to h X}$. In the case of F_{FT} we exploit a model-independent relation to the

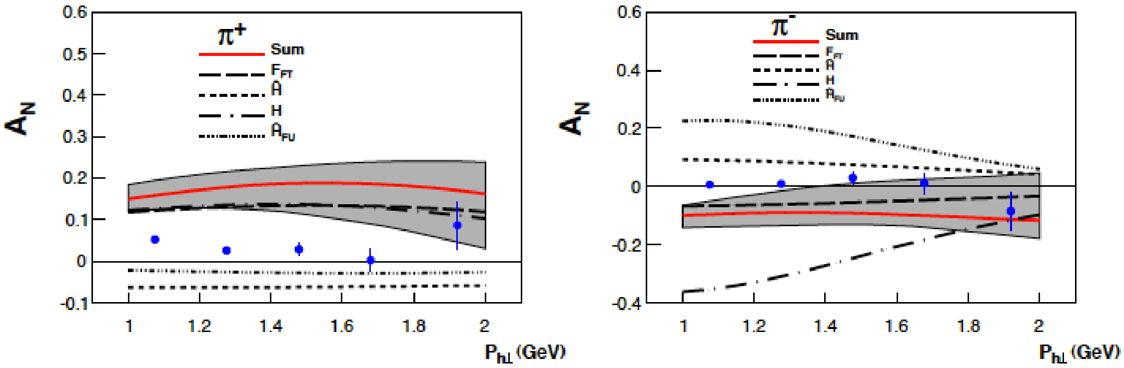

Figure 2: $A_N^{\ell N^\uparrow \to \pi X}$ as function of $P_{h\perp}$ for π^+ (left panel) and π^- (right panel) production for fixed value of the Feynman variable x_F and *cm* energy $\sqrt{S} = 7.25\,\text{GeV}$. Shown are the contributions associated with the various twist-3 functions, the sum of all contributions, and the error band due to statistical uncertainties of the extractions of $f_{1T}^\perp$, h_1, $H_1^\perp$. The data are from HERMES [4]. (See [1] for more details.)

Sivers function $f_{1T}^\perp$ [16], and take $f_{1T}^\perp$ from Ref. [17]. We take D_1 from [18] and h_1 from [19]. The function $\hat{H}$ has a model-independent relation to the Collins fragmentation function [20, 21, 15] for which we use the parameterization of Ref. [19]. The function $\hat{H}_{FU}^{\Im}$ is taken from [22], where it has been fitted to RHIC data for A_N in $p^\uparrow p \to \pi X$. By means of Eq. (2.2) the function H is then fixed. A nonzero $\hat{H}_{FU}^{\Im}$ — in particular through its contribution to H via (2.2) — is critical for the description of $A_N^{p^\uparrow p \to \pi X}$ in collinear twist-3 factorization [22]. Data on $A_N^{\ell N^\uparrow \to h X}$ may therefore, in principle, help to check the phenomenology given in Ref. [22].

In Fig. 2, numerical results for $A_N^{\ell N^\uparrow \to \pi X}$ are shown in comparison with HERMES data [4]. Obviously, the calculation does not agree well with the data. This discrepancy may have several causes. First, only the statistical uncertainties of the extractions of $f_{1T}^\perp$, h_1 and $H_1^\perp$ are taken into account. In particular the (presently unknown) uncertainties of $\hat{H}_{FU}^{\Im}$ (and hence of H) could be significant. Second, possibly the data on $A_N^{p^\uparrow p \to \pi X}$ cannot be described using collinear twist-3 factorization and the LO approximation, in contrast to the assumption of Ref. [22]. Third, higher order pQCD corrections may be very large, especially in the case of $A_N^{\ell N^\uparrow \to h X}$. A recent calculation of the unpolarized cross section for $\ell N \to h X$ indeed revealed large NLO contributions [23]. The impact of NLO corrections on $A_N^{\ell N^\uparrow \to \pi X}$ is presently unknown. Note that for the HERMES experiment even the events at the highest accessible $P_{h\perp}$ values are dominated by quasi-real photoproduction ($Q^2 \sim 0\,\text{GeV}^2$) [4]. On the contrary, in a LO calculation Q and $P_{h\perp}$ are comparable, implying that this framework does not cover the main production mechanism of pions for the kinematics of [4]. We also mention that HERMES has a subset of data with $Q^2 > 1\,\text{GeV}$ which compare reasonably well with our calculation — see Refs. [4, 1] for more discussion about these data.

As already pointed out above, an EIC [12, 13] will be ideal for studying $A_N^{\ell N^\uparrow \to h X}$. In Ref. [1] we made predictions for the production of π^+, π^-, π^0 and, generally, found effects ranging up to 10 %. For π^- production the impact of the twist-3 function $\hat{H}_{FU}^{\Im}$, whose role in the description of $A_N^{p^\uparrow p \to \pi X}$ is currently under debate, is significant — see Fig. 3. Moreover, we showed [1] that measurements at an EIC may also discriminate between the collinear twist-3 approach and the so-called Generalized Parton Model, which has also been used to compute $A_N^{\ell N^\uparrow \to h X}$ [24].

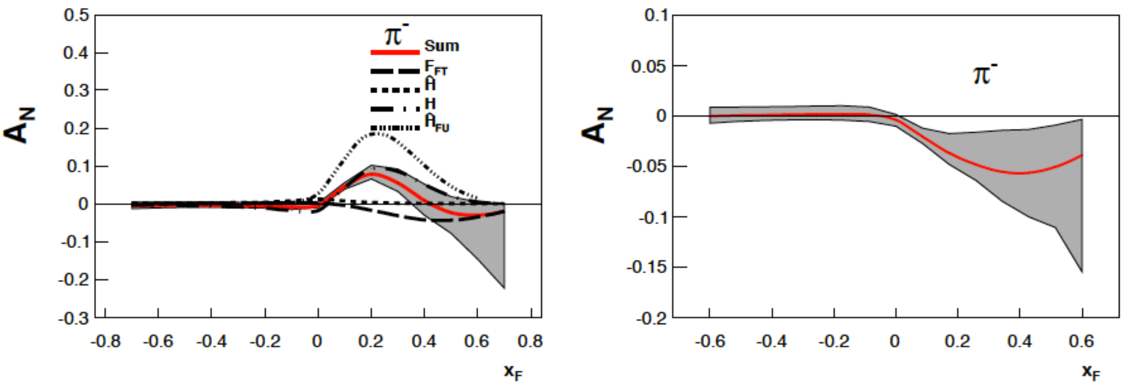

Figure 3: Prediction for $A_N^{\ell N^\uparrow \to \pi X}$ as function of x_F for π^- (left panel) and π^- (right panel with $\hat{H}_{FU}^{\Im} = 0$) production at $P_{h\perp} = 3\,\mathrm{GeV}$ for typical EIC kinematics ($\sqrt{S} = 63\,\mathrm{GeV}$).

3. Transverse single-spin asymmetry in $\ell\, N \to \Lambda^\uparrow\, X$

In Ref. [2], we analyzed the transverse SSA A_N for the production of polarized Λ hyperons, $\ell\, N \to \Lambda^\uparrow\, X$. Again both the twist-3 distribution and fragmentation terms were calculated. (For previous work on the distribution contribution we refer to [25]. See also [26] for closely related work.) We preformed all the calculations in the lightcone gauge as well as the Feynman gauge, and showed that the results are identical. This also provided a general cross-check of the twist-3 formalism for fragmentation, since the related earlier treatments of $A_N^{p^\uparrow p \to h X}$ and $A_N^{\ell N^\uparrow \to h X}$ discussed above used the lightcone gauge only [15, 1]. Currently there exists no numerical estimate of $A_N^{\ell N \to \Lambda^\uparrow X}$, mainly due to lacking information about twist-3 fragmentation functions that enter the asymmetry. The work in [2] contains the key ingredients needed for calculating hyperon polarization in hadronic collisions in collinear QCD factorization. Such a study would be a milestone in transverse spin physics given that the first pioneering measurements date back to the 1970s [27].

4. Longitudinal-transverse double-spin asymmetry in $\vec{\ell}\, N^\uparrow \to h\, X$

Using collinear factorization a complete (gauge invariant) LO result for the twist-3 double-spin asymmetry A_{LT} in $\vec{\ell}\, N^\uparrow \to h\, X$ was obtained in [3]. The calculation was performed in the lepton-nucleon *cm*-frame and in the nucleon-hadron *cm*-frame. Frame-independence of the final result could be achieved after applying the (so-called Lorentz invariance) relation [28, 29, 30, 31, 32]

$$g_T(x) = g_1(x) - 2 \int dx_1 \, \frac{1}{x - x_1} \, G_{DT}(x, x_1) \, , \tag{4.1}$$

between g_T, the quark helicity distribution g_1, and a particular two-argument function. The asymmetry $A_{LT}^{\vec{\ell} N^\uparrow \to h X}$ is very sensitive to the worm-gear function g_{1T}, one of the leading twist transverse momentum dependent quark distributions [33]. We made a comparison with data from JLab [7] by exploring two models for g_{1T} [3]. For one of the models we obtained qualitative agreement with the data. However, at present no definite conclusion can be drawn, since (1) the data have very low $P_{h\perp}$ ($< 0.7\,\mathrm{GeV}$), (2) only the twist-3 distribution term was included, and (3) higher order corrections were neglected. Note also that $A_{LT}^{\vec{\ell} N^\uparrow \to h X}$ decreases as the *cm*-energy of the reaction increases. Therefore, measurements at typical EIC energies don't seem favorable [3].

5. Summary and Conclusions

Twist-3 spin asymmetries in $\ell\, N \to h\, X$ may have considerable physics potential. For three of these asymmetries — arguably the most important ones — LO order results in collinear factorization have been obtained. While the twist-3 framework seems on safe ground, the phenomenology is at an early stage. There is sufficient motivation to further explore these observables. On the experimental side, new data would be very helpful, especially at larger $P_{h\perp}$ where the pQCD expansion converges best. On the theoretical side, NLO corrections need to be computed by extending the work in [23] to the twist-3 case.

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