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

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(Received 28 February 2003; published 17 June 2003)

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

DOI: 10.1103/PhysRevD.67.114014 PACS number(s): 13.85.Ni, 13.60.Hb, 13.87.Fh, 13.88.+e

I. INTRODUCTION

Experimental information on the chirally odd twist-3 proton distribution function $e^a(x)$ [1,2] from deeply inelastic scattering (DIS) would provide valuable insight into the twist-3 structure of the nucleon. Being a spin-average distribution, $e^a(x)$ can be accessed in experiments with unpolarized nucleons. However, because of 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 naturally is led to study processes at moderate Q, to which $e^a(x)$ gives the leading contribution. An observable, where $e^a(x)$ appears as the leading contribution, is the azimuthal asymmetry A_{LU} in pion electroproduction from semi-inclusive DIS of polarized electrons off unpolarized protons [6–8].[1] In this quantity $e^a(x)$ appears in connection with the chirally and T-odd "Collins" fragmentation function $H_1^{\perp a}(z)$, which describes the left-right asymmetry in fragmentation of a transversely polarized quark of flavor a into a pion [6–9]. In the HERMES experiment A_{LU} was found consistent with zero within error bars [10,11]. More recently, however, the CLAS Collaboration reported the measurement of a nonzero A_{LU} in a different kinematics [12,13].

So the CLAS data [12,13] allow one—under the assumption of factorization—to extract experimental information on $e^a(x)$ from DIS, provided one knows $H_1^{\perp}$. The first experimental indications to $H_1^{\perp}$ came from studies of e^+e^- annihilation [14]. The HERMES data on azimuthal asymmetries A_{UL} in pion electroproduction from DIS [10,11] provide further information on $H_1^{\perp}(z)$. In these asymmetries $H_1^{\perp}(z)$ enters in combination with the chirally odd twist-2 nucleon transversity distribution $h_1^a(x)$ [1,2,15], the twist-3 distribution $h_L^a(x)$ [1,2], and quark transverse momentum weighted moments thereof [7]. In Ref. [16] $H_1^{\perp}(z)$ was extracted from the HERMES data [10,11], using for $h_1^a(x)$ and $h_L^a(x)$ predictions from the chiral quark soliton model [17] and the instanton model of the QCD vacuum [18].

In this note we use the information on $H_1^{\perp}(z)$ obtained in Ref. [16] to extract information on the twist-3 distribution $e^a(x)$ from the CLAS data [12,13]. We estimate that the CLAS and HERMES results for A_{LU} are not in contradiction with each other. Furthermore, we predict azimuthal asymmetries A_{UL} for CLAS, which are under current study.

II. 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]

$$e^q(x)=\frac{1}{2M_N}\int\frac{d\lambda}{2\pi}e^{i\lambda x}\langle N|\bar{\psi}_q(0)[0,\lambda n]\psi_q(\lambda n)|N\rangle,$$
$$e^{\bar{q}}(x)=e^q(-x), \tag{1}$$

where $[0,\lambda n]$ is the gauge link and n a lightlike vector. The Q^2 evolution of $e^a(x)$ has been studied in Refs. [19–21]. In the multicolor limit the evolution of $e^a(x)$ simplifies to a Dokshitzer-Gribov-Lipatov-Altarelli-Parisi- (DGLAP)-type evolution—as it does for the other two proton twist-3 distribution functions $h_L^a(x)$ and $g_T^a(x)$. In Ref. [22] the following constraint on $e^a(x)$ was given:[2]

[1]In A_{XY} the $X(Y)$ denotes beam (target) polarization. U means the unpolarized and L the longitudinally (with respect to the virtual photon momentum) polarized case. We use the notation of [6–8], with $H_1^{\perp}(z)$ normalized to $\langle P_{h\perp}\rangle$ instead of M_h.

[2]Let us stress that strictly speaking the inequality in Eq. (2) could be justified only if the "twist-2 (Soffer) inequality" $2|h_1^a(x)|\leq(f_1^a+g_1^a)(x)$ of Ref. [22] were saturated [23]. In the following we will refer to the relation (2) as "twist-3 lower bound," keeping in mind that it does not need to hold in general. In Ref. [24] a bound based on the positivity of the hadronic tensor and the Callan-Gross relation (and formulated in terms of structure functions) was discussed.

$$e^a(x) \geqslant 2|g_T^a(x)| - h_L^a(x). \tag{2}$$

At small x it behaves as (see Ref. [23] for a more detailed discussion)

$$e^a(x) \overset{x\to 0}{\longrightarrow} c_1 x^{-0.04} + c_2 \delta(x), \tag{3}$$

with some constants c_k. 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 behavior 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. (8) below. The second term in Eq. (3), the possibility of a δ function at $x=0$, has been recently discussed in Refs. [23,25].

The first moment of $(e^u+e^d)(x)$ is related to the pion-nucleon sigma term $\sigma_{\pi N}$:

$$\int_{-1}^{1} dx (e^u + e^d)(x) = \frac{\sigma_{\pi N}}{m_{\rm av}}, \tag{4}$$

where $m_{\rm av}$ denotes the average mass of light quarks and

$$\sigma_{\pi N} = \frac{m_{\rm av}}{2M_N} \langle N | (\bar{\psi}_u \psi_u + \bar{\psi}_d \psi_d) | N \rangle. \tag{5}$$

The pion-nucleon sigma term cannot be measured. However, low energy theorems allow one to extract the value of the corresponding form factor at the so-called Cheng-Dashen point $t = 2m_\pi^2$ from pion-nucleon scattering amplitudes:

$$\sigma(2m_\pi^2) = \begin{cases} (64\pm 8) \ \text{MeV} & \text{Ref. [3]}, \\ (79\pm 7) \ \text{MeV} & \text{Ref. [4]}. \end{cases} \tag{6}$$

The difference $\sigma(2m_\pi) - \sigma(0)$ [where $\sigma(0) \equiv \sigma_{\pi N}$] has been calculated in a dispersion-theoretical approach using chiral symmetry constraints and found to be 15 MeV [5]. With $m_{\rm av} \approx 5$ MeV we obtain

$$\int_{-1}^{1} dx (e^u + e^d)(x) \approx 10. \tag{7}$$

However, considering Eq. (3), this does not necessarily imply that $(e^u+e^d)(x)$ itself is large.

The second moment is proportional to the number of respective valence quarks N_q (for the proton $N_u = 2$ and $N_d = 1$) and vanishes in the chiral limit [2]

$$\int_{-1}^{1} dx\, x e^q(x) = \frac{m_q}{M_N} N_q. \tag{8}$$

It should be stressed that the sum rules (4), (8) are exact. In particular, no interaction dependent ("pure twist-3") functions are neglected (see Ref. [2] for a detailed discussion).

Model estimates for $e^a(x)$ have been given in the bag model [2,26] and the chiral quark-soliton model [27]. In the bag model, at an estimated low scale of about 0.4 GeV, the saturation of the "twist-3 lower bound" (2) as $e^a(x) = 2g_T^a(x) - h_L^a(x)$ was observed [26] [in the bag model $2h_1^a(x) = (f_1^a + g_1^a)(x)$ holds; see footnote 2]. Both the bag model and the chiral quark soliton model predict $e^a(x)$ to have a sizable valencelike structure at the corresponding low scales.

Finally, we mention that the twist-3 quark distribution $e^q(x)$ and the unpolarized twist-2 quark distribution $f_1^q(x)$ coincide in the nonrelativistic limit [23]

$$\lim_{\text{non relativistic}} e^q(x) = \lim_{\text{non relativistic}} f_1^q(x) = N_q \delta\left(x - \frac{1}{3}\right). \tag{9}$$

In that limit the current quark mass in Eq. (8) is to be interpreted as the "constituent quark" mass $m_q = \frac{1}{3} M_N$. The sum rule (7) is, however, strongly underestimated in this limit.

III. THE COLLINS FRAGMENTATION FUNCTION

The crucial ingredient for the extraction of the twist-3 distribution function $e^a(x)$ from the azimuthal asymmetry A_{LU} measured by CLAS is the knowledge of the Collins fragmentation function $H_1^\perp$. In this section we will first give a brief overview of what is presently known on this function from the DELPHI and HERMES experiments. Relying on this information we will make an estimate of $H_1^\perp$ for the kinematics of the CLAS experiment.

The fragmentation function $H_1^\perp$ is responsible for a specific azimuthal asymmetry of a hadron in a jet around the axis in the direction of the second hadron in the opposite jet due to transverse spin correlation of q and $\bar{q}$. It was the measurement of this asymmetry, using the DELPHI data collection [14], which provided the first experimental indication of $H_1^\perp$. For the leading particles in each jet of two-jet events, averaged over z and $\mathbf{k}_\perp$ and over quark flavors, a "most reliable" (because less sensitive to the unestimated systematic error) value of the analyzing power of $|\langle H_1^\perp \rangle / \langle D_1 \rangle| = (6.3 \pm 2.0)\%$ 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

$$\left| \frac{\langle H_1^\perp \rangle}{\langle D_1 \rangle} \right| = (12.5 \pm 1.4)\% \quad \text{(DELPHI, extraction)} \tag{10}$$

was also reported. The result in Eq. (10) refers to the scale M_Z^2 and to an average z of $\langle z \rangle \simeq 0.4$ [14].

Combining the information (10) for $H_1^\perp$ with predictions for $h_1^a(x)$ and $h_L^a(x)$ from the chiral quark-soliton model [17] and the instanton model of the QCD vacuum [18], it was possible to describe well the HERMES data on the A_{UL}

asymmetries [10,11] in a parameter-free approach [16]. For that a weak scale dependence of the analyzing power (10) had to be assumed.[3]

Furthermore, in Ref. [16]—assuming the model predictions [17,18] for the proton chiral-odd distributions—the z dependence of the favored pion fragmentation function $H_1^\perp(z)$ for $0.2\leqslant z\leqslant 0.7$ was deduced from HERMES data [10,11]. The result refers to a scale of about 4 GeV^2 and can be parametrized in terms of the favored unpolarized pion fragmentation function $D_1(z)$ as

$$H_1^\perp(z)=azD_1(z), \quad a=0.33\pm0.06, \tag{11}$$

$$\frac{\langle H_1^\perp\rangle}{\langle D_1\rangle}=(13.8\pm2.8)\% \quad (\text{HERMES, extraction}). \tag{12}$$

The result in Eq. (12) refers to $\langle z\rangle=0.41$. The errors in Eqs. (11), (12) are due to the experimental error of the HERMES data [10,11]. The use of the predictions for the proton transversity distribution functions from [17,18] introduces a model dependence into Eqs. (11), (12), which can be viewed as a "systematic error" and estimated to be around 20%. The z-averaged value in Eq. (12) is close to the DELPHI result in Eq. (10), indicating that the ratio $\langle H_1^\perp\rangle/\langle D_1\rangle$ might indeed depend on scale only weakly. Note also that the HERMES data clearly favor a positive sign for the analyzing power. It is noteworthy that a similar relation between the favored fragmentation functions $H_1^\perp(z)$ and $D_1(z)$ (even close numerically) was found in a recent model calculation [29].

In order to estimate the analyzing power $\langle H_1^\perp\rangle/\langle D_1\rangle$ for the kinematics of the CLAS experiment we assume the relation found in Eq. (11) to depend only weakly on scale between HERMES $\langle Q^2\rangle=2.5$ GeV^2 and CLAS $\langle Q^2\rangle=1.5$ GeV^2 (and to be valid up to a somewhat larger $z\leqslant0.8$). For the kinematics of the CLAS experiment ($0.5\leqslant z\leqslant0.8$ and $\langle z\rangle=0.61$ [12,13]) we obtain in this way

$$\frac{\langle H_1^\perp\rangle}{\langle D_1\rangle}=(20\pm4)\% \quad (\text{CLAS, estimate}). \tag{13}$$

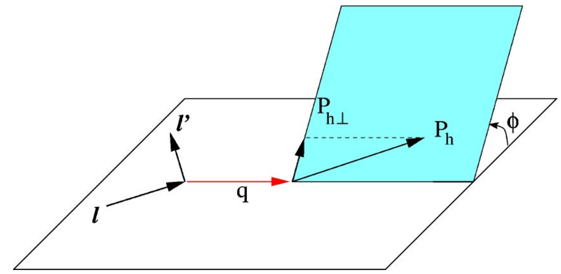

FIG. 1. Kinematics of the process $ep\to e'hX$ in the lab frame.

We will use the result (13) in the next section to gain information on $e^a(x)$ from the CLAS data.

IV. THE AZIMUTHAL ASYMMETRY $A_{LU}^{\sin\phi}$

A. $A_{LU}^{\sin\phi}$ 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 $\vec{e}p\to e'\pi^+X$ were measured in dependence on the azimuthal angle ϕ, i.e., the angle between the lepton scattering plane and the plane defined by the momentum $\mathbf{q}$ of the virtual photon and the momentum $\mathbf{P}_h$ of the pion produced (see Fig. 1). The signs $(\pm)$ refer to the longitudinal polarization of the electrons, with $(+)$ if the polarization is parallel to the beam direction and $(-)$ if antiparallel. 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 the center of mass energy squared $s:=(P+l)^2$, 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

$$x:=\frac{Q^2}{2Pq}, \quad y:=\frac{Pq}{Pl}, \quad z:=\frac{PP_h}{Pq}. \tag{14}$$

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

$$A_{LU}^{\sin\phi}(x)=\frac{\int dydzd\phi\sin\phi[(1/S_e^{(+)})d^4\sigma^{(+)}/dxdydzd\phi-(1/S_e^{(-)})d^4\sigma^{(-)}/dxdydzd\phi]}{\frac{1}{2}\int dydzd\phi(d^4\sigma^{(+)}/dxdydzd\phi+d^4\sigma^{(-)}/dxdydzd\phi)}, \tag{15}$$

where $S_e^{(\pm)}$ denotes the modulus of the electron polarization. When integrating over y and z the experimental cuts have to be considered [12,13]:

$$0.15\leqslant x\leqslant0.4, \quad 0.5\leqslant y\leqslant0.85, \quad 0.5\leqslant z\leqslant0.8,$$

$$1.0\leqslant Q^2/\text{GeV}^2\leqslant3.0, \quad 2.0\leqslant W/\text{GeV}\leqslant2.6. \tag{16}$$

B. $A_{LU}^{\sin\phi}$ in theory

The cross sections entering the asymmetry $A_{LU}^{\sin\phi}$ (15) have been computed in Refs. [7,8] at the tree level up to order $1/Q$. Assuming a Gaussian distribution of quark transverse momenta one obtains, for the $A_{LU}^{\sin\phi}$ asymmetry in Eq. (15),

[3]Such an assumption, however, seems not to be supported by studies of Sudakov suppression effects [28].

$$A_{LU}^{\sin\phi}(x) = \frac{1}{\langle z\rangle\sqrt{1+\langle \mathbf{P}_{\mathrm{N}\perp}^2\rangle/\langle \mathbf{k}_\perp^2\rangle}} \times \frac{\int dy 4y\sqrt{1-y}M_N/Q^5 \sum_a e_a^2 x^2 e^a(x)\langle H_1^{\perp a}\rangle}{\int dy(1+(1-y)^2)/Q^4 \sum_b e_b^2 x f_1^b(x)\langle D_1^b\rangle}, \quad (17)$$

where $\langle \mathbf{P}_{\mathrm{N}\perp}^2\rangle$ denotes the mean square transverse momentum of quarks in the nucleon and $\langle \mathbf{k}_\perp^2\rangle$ that of the fragmenting quarks. The latter is related to the transverse momentum of the pion produced by[4] $\langle \mathbf{k}_\perp^2\rangle = \langle \mathbf{P}_{h\perp}^2\rangle/\langle z^2\rangle$. In the CLAS experiment $\langle P_{h\perp}\rangle = 0.44$ GeV$\approx\langle P_{\mathrm{N}\perp}\rangle$ [12,13].

Equation (17) assumes factorization to hold, and for that a large Q^2 is a necessary condition. Apart from the general problem of factorization of transverse momentum dependent processes there is a subtle question of whether Eq. (17) can be applied to analyze the CLAS experiment where $\langle Q^2\rangle = 1.5$ GeV^2 [12,13]. Here we assume that this can be done. This assumption would receive a certain justification, if our predictions on the asymmetries A_{UL} (see the next section) agreed well with future CLAS data taken at comparably low $\langle Q^2\rangle$. We will have a more definite answer on that, however, only after future experiments performed at higher Q^2 (e.g., COMPASS) have constrained $e^a(x)$ such that a comparison between results at the different scales—taking Q^2 evolution into account—is possible.

C. The extraction of $e^a(x)$ from CLAS data

Using isospin symmetry and favored flavor fragmentation

$$D_1 \equiv D_1^{u/\pi^+} = D_1^{\bar{d}/\pi^+} \gg D_1^{d/\pi^+} = D_1^{\bar{u}/\pi^+} \simeq 0, \quad (18)$$

and the same relations for $H_1^\perp$, in the expression (17) for the azimuthal asymmetry $A_{LU}^{\sin\phi}$, we see that the CLAS data yield information on the flavor combination

$$e(x) \equiv e^u(x) + \frac{1}{4}e^{\bar{d}}(x). \quad (19)$$

With the estimate of the analyzing power (13) and using the parametrization of Ref. [30] for $f_1^a(x)$, we extract from the CLAS data [13] the result for $e(x)$ shown in Fig. 2. For comparison the corresponding flavor combinations of the "twist-3 lower bound"[5] of Eq. (2) and the unpolarized distribution function $f_1^a(x)$ are plotted in Fig. 2. We stress that the comparison is for illustrative purposes: The "twist-3 lower bound" (2) does not hold in general (see footnote 2) and $e^q(x)$ and $f_1^q(x)$ are related to each other only in the nonrelativistic limit [where they coincide; see Eq. (9)].

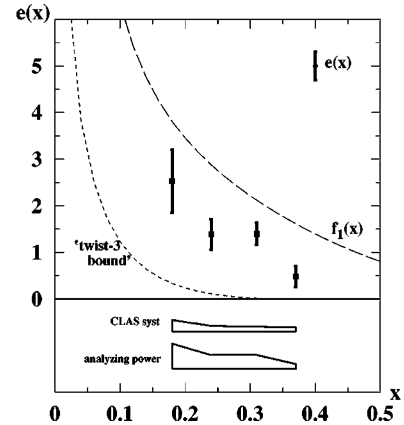

FIG. 2. The combination $e(x) = [e^u + (1/4)e^{\bar{d}}](x)$ extracted from CLAS data [13] vs x at $\langle Q^2\rangle = 1.5$ GeV^2. The error bars are due to the statistical error of the data, and the bands show the systematic errors due to the CLAS data and the uncertainty of the analyzing power in Eq. (13). For didactic comparison the corresponding flavor combinations of $f_1^a(x)$ and the "twist-3 lower bound" (though it does not hold in general; see footnote 2) are shown at $Q^2 = 1.5$ GeV^2.

Note that the uncertainties of $H_1^\perp(z)$ in Eq. (11)—due to the experimental error of the 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 bound" (2), and about two times smaller than $f_1^a(x)$ at the scale of 1.5 GeV^2. The result indicates also that the large number in the sum rule (7) may require a significant contribution from the small x region, which is interesting in the light of the predictions in Eq. (3). When comparing the model predictions [2,27] to the extracted result one has to keep in mind that the model results refer to low scales. It is worthwhile mentioning that the bag model result for $e(x)$ of Ref. [26] (evolved according to naive power counting to the comparable scale of $Q^2 = 1$ GeV^2) is in qualitative agreement with the extracted $e(x)$.

D. $A_{LU}^{\sin\phi}$ 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

$$0.023 \leq x \leq 0.4, \quad 0.2 \leq y \leq 0.85, \quad 0.2 \leq z \leq 0.7,$$

$$1 \leq Q^2/\mathrm{GeV}^2 \leq 15, \quad 2 \leq W/\mathrm{GeV}. \quad (20)$$

[4]Whether these relations hold exactly or only approximately depends on the chosen jet selection scheme, as does the question, whether $\langle \mathbf{k}_\perp^2\rangle$ is a function of z. Considering the large uncertainties on both the experimental and theoretical sides, a discussion of jet selection scheme dependence seems not appropriate here.

[5]We use the "Wandzura-Wilczek (type) approximations" $g_T^a(x) = \int_x^1 d\xi g_1^a(\xi)/\xi$ and $h_L^a(x) = 2x\int_x^1 d\xi h_1^a(\xi)/\xi^2$ which are justified by results from the instanton QCD vacuum model [18,31]. For $h_1^a(x)$ we use the model prediction [17] and for $g_1^a(x)$ the parametrization of Ref. [32].

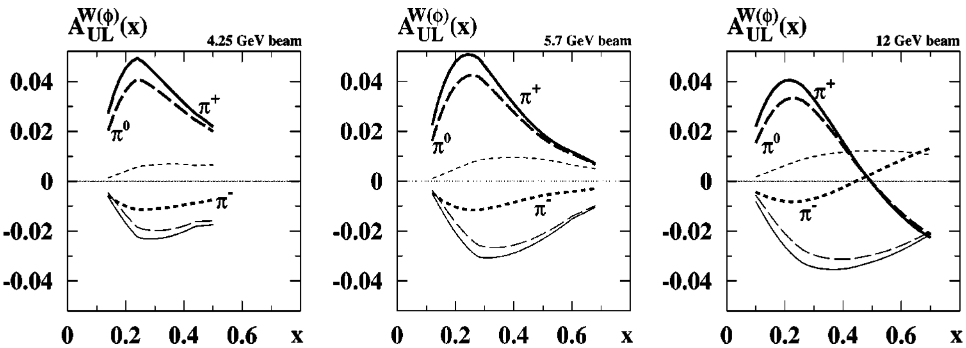

FIG. 3. Predictions for azimuthal asymmetries $A_{UL}^{W(\phi)}(x)$ vs x for different beam energies and the corresponding kinematical cuts at CLAS (with the convention that positive target polarization is opposite to beam momentum). The thick lines correspond to $W(\phi) = \sin\phi$, the thin lines correspond to $W(\phi) = \sin 2\phi$. Hereby solid lines refer to π^+, long-dashed lines to π^0, and short-dashed lines to π^-.

The following results, consistent with zero, for the totally integrated asymmetries were found [10]:

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

$$A_{LU}^{\sin\phi}(\pi^-)_{\rm HERMES} = -0.007 \pm 0.010 \pm 0.004. \qquad (21)$$

In order to see that the HERMES [10] and CLAS [12,13] data are compatible we very roughly "parametrize" $e^a(x) \approx (1/2) f_1^a(x)$ at $\langle Q^2 \rangle = 1.5\ \text{GeV}^2$. This estimate is consistent with CLAS data [for the flavor combination $(e^u + (1/4) e^{\bar{d}})(x)$; see Fig. 2] and describes $e^a(x)$ sufficiently well for our purposes. We can assume this parametrization to be valid also at the scales in the HERMES experiment, since evolution effects are small compared to the crudeness of our "parametrization." 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. (21). We conclude that the $e^a(x)$ extracted from the CLAS experiment (Fig. 2) is not in contradiction with HERMES data [10].

V. 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 [10] and neutral [11] pions from a proton target have been measured as functions of x and z. For π^+ and π^0 sizable $A_{UL}^{\sin\phi}$ asymmetries have been observed, while the other asymmetries have been found consistent with zero within error bars. In Ref. [16] the HERMES data [10,11] were well described in a parameter-free approach, using for $H_1^\perp$ the DELPHI result [14] [see Eq. (10)], and for proton transversity distributions the predictions from the chiral quark soliton model [17] and the instanton model of the QCD vacuum [18]. This approach was used in Ref. [33] to make predictions for A_{UL} azimuthal asymmetries for a deuterium target—which turned out to compare well to the data [34]. 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. [16], assuming that factorization holds at the energies of the CLAS experiment and using our estimate for the analyzing power from Eq. (13). Our predictions[6] 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.

Figure 3 demonstrates that the predicted CLAS asymmetries are as large as the asymmetries measured by HERMES [10,11]. Thus, with the high luminosity of the CLAS experiment, a precise measurement $A_{UL}^{\sin\phi}$ and $A_{UL}^{\sin 2\phi}$ for π^+ and π^0 is probably possible. Moreover, the CLAS kinematics for the 12 GeV beam allows us to observe the change of sign of the $A_{UL}^{\sin\phi}(x)$ asymmetries at $x \simeq 0.5$. This change of sign is due to different signs of the twist-3 and twist-2 contributions. For HERMES kinematics the zero of $A_{UL}^{\sin\phi}(x)$ lies outside the covered x range and is invisible [16,33].

The $A_{UL}^{\sin\phi}(x)$ asymmetries for different pions cross each other at 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 π^+, π^0, and π^- are "linearly independent" because of isospin symmetry and favored flavor fragmentation. Thus, if two curves cross each other at some point, the third one necessarily goes through this point as well. The exact positions of this point and of the zero of $A_{UL}^{\sin\phi}(x)$ 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 favor 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 $1\ \text{GeV}^2 \leqslant Q^2 \leqslant 9\ \text{GeV}^2$ covered in the CLAS experiment [12,13]. It will be exciting to learn from the comparison of these predictions to future CLAS data to what 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.

VI. CONCLUSIONS

We have presented the extraction of the first information of the chirally odd proton twist-3 distribution function $e^a(x)$ from the azimuthal asymmetry A_{LU} in π^+ electroproduction from semi-inclusive DIS of polarized electrons off unpolar-

[6]For explicit expressions for the azimuthal asymmetries and further details see Refs. [16,33,35].

ized protons, which has recently been measured by CLAS. The flavor combination $(e^u+(1/4)e^{\bar{d}})(x)$ extracted in the x region $0.15\leqslant x\leqslant 0.4$ refers to a scale of $1.5\ \mathrm{GeV}^2$ and is sizable—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 electroproduction 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 of whether the CLAS data have 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 the COMPASS experiment at CERN could be one of them. Our predictions for COMPASS will be published elsewhere.

ACKNOWLEDGMENTS

We would like to thank H. Avakian for many very fruitful discussions, and B. Dressler for providing the evolution code. A.E. is partially supported by RFBR grant 03-02-16816 and INTAS grant 00/587 and the DFG and BMBF. This work has partly been performed under the contract HPRN-CT-2000-00130 of the European Commission.

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