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TMDs studied in semi-inclusive deep inelastic scattering at HERMES

Y. Miyachi (for the HERMES collaboration)

Department of Physics, Yamagata University, Kojirakawa-cho 1-4-12, Yamagata 990-8560 Japan

Abstract The HERMES measured azimuthal amplitudes of cross sections and their transverse target single spin asymmetries for hadron productions in semi-inclusive deep inelastic scattering. From the extracted amplitudes, novel parton distribution functions can be studied. The recent results related to Sivers and Boer-Mulders distribution functions are discussed.

Key words nucleon structure, proton spin, intrinsic transverse momentum

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1 Introduction

The Parton distribution function (PDF) is a key tool for investigating the internal structure of the nucleon. Non-perturbative properties are encoded in PDFs. Helicity sum or difference of PDFs, $q(x)$ or $\Delta q(x)$, where x is a momentum fraction carried by the parton, are interpreted as the number density and the helicity distributions at leading order. In a basis of transverse spin eigenstates, one can form the transversity distribution $\delta q(x)$, which describes transversely polarized partons in the transversely polarized nucleon. The unexpected large A_{N} in pion productions in the polarized p-p scattering brought attention to an intrinsic transverse momentum of the parton. With the transverse momentum, PDFs can be expanded to 9 transverse momentum dependent distribution functions (TMDs)[1].

The differential cross section in semi-inclusive deep inelastic scattering (SIDIS) can be expanded to its azimuthal amplitudes [1], in which the TMDs appear in certain combinations with fragmentation functions. There are two azimuthal angles, ϕ_{S} and ϕ_{h}, in SIDIS. They are defined for the transverse target spin $\vec{S}_{\mathrm{T}}$ and the transverse momentum of the produced hadron $\vec{P}_{\mathrm{h}\perp}$ around the virtual photon momentum direction, with respect to the lepton scattering plane, as shown in Fig. 1.

Transversity has been studied in the single hadron and the hadron pair productions in SIDIS by the

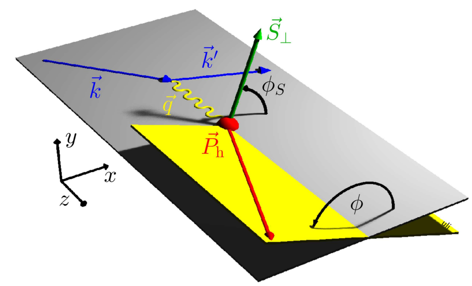

Fig. 1. Azimuthal angles ϕ_{S} and ϕ_{h} in SIDIS.

HERMES and COMPASS experiments [2–4]. Boer-Mulders $h_1^{\perp}$ and Sivers $f_{1\mathrm{T}}^{\perp}$ functions are of special interest. They describes the transversely polarized parton inside the unpolarized nucleon and the unpolarized parton inside the transversely polarized nucleon. Because of their naive T-odd feature, these TMDs appear with different sign in SIDIS and Drell-Yan process [5]. This phenomenon is sometime discussed in the relation with the Aharonov-Bohm effect in QCD [6]. The large azimuthal amplitudes of the pion induced Drell-Yan cross section [7, 8] could be explained with the Boer-Mulders distribution [9]. In single polarized Drell-Yan scattering, convolution of the Boer-Mulders with the transversity and the Sivers with the density distribution functions appears in different azimuthal amplitudes [9]. Sizable amplitudes in Drell-Yan cross section are expected [10], so that experimental confirmation of the sign of naive T-odd

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1) E-mail: miyachi@sci.kj.yamagata-u.ac.jp

TMDs in the both processes would be a fundamental test of QCD.

2 The HERMES experiment

Using the 27.6 GeV electrons or positrons in the HERA storage ring at DESY and the internal gas targets, HERMES had carried semi-inclusive measurements of (un)polarized deep inelastic scattering. A transversely polarized hydrogen target had been used during the 2002-2005 running period. The open-ended target cell was fed by an atomic-beam source based on Stern-Gerlach separation and RF transition of the hyperfine states. The nuclear polarization was flipped at intervals of 1 to 3 minutes. The polarization and the atomic fraction in the target cell were continuously measured. The resulting average transverse polarization of the target proton was $\langle P_{\mathrm{T}}\rangle = 0.74 \pm 0.06$. Unpolarized nucleon targets were also used. The particles scattered and those produced were measured with the HERMES spectrometer [11], which has the geometrical acceptance $40 < |\theta_x| < 140$ mrad and $|\theta_y| < 170$ mrad. Using the electro-magnetic calorimeter, the transition radiation detector, the pre-shower scintillation counter, and the dual radiator ring imaging Cherenkov (RICH) detector, a lepton identification efficiency greater than 98% with hadron contamination of less than 1% was achieved. Hadrons were identified with the RICH detector in the momentum range of $2 < p < 15$ GeV/c.

3 Sivers moments at HERMES

Single transverse target spin asymmetries in SIDIS for identified hadrons, $\pi^{+,0,-}$ and $\mathrm{K}^{+,-}$,

$$A^{\mathrm{h}}_{\mathrm{UT}}(\phi_{\mathrm{h}},\phi_{\mathrm{S}}) = \frac{1}{\langle P_{\mathrm{T}}\rangle}\frac{N^{\uparrow}_{\mathrm{h}}(\phi_{\mathrm{h}},\phi_{\mathrm{S}}) - N^{\downarrow}_{\mathrm{h}}(\phi_{\mathrm{h}},\phi_{\mathrm{S}})}{N^{\uparrow}_{\mathrm{h}}(\phi_{\mathrm{h}},\phi_{\mathrm{S}}) + N^{\downarrow}_{\mathrm{h}}(\phi_{\mathrm{h}},\phi_{\mathrm{S}})} \quad (1)$$

were extracted from the data recorded during the 2001-2005 running period, where $N^{\uparrow(\downarrow)}_{\mathrm{h}}$ represents the hadron yield in the target spin state $\uparrow$ ($\downarrow$). Azimuthal moments, $2\langle\sin(\phi_{\mathrm{h}} - \phi_{\mathrm{S}})\rangle$ and $2\langle\sin(\phi_{\mathrm{h}} + \phi_{\mathrm{S}})\rangle$, are known as Sivers and Collins moments. In total 6 different moments, including the Sivers and Collins moments, were extracted simultaneously from the asymmetries. Because of the limited statistics, the maximum likelihood method was used for the unbinned data with respect to $(\phi_{\mathrm{h}}, \phi_{\mathrm{S}})$. The Sivers moments can be interpreted as

$$2\langle\sin(\phi_{\mathrm{h}} - \phi_{\mathrm{S}})\rangle = -\frac{\sum_{\mathrm{q}} e^2_{\mathrm{q}} f^{\perp}_{1T}(x, p^2_{\mathrm{T}}) \otimes D^{\mathrm{q}}_1(z, K^2_{\mathrm{T}})}{\sum_{\mathrm{q}} e^2_{\mathrm{q}} f^{\mathrm{q}}_1(x) D^{\mathrm{q}}_1(z)} \quad (2)$$

where $\otimes$ is a convolution integral over the transverse momenta, $\vec{p}_{\mathrm{T}}$ and $\vec{K}_{\mathrm{T}}$ for the Sivers and the unpolarized fragmentation functions.

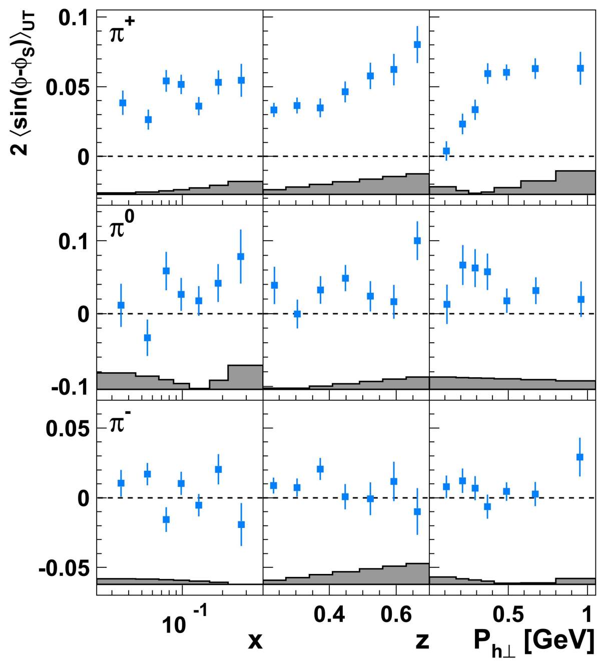

Fig. 2. Extracted Sivers moments for $\pi^{+,0,-}$ at HERMES.

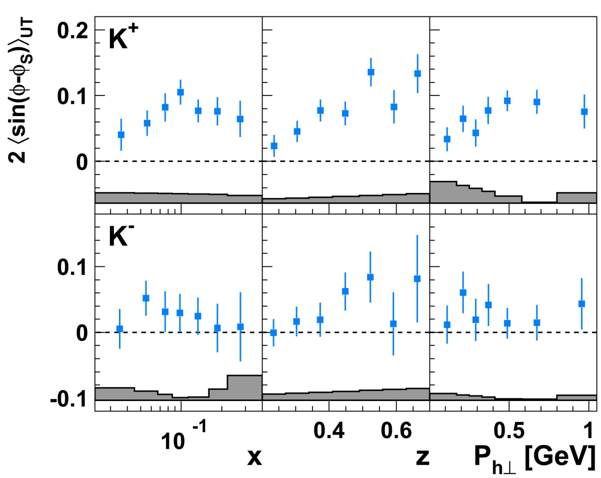

Fig. 3. Extracted Sivers moments for $\mathrm{K}^{+,-}$ at HERMES.

In Fig. 2 and Fig. 3, the Sivers moments extracted by the HERMES experiments [12] are shown as functions of x, z, and $P_{\mathrm{h}\perp}$. The shaded bands represent the systematic uncertainties, which include contributions from the acceptance, the smearing, the QED radiation, and the hadron misidentification. In addition there is a 7.3 % scale uncertainty from the target polarization measurement. The extracted moments are positive and increase with z, except for the π^-.

The π^+ and K^+ moments seem to reach saturation around 0.4 GeV in $P_{h\perp}$.

The positive Sivers moments suggest a large and negative Sivers function for the u-quark, since the dominant contribution in the hadron production comes from scattering off the u-quark. A possible positive d-quark contribution could explain the vanishing π^- moment, which could also explain the small Sivers moments extracted at the COMPASS experiments with the deuteron target [4]. While it would be naively expected that the π^+ and K^+ moments have similar size on the basis of the u-quark dominance, the obtained K^+ moments are roughly twice larger than the π^+. This difference may indicate a significant role of other quark flavors.

4 The Boer-Mulders distribution function at HERMES

The $\cos 2\phi_h$ moment of the unpolarized SIDIS cross section, $2\langle\cos 2\phi_h\rangle_{UU} = \int\cos 2\phi_h d^5\sigma/\int d^5\sigma$ were extracted from the data collected in 2000, 2005, and 2006. The $\cos 2\phi_h$ moments can be interpreted as a convolution of the Boer-Mulders and Collins fragmentation functions. The 5 fold differential cross section depends on the SIDIS kinematic variables, x, y, z, $P^2_{h\perp}$, and ϕ_h [13].

The finite acceptance, the smearing due to the detector resolution, and the QED radiation could cause false moments and distortion in the amplitude extraction. The data were analyzed in a 5-dimensional grid in the 5 kinematic variables [14]. In Fig. 4, the extracted $\cos 2\phi$ moments of hadron production cross section in SIDIS by the HERMES [14] are shown. The positive $\cos 2\phi$ moments were observed for the negative charged hadrons, while the positive hadron moments were small and negative. The deuteron target results show similar behavior [14]. Taking the recent results on the Collins fragmentation function at the Belle experiment [15] into account, the resulting $\cos 2\phi$ moments may indicate that the Boer-Mulders functions have same sign for the u and d quarks.

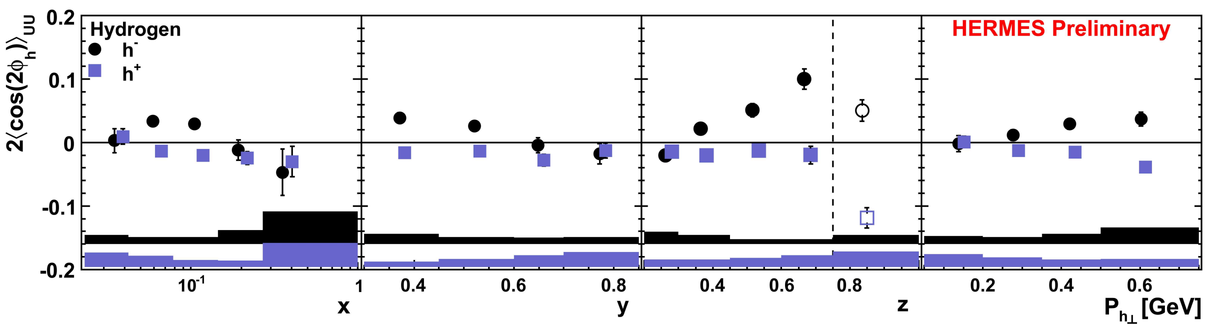

Fig. 4. Extracted $\cos 2\phi$ moments at HERMES

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