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AZIMUTHAL ASYMMETRIES AND COLLINS ANALYZING POWER*

A.V. Efremov,

Joint Institute for Nuclear Research, Dubna, 141980 Russia

K. Goeke

Institute for Theoretical Physics II, Ruhr University Bochum, Germany

and P. Schweitzer

Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Italy

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Spin azimuthal asymmetries in pion electro-production in deep inelastic scattering off longitudinally polarized protons, measured by HERMES, are well reproduced theoretically with no adjustable parameters. Predictions for azimuthal asymmetries for a longitudinally polarized deuteron target are given. The z-dependence of the Collins fragmentation function is extracted. The first information on $e(x)$ is extracted from CLAS $A_{\rm LU}$ asymmetry.

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1. Introduction

Recently azimuthal asymmetries have been observed in pion electro-production in semi inclusive deep-inelastic scattering off longitudinally (with respect to the beam) [1, 2] and transversely polarized protons [3]. These asymmetries contain information on the T-odd "Collins" fragmentation function $H_1^{\perp a}(z)$ and on the transversity distribution $h_1^a(x)$ [4][1]. $H_1^{\perp a}(z)$ describes the left–right asymmetry in fragmentation of transversely polarized quarks into a hadron [5–7] (the "Collins asymmetry"), and $h_1^a(x)$ describes the distribution of transversely polarized quarks in nucleon [4]. Both $H_1^{\perp a}(z)$ and $h_1^a(x)$ are twist-2, chirally odd, and not known experimentally. Only recently experimental indications to $H_1^{\perp}$ in e^+e^--annihilation have appeared [8], while the HERMES and SMC data [1–3] provide first experimental indications to $h_1^a(x)$.

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[1] We use the notation of Ref. [5, 6] with $H_1^{\perp}(z)$ normalized to $\langle P_{h\perp}\rangle$ instead of M_h.

Here we explain the observed azimuthal asymmetries [1, 2] and predict pion and kaon asymmetries from a deuteron target for HERMES by using information on $H_1^\perp$ from DELPHI [8] and the predictions for the transversity distribution $h_1^a(x)$ from the chiral quark-soliton model (χQSM) [9]. Our analysis is free of any adjustable parameters. Moreover, we use the model prediction for $h_1^a(x)$ to extract $H_1^\perp(z)$ from the z-dependence of HERMES data. For more details and complete references see Ref. [10–12]. Finally, using the new information on $H_1^\perp(z)$, we extract the twist-3 distribution $e^a(x)$ from very recent CLAS data [13].

2. Transversity distribution and Collins fragmentation function

The χQSM is a quantum field-theoretical relativistic model with explicit quark and antiquark degrees of freedom. This allows an unambiguous identification of quark *and* antiquark distributions in the nucleon, which satisfy all general QCD requirements due to the field-theoretical nature of the model [14]. The results of the parameter-free calculations for unpolarized and helicity distributions agree within (10–20)% with parameterizations, suggesting a similar reliability of the model prediction for $h_1^a(x)$ [9].

$H_1^\perp$ is responsible in e^+e^- annihilation for a specific azimuthal asymmetry of a hadron in a jet around the axis in direction of the second hadron in the opposite jet [5]. This asymmetry was probed using the DELPHI data collection [8]. For the leading particles in each jet of two-jet events, averaged over quark flavors, the most reliable value of the analyzing power is given by $(6.3 \pm 2.0)\%$. However, the larger "optimistic" value is not excluded

$$\left|\frac{\langle H_1^\perp\rangle}{\langle D_1\rangle}\right| = (12.5 \pm 1.4)\% \tag{1}$$

with unestimated but presumably large systematic errors.

3. The azimuthal asymmetry

In [1, 2] the cross section for $l\vec{p} \to l'\pi X$ was measured in dependence of the azimuthal angle ϕ, *i.e.* the angle between lepton scattering plane and the plane defined by momentum of virtual photon $\boldsymbol{q}$ and momentum $\boldsymbol{P}_h$ of produced pion. The twist-2 and twist-3 azimuthal asymmetries read [6][2]

$$A_{\rm UL}^{\sin 2\phi}(x) \;\propto\; \sum_a e_a^2 h_{1\rm L}^{\perp(1)a}(x)\langle H_1^{\perp a/\pi}\rangle \Big/ \sum_a e_a^2 f_1^a(x)\langle D_1^{a/\pi}\rangle\,, \tag{2}$$

[2] Note a sign-misprint in Eq. (115) of [6] for the $\sin\phi$-term Eq. (3). It was corrected in Eq. (2) of [15]. The conventions in Eqs. (2)–(4) agree with [1, 2]: Target polarization opposite to beam is positive, and z axis is parallel to $\boldsymbol{q}$ (in [6] it is anti-parallel).

$$A_{\rm UL(1)}^{\sin\phi}(x) \;\propto\; \frac{M}{Q}\sum_a e_a^2 x h_{\rm L}^a(x)\langle H_1^{\perp a/\pi}\rangle \Big/ \sum_a e_a^2 f_1^a(x)\langle D_1^{a/\pi}\rangle\,, \tag{3}$$

$$A_{\rm UL(2)}^{\sin\phi}(x) \;\propto\; -\sin\theta_\gamma \sum_a e_a^2 h_1^a(x)\langle H_1^{\perp a/\pi}\rangle \Big/ \sum_a e_a^2 f_1^a(x)\langle D_1^{a/\pi}\rangle\,, \tag{4}$$

with $\sin\theta_\gamma \approx 2x\sqrt{1-y}(M/Q)$ and $A_{\rm UL}^{\sin\phi} = A_{\rm UL(1)}^{\sin\phi} + A_{\rm UL(2)}^{\sin\phi}$. In Eqs. (2)–(4) the pure twist-3 terms are neglected. The results of Ref. [16] justify to use this WW-type approximation in which $xh_{\rm L} = -2h_{1\rm L}^{\perp(1)} = 2x^2\int_x^1 {\rm d}\xi\, h_1(\xi)/\xi^2$.

We assume isospin symmetry and favored fragmentation for D_1^a and $H_1^{\perp a}$, *i.e.* $D_1^\pi \equiv D_1^{u/\pi^+} = D_1^{d/\pi^-} = 2D_1^{\bar u/\pi^0}$ *etc.* and $D_1^{\bar u/\pi^+} = D_1^{u/\pi^-} \simeq 0$ *etc.*

4. Explaining, exploiting and predicting HERMES asymmetries

When using Eq. (1) to explain HERMES data, we assume a weak scale dependence of the analyzing power. We take $h_1^a(x)$ from the χQSM [9] and $f_1^a(x)$ from Ref. [17], both LO-evolved to the average scale $Q^2_{\rm av} = 4\,{\rm GeV}^2$.

In Fig. 1 HERMES data for $A_{\rm UL}^{\sin\phi}(x)$, $A_{\rm UL}^{\sin 2\phi}(x)$ [1,2] are compared with the results of our analysis. We conclude that the azimuthal asymmetries obtained with $h_1^a(x)$ from the χQSM [9] combined with the "optimistic" DELPHI result Eq. (1) for the analyzing power are consistent with data.

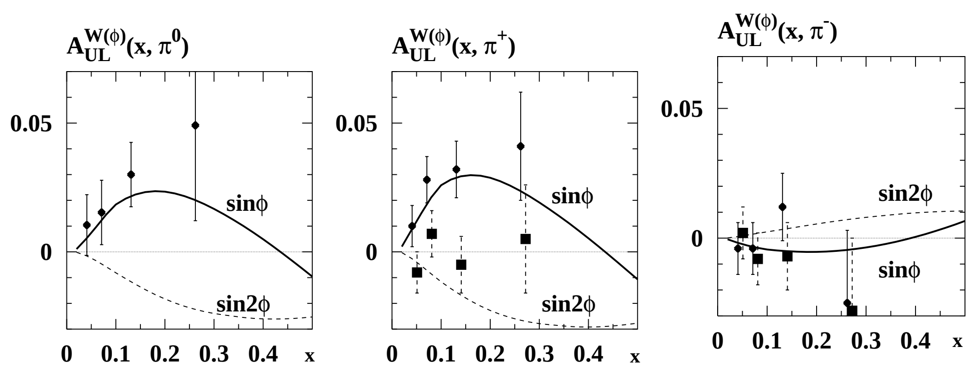

Fig. 1. Azimuthal asymmetries $A_{\rm UL}^{W(\phi)}$ weighted by $W(\phi) = \sin\phi$, $\sin 2\phi$ for pions as function of x. Rhombus (squares) denote data for $A_{\rm UL}^{\sin\phi}$ ($A_{\rm UL}^{\sin 2\phi}$).

We exploit the z-dependence of HERMES data for π^0, π^+ azimuthal asymmetries to extract $H_1^\perp(z)/D_1(z)$. For that we use the χQSM prediction for $h_1^a(x)$, which introduces a model dependence of order (10–20)%. The result is shown in Fig. 2. The data can be described by a linear fit $H_1^\perp(z) =$

$(0.33 \pm 0.06)zD_1(z)$. The average $\langle H_1^\perp\rangle/\langle D_1\rangle = (13.8 \pm 2.8)\%$ is in good agreement with DELPHI result Eq. (1) [3]. The errors are the statistical errors of the HERMES data.

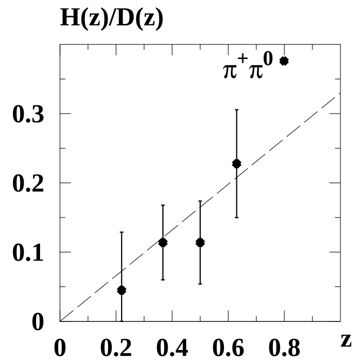

Fig. 2. $H_1^\perp/D_1$ *vs* z, as extracted from HERMES data for π^+ and π^0 production [1,2].

The approach can be applied to predict azimuthal asymmetries in pion and kaon production off *a longitudinally polarized deuterium* target, which are under current study at HERMES. The additional assumption used is that $\langle H_1^{\perp K}\rangle/\langle D_1^K\rangle \simeq \langle H_1^{\perp\pi}\rangle/\langle D_1^\pi\rangle$. The predictions are shown in Fig. 3. The "data points" estimate the expected error bars. Asymmetries for $\bar{K}^0$ and K^- are close to zero in our approach.

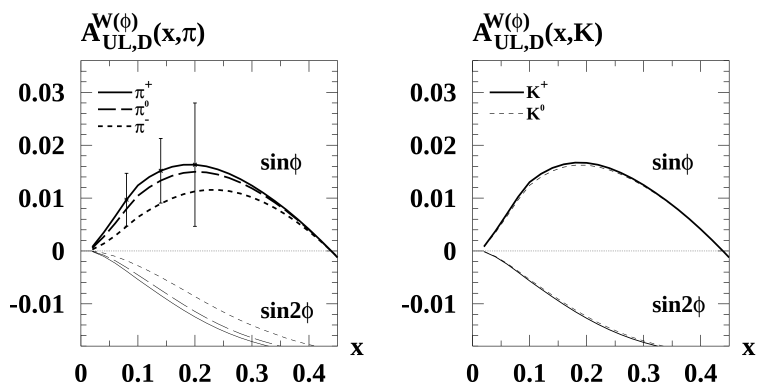

Fig. 3. Predictions for $A_{\rm UL}^{\sin\phi}$, $A_{\rm UL}^{\sin 2\phi}$ from a deuteron target for HERMES. Asymmetries for $\bar{K}^0$, K^- are close to zero in our approach.

Interestingly all $\sin\phi$ asymmetries change sign at $x \sim 0.5$ (unfortunately the HERMES cut is $x < 0.4$). This is due to the negative sign in Eq. (4) and the harder behaviour of $h_1(x)$ with respect to $h_{\rm L}(x)$. This prediction however is sensitive to the favoured fragmentation approximation.

[3] SMC data [3] yield an opposite sign, $\frac{\langle H_1^\perp\rangle}{\langle D_1\rangle} = -(10 \pm 5)\%$, however, seem less reliable.

We learn that transversity could be measured also with a *longitudinally* polarized target, *e.g.* at COMPASS, simultaneously with ΔG.

5. Extraction of $e(x)$ from $A_{\mathrm{LU}}^{\sin\phi}$ asymmetry at CLAS

Very recently the $\sin\phi$ asymmetry of π^+ produced by scattering of polarized electrons off unpolarised protons was reported by CLAS collaboration [13]. This asymmetry is interesting since it allows to access the unknown twist-3 structure functions $e^a(x)$ which are connected with nucleon σ-term:

$$\int_0^1 \mathrm{d}x \sum_a e^a(x) = \frac{2\sigma}{m_u + m_d} \approx 10\,. \tag{5}$$

The asymmetry is given by [6]

$$A_{\mathrm{LU}}^{\sin\phi}(x) \propto \frac{M}{Q} \sum_a e_a^2 e^a(x) \langle H_1^{\perp a/\pi} \rangle \Big/ \sum_a e_a^2 f_1^a(x) \langle D_1^{a/\pi} \rangle\,. \tag{6}$$

Disregarding unfavored fragmentation and using the Collins analysing power extracted from HERMES in Sec. 4, which yields for z-cuts of CLAS $\langle H_1^{\perp\pi}\rangle / \langle D_1^{\pi}\rangle = 0.20 \pm 0.04$, we can extract $e^u(x) + e^{\bar{d}}(x)/4$. The result is presented in Fig. 4. For comparison the Soffer lower bound [18] from twist-3 density matrix positivity, $e^a(x) \geq 2|g_{\mathrm{T}}^a(x)| - h_{\mathrm{L}}^a(x)$[4], and the unpola-

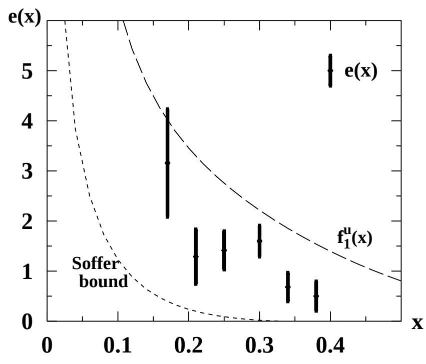

Fig. 4. The flavour combination $e(x) = (e^u + e^{\bar{d}}/4)(x)$, with errorbars due to statistical error of CLAS data, *vs.* x at $\langle Q^2\rangle = 1.5\,\mathrm{GeV}^2$. For comparison $f_1^u(x)$ and the twist-3 Soffer bound are shown.

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[4] For $g_{\mathrm{T}}^a(x)$ we use the Wandzura–Wilczek approximation $g_{\mathrm{T}}^a(x) = \int_x^1 \mathrm{d}\xi\, g_1^a(\xi)/\xi$ and neglect consistently $\tilde{g}_2^a(x)$ which is strongly suppressed in the instanton vacuum [19]. For $h_{\mathrm{L}}^a(x)$ we use the analogous approximation, as described in Sec. 3.

rized distribution function $f_1^u(x)$ are plotted. One can guess that the large number in the sum rule Eq. (5) might be due to, either a strong rise of $e(x)$ in the small x region, or a δ-function at $x = 0$ [20].

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