Azimuthal asymmetries at CLAS:
Extraction of $e^a(x)$ and prediction of $A_{UL}$

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Abstract

First information on the chirally odd twist-3 proton distribution function $e^a(x)$ is extracted from the azimuthal asymmetry, $A_{LU}$, in the electro-production of pions from deeply inelastic scattering of longitudinally polarized electrons off unpolarized protons, which has been recently measured by CLAS collaboration. Furthermore parameter-free predictions are made for azimuthal asymmetries, $A_{UL}$, from scattering of an unpolarized beam on a polarized proton target for CLAS kinematics.

1 Introduction

Experimental information on the chirally odd twist-3 proton distribution function $e^a(x)$ from deeply inelastic scattering (DIS) would provide not only insights into the twist-3 nucleon structure. The first moment of $e^a(x)$ is related to the pion-nucleon $\sigma$-term, which in turn is related to the strangeness content of the nucleon. Here one faces the so called "$\sigma$-term puzzle". Results from chiral perturbation theory and the value $\sigma \simeq (60 - 80)$ MeV extracted from pion-nucleon scattering data imply that around 10% of the nucleon mass is due to the strange quark. This contrasts the fact that strange quarks carry a negligible fraction of the nucleon momentum at say 1 GeV$^2$, the "typical hadronic scale" for nucleon set by the nucleon mass $M_N$.

Since $e^a(x)$ is a spin-average distribution, it can be accessed in experiments with unpolarized nucleons. However, due its chiral-odd nature and twist-3 character it can enter an observable only in connection with another chirally odd distribution or fragmentation function, and with a power suppression $M_N/Q$, where $Q$ is the hard scale of the process. So one is lead to study processes at moderate $Q$, to which $e^a(x)$ gives the leading contribution.

An observable, where $e^a(x)$ appears as leading contribution, is the azimuthal asymmetry $A_{LU}$ in pion electro-production from semi-inclusive DIS of polarized electrons off unpolarized protons. In this quantity $e^a(x)$ appears in connection with the chirally and T-odd twist-2 "Collins" fragmentation function $H_{1\perp}^a(z)$, which describes the left-right asymmetry in fragmentation of a transversely polarized quark of flavour $a$ into a hadron. In the HERMES experiment $A_{LU}$ was found consistent with zero within error bars. More recently, however, the CLAS collaboration reported the measurement of a non-zero $A_{LU}$ in a different kinematics.

So the CLAS data allow – under the assumption of factorization – an extraction of first experimental information on $e^a(x)$ from DIS, provided one knows $H_{1\perp}^a$. First experimental indications to $H_{1\perp}^a$ came from studies of $e^+e^-$-annihilation. The HERMES data on azimuthal asymmetries

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1 In $A_{XY}$ $X(Y)$ denotes beam (target) polarization, and one should take the values $U$ for unpolarized, $L$ for longitudinally polarized. We use the notation of \(F_{h\perp}\), with $H_{1\perp}^a(z)$ normalized to $\langle P_{h\perp} \rangle$ instead of $M_h$. 
$A_{UL}$ in pion electro-production from DIS [8, 9] provide further information on $H_1^+(z)$. In these asymmetries $H_1^+(z)$ enters in combination with the chirally odd twist-2 nucleon transversity distribution $h_1^q(x)$ [1, 2, 12], the twist-3 distribution $h_3^q(x)$ [1, 2], and quark transverse momentum weighted moments thereof [13]. In Ref. [13] $H_1^+(z)$ has been extracted from the HERMES data [8, 9], using for $h_1^q(x)$ and $h_3^q(x)$ predictions from the chiral quark soliton model [14] and the instanton model of the QCD-vacuum [15].

In this note we will use the information on $H_1^+(z)$ obtained in Ref. [13] to extract the twist-3 distribution $e^a(x)$ from the CLAS data [10]. Furthermore, we will predict azimuthal asymmetries $A_{UL}$ for CLAS, which are under current study.

2 The twist-3 distribution function $e^a(x)$

The twist-3 quark and antiquark distribution functions $e^q(x)$ and $e^\bar{q}(x)$ are defined as [1, 2]

$$e^q(x) = \frac{1}{2M_N} \int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle N| \bar{\psi}_a(0)\psi_a(\lambda x)|N \rangle, \quad e^{\bar{q}}(x) = e^q(-x) \quad (1)$$

where the insertion of the gauge-link is understood. The Q$^2$-evolution has been studied in Refs. [10, 17, 15]. In the multi-colour limit the evolution of $e^q(x)$ simplifies to a DGLAP-type evolution – as it does for the other two proton twist-3 distributions $h_1^q(x)$ and $g_2^q(x)$. The latter give a constraint on $e^a(x)$, the “twist-3 Soffer inequality”, as follows from [19]

$$e^a(x) \geq 2|g_2^q(x)| - h_1^a(x) \quad (2)$$

At small $x$ it behaves as, with some constants $c_k$,

$$e^a(x) \xrightarrow{x \rightarrow 0} c_1 x^{-0.04} + c_2 \delta(x) \quad (3)$$

The first term follows from Regge phenomenology $e(x) \approx x^{-(\alpha+1)}$. However the Pomeron residue is, as is known, non-spin-flip, and thus decouples from the chirally odd $e^a(x)$. Therefore the small $x$-behaviour of $e^a(x)$ is determined by the lowest lying spin flip trajectory, i.e. the one with the scalar meson $f_0(980)$. With the usual slope $\alpha' \approx 1$ GeV$^{-2}$ this yields a rise like $x^{-0.04}$. The constant $c_1$ in Eq. (3) is proportional to $m_q/M_N$ due to Eq. (6) below. The second term in Eq. (3), the possibility of a $\delta$-function at $x = 0$, has been recently discussed in Ref. [20].

The first moment of $(e^u + e^d)(x)$ is related to the pion-nucleon sigma-term

$$\int_{-1}^{1} dx \ (e^u + e^d)(x) = \frac{1}{2M_N} \langle N| (\bar{\psi}_u \psi_u + \bar{\psi}_d \psi_d) |N \rangle \equiv \frac{\sigma}{m_{av}}, \quad (4)$$

$$\sigma = \frac{m_{av}}{2M_N} \langle N| (\bar{\psi}_u \psi_u + \bar{\psi}_d \psi_d) |N \rangle = \begin{cases} (64 \pm 8) \text{MeV} \quad \text{Ref. [3]} \\ (79 \pm 7) \text{MeV} \quad \text{Ref. [4]}. \end{cases} \quad (5)$$

With the average mass of the light quarks $m_{av} \equiv \frac{1}{2} (m_u + m_d) \approx 5$ MeV one obtains

$$\int_{-1}^{1} dx \ (e^u + e^d)(x) \simeq (12 - 16) \quad (6)$$

However, considering Eq. (6), this does not necessarily imply that $(e^u + e^d)(x)$ itself is large. The second moment is proportional to the number of the respective valence quarks $N_q$ (for proton $N_u = 2$ and $N_d = 1$) and vanishes in the chiral limit [3]

$$\int_{-1}^{1} dx \ x e^q(x) = \frac{m_q}{M_N} N_q \quad (7)$$
A model estimate for quark distributions \( e^q(x) \) has been given in the framework of the bag model \([2, 21]\). At the estimated model scale of about 0.4 GeV the saturation of the “twist-3 Soffer inequality” \( \text{Eq. (2)} \) as \( e(x) = 2g_T(x) - h_L(x) \) has been observed \([24]\). The flavour index is dropped, since the quark distributions of Refs. \([2, 21]\) are flavour independent.

Finally we remark that the twist-3 quark distribution \( e^q(x) \) and the unpolarized twist-2 quark distribution \( f_1^q(x) \) coincide in the non-relativistic limit

\[
\lim_{\text{non relativistic}} e^q(x) = \lim_{\text{non relativistic}} f_1^q(x) = N_q \delta \left( x - \frac{1}{3} \right), \quad (8)
\]

in which the current quark mass in \( \text{Eq. (7)} \) is to be interpreted as the “constituent quark” mass \( m_q = \frac{1}{3} M_S \). The sum rule \( \text{Eq. (6)} \) is however strongly underestimated in this limit.

### 3 The Collins fragmentation function

The crucial ingredient for the extraction of the twist-3 distribution function \( e^q(x) \) from the azimuthal asymmetry \( A_{LL} \) is the knowledge of \( H_1^+(z) \).

This fragmentation function is responsible for a specific azimuthal asymmetry of a hadron in a jet around the axis in direction of the second hadron in the opposite jet due to transversal spin correlation of \( q \) and \( \bar{q} \). It was the measurement of this asymmetry, using the DELPHI data collection \([11]\), which provided first experimental indication to \( H_1^+ \). For the leading particles in each jet of two-jet events, averaged over \( z \) and \( k_T \) and over quark flavours, a “most reliable” (because less sensitive to the unestimated systematic error) value of the analyzing power of \( \left| \langle H_1^+ \rangle / \langle D_1 \rangle \right| = (6.3 \pm 2.0) \% \) was found. Using the whole available range of the azimuthal angle (and thus a larger statistics) the “more optimistic” (and also more sensitive to the systematic errors) value for the analyzing power

\[
\left| \langle H_1^+ \rangle / \langle D_1 \rangle \right| = (12.5 \pm 1.4) \% \quad \text{[DELPHI, extraction]} \quad (9)
\]

was found. The result \( \text{Eq. (8)} \) refers to the scale \( M_Z^2 \) and to an average \( z \) of \( \langle z \rangle \approx 0.4 \) \([11]\).

Combining the information \( \text{Eq. (1)} \) for \( H_1^+ \) with predictions for \( h_T^q(x) \) and \( h_L^q(x) \) from the chiral quark soliton model \([14]\) and the instanton model of the QCD-vacuum \([15]\), it was possible to describe well the HERMES data on the \( A_{UL} \) asymmetries \([8, 9]\) in a parameter-free approach \([13]\). For that a weak scale dependence of the analysing power \( \text{Eq. (1)} \) had to be assumed, which however is not supported by studies of Sudakov suppression effects \([22]\).

Furthermore, in Ref. \([13]\) – assuming the model predictions \([14, 17]\) for the proton chiral odd distributions – the \( z \)-dependence of the favoured pion fragmentation function \( H_1^+(z) \) has been deduced from HERMES data \([8, 9]\). The result refers to a scale of about 4 GeV\(^2\) and can be parametrized by a simple fit

\[
H_1^+(z) = a \, z \, D_1(z) \quad \text{with} \quad a = 0.33 \pm 0.06 \quad \text{for} \quad 0.2 \leq z \leq 0.7, \quad (10)
\]

\[
\langle H_1^+ \rangle / \langle D_1 \rangle = (13.8 \pm 2.8) \% \quad \text{for} \quad \langle z \rangle = 0.41 \quad \text{[HERMES, extraction]}, \quad (11)
\]

where \( D_1(z) \) is the favoured unpolarized pion fragmentation function. The errors in Eqs. \([10]\) are due to experimental error of HERMES data \([8, 9]\). The assumption of the predictions from \([14, 15]\) introduces a model dependence, which can be viewed as a “systematic error” and is estimated to be around 20%. The \( z \)-averaged value \( \text{Eq. (1)} \) is close to the DELPHI result \( \text{Eq. (8)} \), indicating that the ratio \( \langle H_1^+ \rangle / \langle D_1 \rangle \) might indeed depend on scale only weakly. Note also, that HERMES data favour clearly a positive sign for the analyzing power. It is noteworthy that a similar relation
between the favoured fragmentation functions \( H^+_1(z) \) and \( D_1(z) \) (even close numerically!) was found in a recent model calculation \[23\].

In order to estimate the analyzing power for the CLAS experiment we assume the result Eq. (10) to be valid up to \( z \leq 0.8 \), and to be only weakly scale dependent between HERMES \( \langle Q^2 \rangle = 4 \text{ GeV}^2 \) and CLAS \( \langle Q^2 \rangle = 1.5 \text{ GeV}^2 \) \[10\]. Due to the particular fit Eq. (10), the analyzing power is related to the average \( z \) of the experiment by \( \langle H^+_1 \rangle / \langle D_1 \rangle = a \langle z \rangle \) with the constant \( a \) from Eq. (10). For the CLAS experiment \[10\] we obtain

\[
\frac{\langle H^+_1 \rangle}{\langle D_1 \rangle} = (20 \pm 4)\% \text{ for } \langle z \rangle = 0.61 \text{ [CLAS, prediction].}
\]

4 The azimuthal asymmetry \( A^{\sin \phi}_{LU} \)

\( A^{\sin \phi}_{LU} \) in the CLAS experiment. In the CLAS experiment a longitudinally polarized 4.3 GeV electron beam was scattered off an unpolarized proton target. The cross sections \( \sigma(\pm) \) for the process \( ep \rightarrow e' \pi^+ X \) were measured in dependence of the azimuthal angle \( \phi \), i.e. the angle between the lepton scattering plane and the plane defined by the momentum \( q \) of the virtual photon and momentum \( P_h \) of the produced pion, see Fig. 1. The signs \( (\pm) \) refer to the longitudinal polarization of the electrons, with \( (+) \) if polarization parallel to beam direction, and \( (-) \) if anti-parallel. Let \( P (P_h) \) be the momentum of the incoming (proton, outgoing pion) and \( l (l') \) the momentum of the incoming (outgoing) electron. The relevant kinematical variables are center of mass energy square \( s := (P + l)^2 \), four momentum transfer \( q := l - l' \) with \( Q^2 := -q^2 \), invariant mass of the photon-proton system \( W^2 := (P + q)^2 \), and \( x, y \) and \( z \) defined by

\[
x := \frac{Q^2}{2Pq}, \quad y := \frac{2Pq}{s}, \quad z := \frac{P_h}{Pq}.
\]

(13)

In this notation the azimuthal asymmetry \( A^{\sin \phi}_{LU} (x) \) measured by CLAS is given by

\[
A^{\sin \phi}_{LU} (x) = \int dy \, dz \, d\phi \, \sin \phi \left( \frac{1}{S^{(+)}_e} \frac{d^4\sigma^{(+)}}{dx \, dy \, dz \, d\phi} - \frac{1}{S^{(-)}_e} \frac{d^4\sigma^{(-)}}{dx \, dy \, dz \, d\phi} \right) = \frac{1}{2} \int dy \, dz \, d\phi \left( \frac{d^4\sigma^{(+)}}{dx \, dy \, dz \, d\phi} + \frac{d^4\sigma^{(-)}}{dx \, dy \, dz \, d\phi} \right),
\]

(14)

where \( S^{(\pm)}_e \) denotes the electron polarization. When integrating over \( y \) and \( z \) the experimental cuts have to be considered \[10\]

\[
0.15 \leq x \leq 0.4, \quad 0.5 \leq y \leq 0.85, \quad 0.5 \leq z \leq 0.8, \\
1.0 \leq Q^2/\text{GeV}^2 \leq 3.0, \quad 2.0 \leq W/\text{GeV} \leq 2.6.
\]

(15)

\( A^{\sin \phi}_{LU} \) in theory. The cross sections entering the asymmetry \( A^{\sin \phi}_{LU} \) Eq. (14) have been computed in Ref. \[6\] at tree-level up to order \( 1/Q \). Assuming a Gaussian distribution of quark transverse momenta one obtains for the \( A^{\sin \phi}_{LU} \) asymmetry Eq. (14)

\[
A^{\sin \phi}_{LU} (x) = \frac{1}{\langle z \rangle \sqrt{1 + (P_{lu}^2) / (k^2)}} \int dy \, dy' \frac{\sqrt{1 - y} M_N / Q^5 \sum_a \epsilon^a x e^a(x) \langle H^+_{1/a} \rangle}{\langle D^+_{1/a} \rangle} \int dz \, dz' \frac{\sqrt{1 - y'} M_N / Q^5 \sum_b \epsilon^b z f^b(x) \langle D^+_{1/a} \rangle}{\langle D^+_{1/a} \rangle},
\]

(16)

Figure 1: Kinematics of the process \( ep \rightarrow e' \pi X \) in the lab frame.
where \( \langle P_{L,N}^2 \rangle \) denotes the mean square transverse momentum of quarks in the nucleon and \( \langle k_f^2 \rangle \) of the fragmenting quarks. The latter is related to the transverse momentum of the produced pion by \( \langle k_f^2 \rangle = \langle P_{L,N}^2 \rangle / \langle z^2 \rangle \). In the CLAS experiment \( \langle P_{L,N} \rangle = 0.44 \text{ GeV} \approx \langle R_N \rangle \). 

Eq. (14) assumes factorization to hold, and for that a large \( Q^2 \) is a necessary condition. Aside the general problem of factorization of \( p_T \)-dependent processes there is a subtle question is whether Eq. (14) can be applied to analyze the CLAS experiment where \( \langle Q^2 \rangle = 1.5 \text{ GeV}^2 \). Here we will assume that this can be done. This assumption will receive a certain justification, if our predictions on the asymmetries \( A_{UL} \) (see next section) will agree well with future CLAS data taken at comparably low \( \langle Q^2 \rangle \). However, one will not have a more definite answer on that, until future experiments performed at higher \( Q^2 \) will have constrained \( e^a(x) \) such that a comparison between results at the different scales – taking \( Q^2 \)-evolution into account – will be possible.

### The extraction of \( e^a(x) \) from preliminary CLAS data.

Using isospin symmetry and favoured flavour fragmentation

\[
D_1 \equiv D_1^{u/u^+} = D_1^{d/d^+} \gg D_1^{d/d^+} = D_1^{u/u^+} \simeq 0
\]  

and the same relations for \( H_{LL}^1 \), in the expression for the azimuthal asymmetry \( A_{UL}^{u/d} \) Eq. (13), we see that the CLAS data yield information on the flavour combination

\[
e(x) \equiv e^u(x) + \frac{1}{4} e^d(x).
\]

With the estimate of the analyzing power Eq. (12) and using for \( f_1^u(x) \) the parameterization of Ref. [24] we obtain the result for \( e(x) \) of Eq. (18) shown in Fig. 2. For comparison the corresponding flavour combinations of the twist-3 Soffer bound of Eq. (21) and the unpolarized distribution function \( f_1^u(x) \) are plotted in Fig. 2.

Note that the uncertainties of \( H_{LL}^1(z) \) in Eq. (14) – due to experimental error of HERMES data and theoretical assumptions in their analysis – affect the overall normalization of the extracted \( e(x) \). Its \( x \)-dependence, however, is entirely due to the CLAS data.

The extracted \( e(x) \) is clearly larger than our estimate of its twist-3 Soffer bound Eq. (2), about two times smaller than \( f_1^u(x) \) at the scale of 1.5 GeV\(^2\). The result indicates also that the large number in the sum rule Eq. (3) may require a significant contribution from the small \( x \)-region, which is interesting in the light of the predictions in Eq. (3).

It is worthwhile mentioning that the bag model result for \( e(x) \) of Ref. [21] (evolved according to naive power counting to the comparable scale of \( Q^2 = 1 \text{ GeV}^2 \)) is in qualitative agreement with the extracted \( e(x) \).

\(^2\) Whether these relations hold exactly or only approximately, depends on the chosen jet selection scheme, as does the question, whether \( (k_f^2) \) is a function of \( x \). Considering the large uncertainties on both experimental and theoretical side, a discussion of jet selection scheme dependence seems not appropriate here.

\(^3\) We use the “Wandzura-Wilczek approximations” \( g_T^u(x) = \int_x^1 d\xi g_T^u(\xi)/\xi \) and \( h_T^u(x) = 2x \int_1^1 d\xi h_T^u(\xi)/\xi^2 \). The neglect of the pure twist-3 \( h_T^u(x) \) and \( g_T^u(x) \) is justified in the instanton QCD vacuum model [13, 29]. For \( h_T^u(x) \) the model prediction [3] is used, for \( g_T^u(x) \) the parameterization of Ref. [24].
$A_{LU}^{\sin \phi}$ in the HERMES experiment. In the HERMES experiment the asymmetry $A_{LU}^{\sin \phi}$ has been measured with a longitudinally polarized 27.6 GeV positron beam in the kinematical range

$$0.23 \leq x \leq 0.4 , \quad 0.2 \leq y \leq 0.85 , \quad 0.2 \leq z \leq 0.7 , \quad 1 \leq Q^2/\text{GeV}^2 \leq 15 , \quad 2 \leq W/\text{GeV} ,$$

and the following, consistent with zero result for the totally integrated asymmetries found [8]

$$A_{LU}^{\sin \phi} (\pi^+)^{\text{HERMES}} = -0.005 \pm 0.008 \pm 0.004$$

$$A_{LU}^{\sin \phi} (\pi^-)^{\text{HERMES}} = -0.007 \pm 0.010 \pm 0.004 \quad [\text{HERMES}] .$$

In order to see that the CLAS [10] and HERMES [8] data are compatible we very roughly ’parameterize’ $e^0(x) \approx \frac{1}{2} f_0^q(x)$ at $\langle Q^2 \rangle = 1.5 \text{GeV}^2$. This estimate is consistent with CLAS data (for the flavour combination $(e^+ + \frac{1}{2} e^0)(x)$, see Fig. 2) and describes $e^0(x)$ sufficiently well for our purposes. We can assume this parameterization to be valid also at the scales in the HERMES experiment, since evolution effects are small compared to the crudeness of our ’parameterization’. This allows us to estimate $A_{LU}^{\sin \phi} (\pi^+) \approx 0.008$ and $A_{LU}^{\sin \phi} (\pi^-) \approx 0.007$ for HERMES kinematics, which is in agreement with the data in Eq. (20). We conclude that the $e^0(x)$ extracted from the CLAS experiment (Fig. 2) is not in contradiction with HERMES data [8].

5 Predictions for $A_{UL}$ asymmetries at CLAS

In the HERMES experiment the azimuthal asymmetries $A_{UL}^{\sin \phi}$ and $A_{UL}^{\sin 2\phi}$ in the production of charged [8] and neutral [1] pions from a proton target have been measured as functions of $x$ and $z$. For $\pi^+$ and $\pi^0$ sizeable $A_{UL}^{\sin \phi}$ asymmetries have been observed, while the other asymmetries have been found consistent with zero within error bars. In Ref. [13] the HERMES data [8, 1] has been well described in a parameter-free approach, using for $H_1^+ \perp$ the DELPHI result [11], see Eq. (9), and for proton transversity distributions the predictions from the chiral quark soliton model [14] and the instanton model of the QCD vacuum [15]. This approach has been used in Ref. [27] to predict $A_{UL}^{\sin \phi}$ asymmetries for a deuterium target. Here we predict $A_{UL}^{\sin \phi}$ and $A_{UL}^{\sin 2\phi}$ for pion production from a proton target for CLAS in an approach similar to Ref. [13], relying on the assumption that factorization holds at the energies of the CLAS experiment. For the CLAS kinematics, however, the DELPHI result [11] for $H_1^+ \perp$ Eq. (9) cannot be used, as it refers to a different $z$. Instead we use our estimate from Eq. (13). Our predictions are shown in Fig. 3, for beam energies of 4.25 GeV, 5.7 GeV and 12 GeV which are currently available or proposed for the CLAS experiment.

Fig. 3 demonstrates that the predicted CLAS asymmetries are as large as the asymmetries measured by HERMES [8, 1]. Thus, with the high luminosity of the CLAS experiment, a precise measurement $A_{UL}^{\sin \phi}$ and $A_{UL}^{\sin 2\phi}$ for $\pi^+$ and $\pi^0$ is probably possible. Moreover, the CLAS kinematics for the 12 GeV beam allows to observe the change of sign of the $A_{UL}^{\sin \phi} (x)$ asymmetries at $x \approx 0.5$. This change of sign is due to different signs of the twist-3 and twist-2 contributions. For the 5.7 GeV beam the $A_{UL}^{\sin \phi} (x)$ become zero close to the upper $x$-cut, which makes this phenomenon more difficult to observe. For HERMES kinematics the zero of $A_{UL}^{\sin \phi} (x)$ lies outside the covered $x$-range and is invisible [13, 27].

The $A_{UL}^{\sin \phi} (x)$ asymmetries for different pions cross each other in a single point, see Fig. 3. This interesting observation is due to the fact, that only two of the three cross sections for the production of $\pi^+, \pi^0$ and $\pi^-$ are “linearly independent” because of isospin symmetry and favoured

\footnote{For explicit expressions for the azimuthal asymmetries and further details see Refs. [1, 27, 28].}
flavour fragmentation. Thus, if two curves cross each other in some point, the third one necessarily goes through this point as well. The exact positions of this point and of the zero of $A_W^{UL}(x)$ depend on the beam energy and move to smaller $x$ with the energy growth. The experimental check of this prediction, especially at COMPASS energies, would give an argument in favour of the handbag mechanism of the asymmetry with different signs of twist-2 and twist-3 contributions.

Our predictions are based on the assumption that factorization holds at the scales $1 \text{GeV}^2 \leq Q^2 \leq 9 \text{GeV}^2$ covered in CLAS experiment \cite{10}. It will be exciting to learn from the comparison of these predictions to future CLAS data, to which extent factorization holds. In particular, this will give valuable indications on the correct interpretation of the data on the $A_{LU}$ asymmetry and the extraction of the twist-3 distribution function $e^a(x)$ given in the previous section.

6 Conclusions

We have presented the extraction of first information of the chirally odd proton twist-3 distribution function $e^a(x)$ from the azimuthal asymmetry $A_{LU}$ in $\pi^+$ electro-production from semi-inclusive DIS of polarized electrons off unpolarized protons, which has been recently measured by CLAS. The flavour combination $(e_u + \frac{1}{2}e_d)(x)$ extracted in the $x$-region $0.15 \leq x \leq 0.4$ refers to a scale of $1.5 \text{GeV}^2$ and is sizeable – roughly half the magnitude of the unpolarized distribution function at that scale. But it is not large enough to explain the large number for the first moment of $(e_u + e_d)(x)$, related to the pion nucleon sigma term, by contributions from valence $x$-regions alone.

The extraction relies on the assumption of factorization, which might be questioned at the $Q^2$ of the CLAS experiment. To test this assumption, we have predicted azimuthal asymmetries $A_{UL}$ in pion electro-production from DIS of unpolarized electrons off polarized protons for CLAS kinematics, which are under current study. The predictions are based on a parameter-free approach, which has been shown to describe well the corresponding data from the HERMES experiment. A successful comparison of these predictions to future CLAS data would support the assumption of applicability of factorization at the moderate scale.

For a definite clarification of the question, whether the CLAS data has been interpreted here correctly, we have to wait for data from future high luminosity (needed to resolve the twist-3 effect) experiments performed at scales where factorization is less questioned. Maybe COMPASS experiment at CERN could be one of them. Our predictions for COMPASS will be published elsewhere.
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