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SIDIS measurements of higher-twist spin azimuthal asymmetries

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Summary. — We review measurements of higher-twist spin azimuthal asymmetries in SIDIS and discuss possibilities of extraction of underlying higher twist distribution functions using production of hadron pairs in the current fragmentation region.

PACS 13.60.-r – Photon and charged-lepton interactions with hadrons.
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1. – Introduction

In recent years, measurements of azimuthal moments of polarized hadronic cross sections in hard processes have emerged as a powerful tool to probe nucleon structure. Many experiments worldwide are currently trying to pin down various effects related to the nucleon structure through semi-inclusive deep-inelastic scattering (HERMES at DESY [1-4], COMPASS at CERN [5], Jefferson Lab [6-9]) polarized proton-proton collisions (PHENIX, STAR and BRAHMS at RHIC) [10-12], and electron-positron annihilation (Belle at KEK) [13, 14]. Azimuthal distributions of final state particles in semi-inclusive deep inelastic scattering, in particular, are sensitive to the orbital motion of quarks and play an important role in the study of transverse momentum distributions (TMDs) of quarks in the nucleon.

Significant azimuthal moments in leptoproduction ($A_{UU}^{\cos\phi}$) which have been measured in SIDIS already by EMC Collaboration [15,16], were reproduced by latest measurements at CERN, HERMES and JLab [8, 9, 17-20]. The first unambiguously measured single-spin phenomena in SIDIS, which triggered important theoretical developments, were the sizable longitudinal target ($A_{UL}^{\sin\phi}$) and beam ($A_{LU}^{\sin\phi}$) spin asymmetries observed at HERMES and JLab [1,2,4,6,7,21,22]. They could be interpreted in terms of higher twist distribution functions.

At twist-3, and before integration over transverse momentum, there are 16 distribution functions (see table I) for different combinations of target (rows in table I) and quark (columns in table I) polarizations. Only three functions survive integration over

TABLE I. – *Twist-3 transverse-momentum–dependent distribution functions. The U, L, T correspond to unpolarized, longitudinally polarized and transversely polarized nucleons (rows) and quarks (columns).*

N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	f_T, $f_T^{\perp}$	g_T, $g_T^{\perp}$	h_T, e_T, $h_T^{\perp}$, $e_T^{\perp}$

transverse momentum (collinear functions): e, h_L and g_T. Together with the twist-2 PDFs (f_1, g_1, h_1), they give a detailed picture of the nucleon in longitudinal momentum space. Higher-twist (HT) functions are of interest for several reasons. Most importantly they offer insights into the physics of the largely unexplored quark-gluon correlations which provide direct and unique insights into the dynamics inside hadrons, see, *e.g.*, [23]. They describe multiparton distributions corresponding to the interference of higher Fock components in the hadron wave functions, and as such have no probabilistic partonic interpretations. Yet they offer fascinating doorways to studying the structure of the nucleon. The third Mellin moment of the HT function e, for instance, describes the average transverse force acting on a transversely polarized quark in an unpolarized target after interaction with the virtual photon [24]. Recently Lorentz-invariant amplitudes related to all three collinear HT distributions have been extracted on lattice, confirming that HT distributions are large and comparable to unpolarized leading twist distribution f_1 [25].

HT contributions are also indispensable to correctly extract twist-2 parts from data. Understanding of azimuthal modulations due to HT effects (see fig. 1) may be crucial for flavor decomposition using the data which usually has significant non-uniformity in azimuthal angle and transverse momentum due to detector acceptances. In addition, even suppressed with respect to twist-2 observables by $1/Q$, twist-3 observables are not small in the kinematics of fixed target experiments. This is illustrated by the fact that the twist-3 asymmetry $A_{UL}^{\sin\phi}$ is a large and cleanly seen effect, while the twist-2 asymmetry $A_{UL}^{\sin 2\phi}$ seems to be smaller in the kinematics of HERMES, JLab, and COMPASS [1,2,22,26,27].

The theoretical description of twist-3 observables is challenging in single-hadron SIDIS. Although lots of effort was devoted to their study [28-41], these observables are still not understood. Partially, this has to do with the problem of formulating a TMD-factorization at twist-3 level [42,43]. The technical tools used to subtract light-cone divergences in leading order factorization proofs [44-47] cannot be straightforwardly carried over to the subleading twist case [42]. At present one has to *assume* TMD factorization at subleading twist in SIDIS. In addition even assuming TMD factorization holds in SIDIS at subleading twist, in the $1/Q$ expansion subleading structure functions receive 4–6 contributions: from the 16 twist-3 TMDs convoluted with the 2 twist-2 fragmentation functions, and from the 8 twist-2 TMDs convoluted with 4 (if unpolarized hadrons are produced) subleading twist fragmentation functions. Most of the subleading twist TMDs and fragmentation functions were introduced in [48] and some were supplemented in [39-41, 49-51]. Some HT structure functions are listed in eqs. (1)–(4):

$$F_{UU}^{\cos\phi_h} \propto \frac{M}{Q} \sum_a e_a^2 \left(f_1^a \tilde{D}^{\perp a} + h_1^{\perp a} \tilde{H}^a + f^{\perp a} D_1^a + h^a \, H_1^{\perp a} \right), \tag{1}$$

$$F_{LU}^{\sin\phi_h} \propto \frac{M}{Q} \sum_a e_a^2 \left(e^a \, H_1^{\perp a} + f_1^a \tilde{G}^{\perp a} + g^{\perp a} D_1^a + h_1^{\perp a} \tilde{E}^a \right), \tag{2}$$

$$F_{UL}^{\sin\phi_h} \propto \frac{M}{Q} \sum_a e_a^2 \left(h_L^a H_1^{\perp a} + g_1^a \tilde{G}^{\perp a} + f_L^{\perp a} D_1^a + h_{1L}^{\perp a} \tilde{H}^a \right), \tag{3}$$

$$F_{LL}^{\cos\phi_h} \propto \frac{M}{Q} \sum_a e_a^2 \left(e_L^a H_1^{\perp a} + g_1^a \tilde{D}^{\perp a} + g_L^{\perp a} D_1^a + h_{1L}^{\perp a} \tilde{E}^a \right). \tag{4}$$

Of special interest are the structure functions $F_{UL}^{\sin\phi_h}$ and $F_{LU}^{\sin\phi_h}$ in SIDIS with respectively longitudinally polarized nucleons and electrons which were measured at HERMES and JLab [1, 2, 4, 6, 7, 21, 22] and further data from Jefferson Lab and COMPASS are expected [20, 52]. Both structure functions were subject to numerous theoretical and phenomenological studies [28-37, 53-61], see also [39-41, 49, 51]. Nevertheless there is presently no satisfactory understanding which functions in (2), (3) contribute how much.

The TMDs e^a and $g^{\perp a}$ are pure twist-3 interaction-dependent quark-gluon correlators, *i.e.* $e^a = \tilde{e}^a$ and $g^{\perp a} = \tilde{g}^{\perp a}$ up to current quark mass terms, and hence vanish in the Wandzura-Wilczek–type approximation discussed above. This makes $F_{LU}^{\sin\phi_h}$ a particularly well suited observable to cleanly observe pure twist-3 effects. Forthcoming data [20, 52] will shed important light on the quark-gluon dynamics.

Understanding of quark-gluon dynamics is crucial for interpretation of upcoming SIDIS data from upgraded to 12 GeV Jefferson Lab, where studies of TMDs are one of main driving forces. Significantly higher, compared to JLab, P_T range accessible at JLAb12 would allow for studies of transverse momentum dependence of different distribution and fragmentation functions as well as transition from TMD regime to perturbative regime. Measurements of spin and azimuthal asymmetries as a function of the final hadron transverse momentum at JLab12 will extend (see fig. 2) measurements at JLAB [62] to significantly higher P_T. Much higher Q^2 range accessible at JLab12 with CLAS12 would allow for studies of Q^2-dependence of different higher twist spin-azimuthal

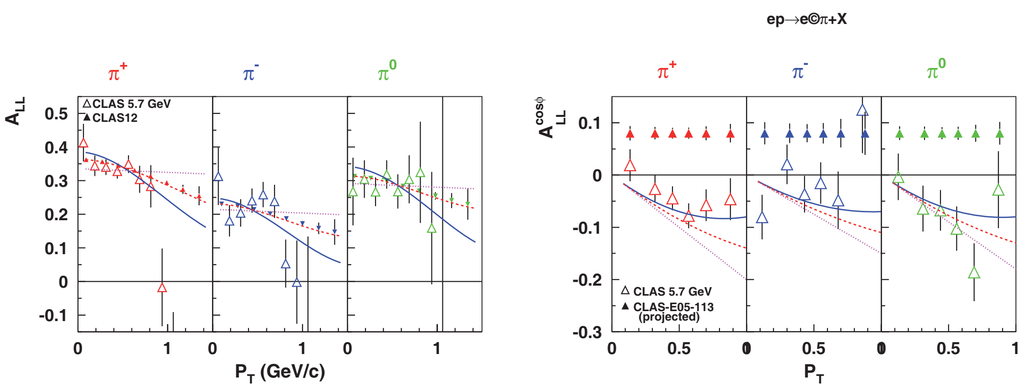

Fig. 1. – CLAS measurements of the double spin asymmetry (left) and the $\cos\phi$-moment of the double spin asymmetry. Projections for CLAS12 and new 6 GeV experiment are shown as well [63, 64].

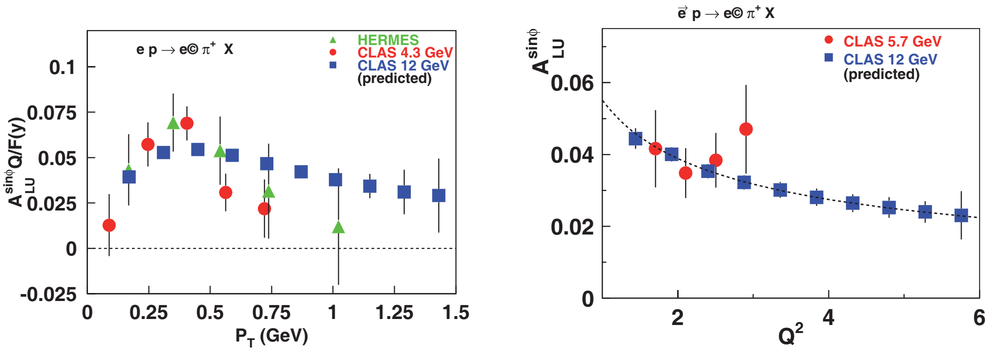

Fig. 2. – Projections for higher-twist lepton spin asymmetry $A_{LU}^{\sin\phi}$ for positive pion production as a function of P_T (left) and Q^2 (right) compared to published data from CLAS [6] and HERMES [4] and projected CLAS12 [62] in one x, z bin ($0.2 < x < 0.3$, $0.5 < z < 0.55$).

asymmetries (fig. 2), which, apart from providing important information on quark-gluon correlations are needed for understanding of possible corrections from higher twists to leading twist observables.

An important process which can provide independent information on twist-3 TMDs is the di-hadron production in SIDIS described by interference functions [65-71]. In fact, the measurement of single-spin asymmetries with longitudinally polarized target or beam is sensitive in particular to the twist-3 chiral-odd distribution functions e and h_L, in combination with the chiral-odd interference fragmentation function $H_1^{\sphericalangle}$ [69]. This effect survives after integration over quark transverse momenta and can be analyzed in the framework of collinear factorization. The dihadron production, thus, becomes a unique tool to study the higher-twist effects appearing as $\sin\phi$ modulations in target or beam spin-dependent azimuthal moments of the SIDIS cross section [72]. The interference fragmentation function $H_1^{\sphericalangle}$ has been used to obtain information on the transversity parton distribution function [73]. The JLab 12 GeV upgrade will provide the unique combination of wide kinematic coverage, high beam intensity (luminosity), high energy, high polarization, and advanced detection capabilities necessary to study the transverse momentum and spin correlations in di-hadron production in double-polarized semi-inclusive processes both in the target and current fragmentation regions.

The relevant spin asymmetries for $\ell(l) + N(P) \to \ell(l') + h_1(P_1) + h_2(P_2) + X$ can be built as ratios of structure functions. In the limit $M_h^2 \ll Q^2$ the structure functions for the longitudinal polarization of the beam or of the target (LU and UL) can be written in terms of PDF and Dihadron Fragmentation Functions (DiFF) [69]:

$$F_{UU,T} = x f_1^q(x)\, D_1^q\big(z, \cos\theta, M_h\big), \tag{5}$$

$$F_{LU}^{\sin\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q} \times\left[\frac{M}{M_h}\, x\, e^q(x) H_1^{\sphericalangle\, q}\big(z,\cos\theta, M_h\big) + \frac{1}{z}\, f_1^q(x)\, \widetilde{G}^{\sphericalangle\, q}\big(z,\cos\theta, M_h\big)\right], \tag{6}$$

$$F_{UL}^{\sin\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q} \times\left[\frac{M}{M_h}\, x\, h_L^q(x)\, H_1^{\sphericalangle\, q}\big(z,\cos\theta, M_h\big) + \frac{1}{z}\, g_1^q(x)\, \widetilde{G}^{\sphericalangle\, q}\big(z,\cos\theta, M_h\big)\right], \tag{7}$$

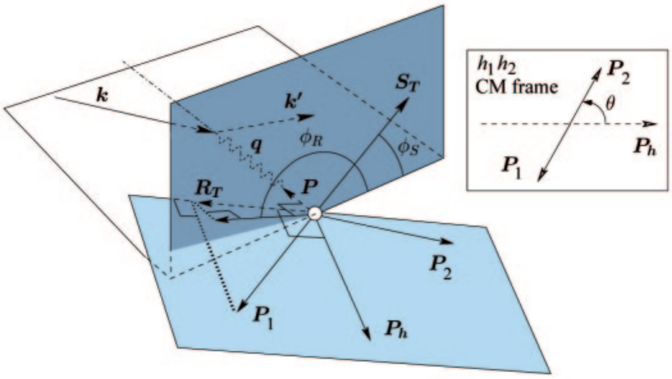

Fig. 3. – Depiction of the azimuthal angles ϕ_R of the dihadron and ϕ_S of the component $\boldsymbol{S}_T$ of the target-polarization transverse to both the virtual-photon and target-nucleon momenta $\boldsymbol{q}$ and $\boldsymbol{P}$, respectively. Both angles are evaluated in the virtual-photon-nucleon center-of-momentum frame. Explicitly, $\phi_R \equiv \frac{(\boldsymbol{q}\times\boldsymbol{k})\cdot\boldsymbol{R}_T}{|(\boldsymbol{q}\times\boldsymbol{k})\cdot\boldsymbol{R}_T|}\arccos\frac{(\boldsymbol{q}\times\boldsymbol{k})\cdot(\boldsymbol{q}\times\boldsymbol{R}_T)}{|\boldsymbol{q}\times\boldsymbol{k}||\boldsymbol{q}\times\boldsymbol{R}_T|}$ and $\phi_S \equiv \frac{(\boldsymbol{q}\times\boldsymbol{k})\cdot\boldsymbol{S}_T}{|(\boldsymbol{q}\times\boldsymbol{k})\cdot\boldsymbol{S}_T|}\arccos\frac{(\boldsymbol{q}\times\boldsymbol{k})\cdot(\boldsymbol{q}\times\boldsymbol{S}_T)}{|\boldsymbol{q}\times\boldsymbol{k}||\boldsymbol{q}\times\boldsymbol{S}_T|}$. Here, $\boldsymbol{R}_T = \boldsymbol{R} - (\boldsymbol{R}\cdot\hat{\boldsymbol{P}}_h)\hat{\boldsymbol{P}}_h$, with $\boldsymbol{R} \equiv (\boldsymbol{P}_1 - \boldsymbol{P}_2)/2$, $\boldsymbol{P}_h \equiv \boldsymbol{P}_1 + \boldsymbol{P}_2$, and $\hat{\boldsymbol{P}}_h \equiv \boldsymbol{P}_h/|\boldsymbol{P}_h|$, thus R_T is the component of P_1 orthogonal to P_h, and $\phi_{R\perp}$ is the azimuthal angle of R_T about the virtual-photon direction. The dotted lines indicate how vectors are projected onto planes. The short dotted line is parallel to the direction of the virtual photon. Also included is a description of the polar angle θ, which is defined as the angle between the direction of P_1 in the hadron pair center-of-mass frame, and the direction of P_h in the photon-target rest frame.

where all relevant angles are defined in fig. 3 [74, 75],

$$|\boldsymbol{R}| = \frac{1}{2}\sqrt{M_h^2 - 2(M_1^2 + M_2^2) + (M_1^2 - M_2^2)^2/M_h^2}. \tag{8}$$

In the above structure functions, there are three kinds of combinations of PDF and fragmentation functions (FF): leading-twist PDF and FF (*e.g.*, $f_1 D_1$), leading-twist PDF and subleading-twist FF (*e.g.*, $f_1 \widetilde{G}^{\sphericalangle}$), subleading-twist PDF and leading-twist FF (*e.g.*, $e H_1^{\sphericalangle}$).

The chiral-odd Dihadron Fragmentation Function $H_1^{\sphericalangle\, q}$ [67] describes the correlation between the transverse polarization of the fragmenting quark with flavor q and the azimuthal orientation of the plane containing the momenta of the detected hadron pair. The subleading-twist fragmentation function $\widetilde{G}^{\sphericalangle}$ originate from quark-gluon correlation functions on the fragmentation side. They vanish in the so-called Wandzura-Wilczek approximation [76]. The extraction of the e and h_L PDF is possible by the fact that $H_1^{\sphericalangle}$ has been recently extracted [73] from BELLE measurements [14].

To isolate the crucial quantities one can construct the following combination of asymmetries:

$$\begin{aligned}
&A_{ULU}^{\sin\phi_R \sin\theta}(x, y, z, M_h, Q) = \\
&A_{UL}^{\sin\phi_R \sin\theta}\,\frac{1}{4g_1^{u-\bar{u}}(x) - g_1^{d-\bar{d}}(x)} - A_{LU}^{\sin\phi_R \sin\theta}\,\frac{1}{4f_1^{u-\bar{u}}(x) - f_1^{d-\bar{d}}(x)} = \\
&\frac{M}{Q}\,\frac{1}{2}\sqrt{1 - 4\frac{m_\pi^2}{M_h^2}}\;\frac{x H_{1,sp}^{\sphericalangle,u}(z, M_h)}{D_1^u(z, M_h)\left[4f_1^{u+\bar{u}}(x) + f_1^{d+\bar{d}}(x)\right] + D_1^s(z, M_h)\, f_1^{s+\bar{s}}(x)} \\
&\quad\times\left\{\frac{W(y)}{A(y)}\,\frac{4e^{u-\bar{u}}(x) - e^{d-\bar{d}}(x)}{4f_1^{u-\bar{u}}(x) - f_1^{d-\bar{d}}(x)} - \frac{V(y)}{A(y)}\,\frac{4h_L^{u-\bar{u}}(x) - h_L^{d-\bar{d}}(x)}{4g_1^{u-\bar{u}}(x) - g_1^{d-\bar{d}}(x)}\right\},
\end{aligned} \tag{9}$$

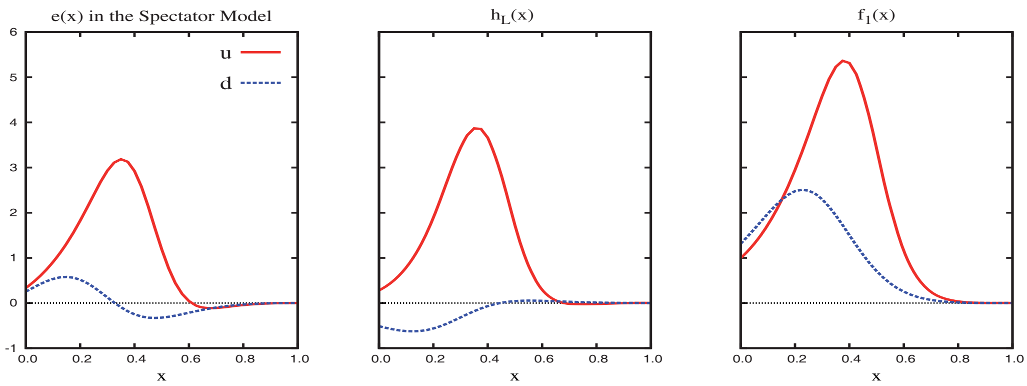

Fig. 4. – The function $e^q(x)$, $h_L^q(x)$, $f_1^q(x)$, for $q = u$ (solid red line) and $q = d$ (dotted blue line) in the spectator model of ref. [83].

where $H_{1,sp}^{\triangleleft q}$ is the component of $H_1^{\triangleleft q}$ that is sensitive to the interference between the fragmentation amplitudes into pion pairs in relative s wave and in relative p wave, from which comes the common name of Interference Fragmentation Functions [65]. The twist-3 PDFs $e(x)$ and $h_L(x)$ can be written in the following way [51, 77]

$$xe = x\tilde{e} + \frac{m}{M} f_1, \tag{10}$$

$$xh_L = x\tilde{h}_L + \frac{p_T^2}{M^2} h_{1L}^{\perp} + \frac{m}{M} g_{1L}. \tag{11}$$

The functions on the l.h.s. can be expressed in terms of quark fields only. This property allows an explicit calculation in quark models [78]. The functions with the tilde on the r.h.s. are related to quark-gluon-quark correlators and are specifically referred to as "pure twist-3" contributions [79]. The rest of each expression on the r.h.s. contains only twist-2 functions and corresponds to its Wandzura-Wilczek part. Neglecting quark masses, the function $xe(x)$ is entirely determined by pure twist-3 contributions. It has attracted a lot of interest [37] because it is directly related to the soft physics of chiral symmetry breaking [80]. The first Mellin moment of the isoscalar flavor-combination of $e^a(x)$ is related to the pion-nucleon sigma-term. The second moment of $e(x)$ is equally interesting, as it arises from the mass term in (10) suggesting that, in principle, an "extraction" of current quark masses from SIDIS is possible [78].

There are few model calculations concerning the twist-3 PDFs: MIT bag model [78, 81, 82], diquark spectator model [83], instanton QCD vacuum calculus [84, 85], chiral quark soliton model [57, 86-89], and the perturbative light-cone Hamiltonian approach to $\mathcal{O}(\alpha_S)$ with a quark target [90, 91]. In these calculations there are no contributions from either strange or sea quarks, except for the chiral quark soliton model. The contribution to $e(x)$ in the bag is entirely due to the bag boundary, and therefore to the quark-gluon-quark correlation. The results for the twist-3 PDF $e(x)$, $h_L(x)$, and the unpolarized $f_1(x)$ in the spectator model of ref. [83] are shown in fig. 4 for both the u and d flavor.

Measured single and double sub-leading twist asymmetries for pion and kaon pairs in a large range of kinematic variables (x, Q^2, z, M_h and ϕ_R) with unpolarized and longitudinally polarized targets, combined with similar measurements with single hadrons [63]

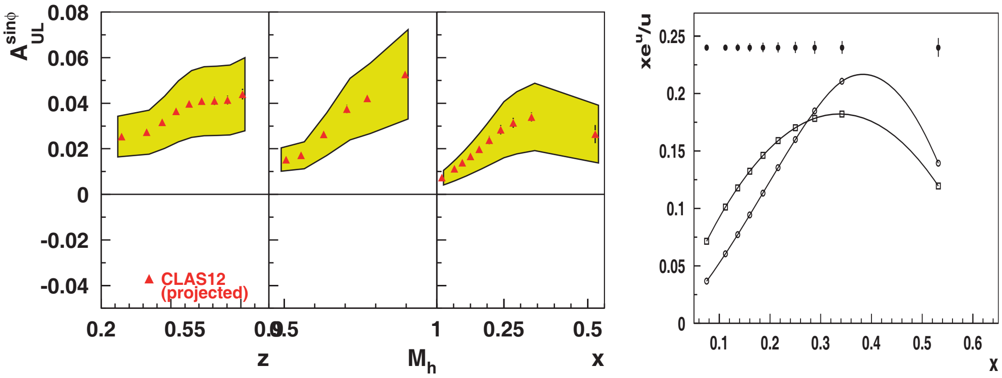

Fig. 5. – The projected statistical error for hydrogen target (30 days of NH_3) for the target asymmetry $A_{UL}^{\sin\phi_R \sin\theta}$ in $(z,\ M_h,\ x)$. The band represent the spread in predictions for two different models for $h_L(x)$. The (z, M_h)-dependence is deduced from the extracted DiFF. Right panel shows projection for reconstructed HT pdf e [72] and the curves are predictions from the bag model of ref. [78] and from the spectator model of ref. [83].

will provide detailed information on the flavor and polarization dependence of the HT distributions of quarks in the valence region, and in particular, on the x dependence of the HT functions e and h_L. Projections for the resulting kinematic dependence of the beam SSA for proton target are shown in fig. 5 for $\pi^+\pi^-$ pairs. The new data [72] will also allow a more precise test of the factorization ansatz and the investigation of the Q^2 dependence of $\sin\phi$, and $\cos\phi$ asymmetries. This will enable studies of the higher-twist nature of the corresponding observables [39, 40, 47, 49, 54, 78, 92].

2. – Summary

In recent years significant experimental, phenomenological and theoretical efforts have been made to understand the QCD beyond twist-2. Twist-3 functions describing multi-parton distributions corresponding to the interference of higher Fock components in the hadron wave functions, offer fascinating insights into the nucleon structure [24].

The formalism of DiFFs, based on collinear factorization with well-defined evolution equations, would allow to extract information on the twist-3 collinear pdfs $e(x)$ and $h_L(x)$. Measurements of hadron pairs in SIDIS at JLab12 will provide data on sub-leading asymmetries which would provide valuable insights, and especially provide an answer to the interesting question why subleading twist effects appear to be larger than leading twist effects ($A_{UU}^{\cos\phi}$ was larger than $A_{UU}^{\cos 2\phi}$ [16], $A_{UL}^{\sin\phi}$ was larger than $A_{UL}^{\sin 2\phi}$ [1]). JLab12 data, combined with the data from HERMES, COMPASS, and BELLE, will provide independent (complementary to e^+e^-) measurement of polarized and unpolarized pion and kaon DiFFs and will allow a complementary to pion SIDIS study of leading-twist distributions.

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