Final HERMES Results on Single-Spin Asymmetries in Lepto-Production of Oppositely Charged Pion Pairs from a Transversely Polarized Hydrogen Target

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For the first time, a non-zero single spin azimuthal asymmetry in lepto-production of $\pi^+\pi^-$ pairs was observed in deep-inelastic scattering from a transversely polarized hydrogen target. The measurement of this asymmetry was carried out by the HERMES collaboration at DESY. The asymmetry is related to the product of the little-known chiral-odd transversity distribution and the unknown naive-T-odd chiral-odd dihadron fragmentation function, hence providing an independent way to constrain transversity.

1 Introduction

Quark spin structure of the nucleon is one of the fundamental topics in physics. Three fundamental quark distribution functions describe the structure of the nucleon at leading twist of QCD: the unpolarized distribution, $f_1$, the helicity distribution, $g_1$, and the transversity distribution, $h_1$. Transversity describes the distribution of transversely polarized quarks in a nucleon polarized transverse to the direction of the hard probe and is not known very well. Different from the other two, it is inaccessible in inclusive deep-inelastic scattering (DIS) and difficult to measure [2].

In semi-inclusive DIS process, this chiral-odd transversity distribution function can be accessed by coupling to a chiral-odd fragmentation function, such as the Collins fragmentation function $H_1^\perp$ (also called Collins effect) or the dihadron fragmentation function $H_1^\perp$ [1]. Azimuthal single-spin asymmetries in single-hadron production in semi-inclusive DIS on a transversely polarized target, where the Collins effect can be probed, were measured by the HERMES and COMPASS collaborations. Ref. [3] extracted transversity by combining those measurements with the Collins fragmentation function measured by the Belle collaboration [4]. The azimuthal asymmetries of the lepto-production of hadron pairs from the transversely polarized target is sensitive to the product of transversity and the dihadron fragmentation function, thereby providing an independent way to probe transversity. The dihadron fragmentation function describes the transfer of the transverse spin of the fragmenting quark to the relative orbital angular momentum of the hadron pair.

This paper reports a measurement of a Fourier amplitude of an azimuthal single-spin asymmetry in lepto-produced $\pi^+\pi^-$ pairs from a transversely polarized hydrogen target at the HERMES experiment, providing the world first evidence of a naive-T-odd chiral-odd dihadron fragmentation function $H_1^\perp$, which can provide access to transversity $h_1$. Among the various contributions to $H_1^\perp$, the interference $H_1^{s,p}$ between the s- and p-wave components of the $\pi^+\pi^-$ pair. The focus here is on the s-p interference, since it has received the most theoretical attention. The available theoretical models indicate that $H_1^{s,p}$ should...
be maximal in the vicinity of the $\rho^0$ mass \cite{5, 6, 7}. In particular, in Ref. \cite{5} $H^{<,sp}_1$ was predicted to change the sign around the $\rho^0$ mass of the invariant mass $M_{\pi\pi}$ of the $\pi^+\pi^-$ pair. However, other models \cite{6, 7} predict a completely different behavior.

2 The HERMES Experiment

The HERMES experiment \cite{8} was designed to perform a precise measurement of the quark spin structure of the nucleon in inclusive and semi-inclusive DIS processes. The experiment was carried out at DESY in Germany, utilizing the longitudinally polarized 27.6 GeV electron/positron beam of the HERA storage ring in combination with an longitudinally or transversely polarized atomic gas target internal to the beam pipe. Electron–hadron separation was achieved with efficiency of more than 98%. A Ring Imaging Čerenkov (RICH) detector allows the precise identification of pions, kaons and protons over the essential momentum range of the experiment. From 2002 to 2005, a transversely polarized hydrogen target was installed with average polarization $|S_T| = 0.74 \pm 0.06$.

3 Extraction of the Asymmetries

At leading twist, the cross sections of pion pairs in semi-inclusive DIS process are \cite{9}

\[
\frac{d^7\sigma_{UU}}{dx \, dy \, dz \, d\phi_S \, d\phi_{R\perp} \cos \theta \, dM_{\pi\pi}} = \sum_q \frac{\alpha^2 e_q^2}{2 \pi s x y^2} (1 - y + \frac{y^2}{2}) f_q^T(x) D_{1,q}(z, M_{\pi\pi}, \cos \theta),
\]

\[
\frac{d^7\sigma_{UT}}{dx \, dy \, dz \, d\phi_S \, d\phi_{R\perp} \cos \theta \, dM_{\pi\pi}} \equiv \frac{1}{2} \left( d^7\sigma_{U\uparrow} - d^7\sigma_{U\downarrow} \right) =
\]

\[
-|S_T| \sum_q \frac{\alpha^2 e_q^2}{2 \pi s x y^2} (1 - y) \frac{1}{2} \sqrt{1 - 4 \frac{M_{\pi\pi}^2}{M_{\pi}^2}} \sin(\phi_{R\perp} + \phi_S) \sin \theta h_1^q(x) H_{1,q}^{<}(z, M_{\pi\pi}, \cos \theta),
\]

where the azimuthal angles $\phi_S, \phi_{R\perp}$ and the angle $\theta$ are illustrated in Figure 1. Eq. (1) is for an unpolarized target and Eq. (2) for a transversely polarized target. The dihadron fragmentation functions $D_{1,q}$ and $H_{1,q}^{<}$ can be expanded in terms of Legendre functions of $\cos \theta$. Thus

\[
D_{1,q}(z, M_{\pi\pi}, \cos \theta) \simeq D_{1,q}^p(z, M_{\pi\pi}) + D_{1,q}^{pp}(z, M_{\pi\pi}) \cos \theta + D_{1,q}^{<}(z, M_{\pi\pi}) \frac{1}{4} (3 \cos^2 \theta - 1),
\]

\[
H_{1,q}^{<}(z, M_{\pi\pi}, \cos \theta) \simeq H_{1,q}^{<,sp}(z, M_{\pi\pi}) + H_{1,q}^{<,pp}(z, M_{\pi\pi}) \cos \theta,
\]

DIS 2008
where the Legendre expansions are truncated to include only the s- and p-wave components. The interesting amplitude \( A_{UT}^{\sin(\phi_{R\perp} + \phi_S)\sin \theta} \) of the single-spin asymmetry \( A_{UT} \equiv \frac{1}{\text{N}^{\uparrow} - \text{N}^{\downarrow}} \sigma_{UT}' / \sigma_{UT} \), which is related to the product of transversity \( h_1 \) and the dihadron fragmentation function \( H_1^{q,sp} \), is defined as

\[
A_{UT}^{\sin(\phi_{R\perp} + \phi_S)\sin \theta} \equiv \frac{2}{|ST|} \frac{\int \text{d} \cos \theta \, \text{d} \phi_{R\perp} \, \text{d} \phi_S \sin(\phi_{R\perp} + \phi_S) \, \text{d} \sigma_{UT}' / \sin \theta}{\int \text{d} \cos \theta \, \text{d} \phi_{R\perp} \, \text{d} \phi_S \, \text{d} \sigma_{UT} / \sin \theta} = - \frac{(1 - y)}{1 - y + \frac{y}{2}} \left( \frac{1}{2} \right) \left( \frac{1 - 4 \frac{M_z^2}{M_{\pi \pi}^2}}{\sum \sqrt{\frac{e_q^2}{f_q^2}} \left( \theta^2 \right)} \right) \sin(\phi_{R\perp} + \phi_S),
\]

(5)

In the experiment, the single–spin asymmetry \( A_{U \perp} \equiv \frac{1}{|S_{1\perp}|} \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \) can be extracted where \( N_{1\uparrow(\downarrow)} \) is the luminosity-normalized number of semi-inclusive \( \pi^+ \pi^- \) pairs detected while the target is in the \( \uparrow(\downarrow) \) spin state with polarization perpendicular to the lepton beam. A \( \chi^2 \) fit was performed, binned in \( (\phi_{R\perp} + \phi_S) \) versus \( \theta' \equiv ||\theta - \pi/2| - \pi/2| \), with a function of the form

\[
A_{U \perp}(\phi_{R\perp} + \phi_S, \theta') = \sin(\phi_{R\perp} + \phi_S) \frac{a \sin \theta}{1 + b \left( 3 \cos^2 \theta' - 1 \right)},
\]

(6)

where \( a \equiv A_{U \perp}^{\sin(\phi_{R\perp} + \phi_S)\sin \theta} \) is a free parameter of the fit, which approximates \( A_{UT}^{\sin(\phi_{R\perp} + \phi_S)\sin \theta} \) in Eq. (5). The parameter \( b \) is varied to study the influence of the unknown contribution \( D_{1,q}^{pp} \) to the polarization-averaged dihadron cross section within the positivity limits

\[
- \frac{3D_{1,q}^p(z, M_{\pi \pi})}{2D_{1,q}^p(z, M_{\pi \pi})} \leq b \leq \frac{3D_{1,q}^p(z, M_{\pi \pi})}{D_{1,q}^p(z, M_{\pi \pi})},
\]

(7)

where \( D_{1,q}^p(z, M_{\pi \pi}) \) indicates the pure p-wave component of the fragmentation functions \( D_{1,q}(z, M_{\pi \pi}) \). The size of this component was estimated using the PYTHIA6 event generator tuned to HERMES data. The extracted values for \( a \) are the central values in the ranges of \( a \) obtained by varying \( b \) between its lower and upper bounds, while a systematic uncertainty was assigned as the “b-scan” uncertainty, which is taken to be the standard deviation of \( a \).

An additional substantial contribution to the systematic uncertainty is the acceptance effect. It was estimated from the difference of the amplitudes extracted from the experimental acceptance and of the 4\( \pi \) acceptance based on Monte Carlo studies, which is explained in more detail in Ref. [10].

The values of the amplitudes \( A_{U \perp}^{\sin(\phi_{R\perp} + \phi_S)\sin \theta} \) extracted as functions of \( M_{\pi \pi}, x \), and \( z \), are shown in Fig. 2. The measured \( A_{U \perp}^{\sin(\phi_{R\perp} + \phi_S)\sin \theta} \) from events summed over the experimental acceptance is \( A_{U \perp}^{\sin(\phi_{R\perp} + \phi_S)\sin \theta} = 0.018 \pm 0.005(\text{stat}) \pm 0.004(\text{syst}) \), with an additional 8.1% scale uncertainty coming from the uncertainty in the determination of the target polarization. The mean values of the kinematic variables are \( \langle x \rangle = 0.07, \langle y \rangle = 0.64, \langle Q^2 \rangle = 2.35 \text{ GeV}^2, \langle z \rangle = 0.43, \) and \( \langle |P_{h \perp}| \rangle = 0.42 \text{ GeV} \).

4 Summary

A measurement of \( A_{U \perp}^{\sin(\phi_{R\perp} + \phi_S)\sin \theta} \) of the single transverse target–spin asymmetry in lepto-produced \( \pi^+ \pi^- \) pairs was performed at HERMES from data taken during 2000–2005. It
provided the first evidence that the naïve–T–odd chiral–odd dihadron fragmentation function $H_{T,q}$ and in particular $H_{T,q}^{\pi^+\pi^-}$ is nonzero, resulting in an independent way to constrain transversity. The amplitude is positive in the whole range in the invariant mass of the $\pi^+\pi^-$ pairs, in contrast to a previous expectation [5] of a sign change around the mass of the $\rho^0$ meson.

A mechanism analogous to the one investigated in this paper can also be studied in semi-inclusive DIS process at COMPASS and in $pp$ collisions at RHIC. The Belle collaboration can extract dihadron fragmentation functions from their $e^+e^-$ data. Such results could then be combined with DIS and $pp$ data to extract transversity in the nucleon.

References

[1] Slides: http://indico.cern.ch/contributionDisplay.py?contribId=272&sessionId=22&confId=24657

DIS 2008