SPIN PHYSICS WITH SPIN-0 HADRONS

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We discuss various azimuthal asymmetries in semi-inclusive DIS and $e^+e^- \rightarrow h_1h_2X$ which involve chiral odd quantities like the transversity distribution $h_1$ and a fragmentation function $H_{\perp}^1$. For the fragmentation described by $H_{\perp}^1$ azimuthal angular dependence has to be measured, but no polarization vector of a final state hadron. We present first results on asymmetries including the electroweak currents in one-hadron inclusive DIS.

1 Transversity Distribution $h_1(x)$

Besides the quite well-known parton distribution $f_1(x)$ there are two different spin distributions: the longitudinal spin distribution $g_1(x)$, on which a number of new experimental results have been reported at this conference, the second one, the transversity distribution $h_1(x)$, remains completely unknown as far as experimental data are concerned. The transversity distribution $h_1$ is equally important for the description of quarks in nucleons as the more familiar function $g_1$; their information is complementary.

The reason why $h_1$ is not determined yet, is the fact that it is a chiral odd

\[ f_1 = \quad g_1 = \quad h_1 = \]

Figure 1: Schematic interpretation of the three distribution functions $f_1(x)$, $g_1(x)$ and $h_1(x)$ in terms of (differences of) probabilities. The longitudinal direction is assumed to be along the horizontal axis.

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aThe function $h_1(x)$ was first discussed by Ralston and Soper in Drell-Yan scattering.

bThe alternative notations $q(x)$, $\Delta q(x)$ and $\delta q(x)$ (or sometimes $\Delta T q(x)$ for the latter) are also in use instead of $f_1$, $g_1$ and $h_1$, respectively.
function, and consequently suppressed in simple processes like totally inclusive DIS. The quark content of \( h_1(x) \) in terms of left-handed and right-handed quarks (defined via projection operators \( P_{R/L} = (1 \pm \gamma_5)/2 \)) is of the form \( RL - LR \), i.e., contains a transition from \( R \) to \( L \) and vice versa. Since QCD interactions conserve chirality, \( h_1(x) \) cannot occur alone in a process (case \( a \) in the figure below), but has to be accompanied by a second chiral odd quantity, like e.g., the fragmentation function \( H_1(z) \) (case \( c \) below) which is the pendant to \( h_1 \) for the fragmentation; obviously also the fragmentation function \( H_1 \) cannot occur alone (as in case \( b \)), i.e., is not accessible in \( e^+e^- \to hX \) (see also a recent article by Jaffe).

Figure 2: Chiral odd functions can hardly be probed in the simple processes \( a \) (DIS) and \( b \) \( (e^+e^- \to hX) \), where they contribute only via (suppressed) quark mass effects. But they are accessible when combined with another chiral odd quantity like e.g. in \( c \) \( (\ell H \to \ell'hX) \).

2 Azimuthal Asymmetry in SIDIS / ‘Collins Effect’

To measure transversity in one-hadron inclusive DIS one can look for parts of the cross section involving \( h_1 \) and \( H_1 \). It has the disadvantage that the polarization vector of an observed spin-1/2 hadron in the final state has to be determined. Although not impossible in principle, for instance the decay of \( \Lambda \)'s would offer this possibility, it is experimentally difficult.

Alternatively, one can measure azimuthal angular dependences in the production of spin-0 or (on average) unpolarized hadrons. This production is described by the transverse momentum dependent fragmentation function \( H_1^\perp(x, k_T) \) which is also chiral odd and, moreover, “naive time-reversal odd”, i.e., non-vanishing only due to final state interactions. For a more detailed discussion of \( H_1^\perp(x, k_T) \) see elsewhere. The use of a “naive time-reversal odd” observable and azimuthal angular dependence to obtain information on \( h_1(x) \) was proposed by Collins. A particular useful reformulation of this proposal for \( \ell H \to \ell'hX \) can be given in terms of appropriately weighted cross sections

\[
\langle W \rangle \overset{\text{def}}{=} \int \frac{d\phi'}{2\pi} d^2q_T W \frac{d\sigma(eH \to e'hX)}{d\phi_H d\phi_T d^2q_T}.
\]
We find \((\phi_{\ell h}^f, \phi_{\ell S}^f)\) are the azimuthal angles of \(h\) and the target spin, respectively)

\[
\langle Q_T M_h \sin(\phi_{\ell h}^f + \phi_{\ell S}^f) \rangle = -\frac{4\pi\alpha_2^2}{Q^2} |S_T| (1-y) \sum_{a,\bar{a}} e_a^2 x_a \ h_1^a(x_a) \ \hat{H}_1^{\perp(1)a}(z_h) \tag{2}
\]

containing the (flavor summed) product of the transversity distribution with a \(k_T^2\)-moment of \(H_1^\perp\)

\[
H_1^{\perp(n)}(z) \overset{\text{def}}{=} z^2 \int d^2k_T \left( \frac{k_T^2}{2M_h^2} \right)^n H_1^\perp(z, -z k_T). \tag{3}
\]

3 \(H_1^\perp\) from \(e^+e^-\) Annihilation \((e^+e^- \rightarrow h_1 h_2 X)\)

Recently we proposed a way to obtain information on the first \(k_T^2\)-moment of \(H_1^\perp\) from a \(\cos(2\phi)\) angular dependence in two-hadron production in \(e^+e^-\) annihilation. The two hadrons have to be in the quark and anti-quark jet of an almost back-to-back jet event, respectively, and their momenta should be reconstructed. Since the fragmentation functions involved are \(H_1^\perp\) and \(\overline{H}_1^\perp\) (the corresponding one for the anti-quark) the effect is independent of the spin of the produced hadrons; to look for a pair of pions is the most obvious choice, since they are abundantly produced. Again the appropriate way to pick out

\[
\langle W \rangle \overset{\text{def}}{=} \int \frac{d\phi}{2\pi} d^2q_T W \frac{d\sigma(e^+e^- \rightarrow h_1 h_2 X)}{d\Omega \ dz_1 d\Omega \ dz_2 d^2q_T} \tag{4}
\]

\(^c\text{This is spin physics with spin-0 hadrons!}\)
At the $Z$-pole, i.e., $Q^2 \simeq M_Z^2$, where most of the LEP data are available, the annihilation via a $Z$ boson dominates and the product of $H_1^{±(1)a}$ with $\overline{T}_1^{±(1)a}$ can be obtained from the weighted cross section

$$
\left\langle \frac{Q_\ell^2}{4M_1M_2} \cos(2\phi) \right\rangle = \frac{3\alpha^2 Q^2 y(1-y) \sum_{a,\bar{a}} c_1^a c_2^a H_1^{±(1)a}(z_1) \overline{T}_1^{±(1)a}(z_2)}{4 s_W^2 c_W^2 \left[ (Q^2 - M_Z^2)^2 + \Lambda_Z^2 M_Z^2 \right]} \tag{5}
$$

where $s_W(c_W)$ is the sin(cos) of $\theta_W$; the factors $c_1 = g_V^2 + g_A^2$, $c_2 = g_V^2 - g_A^2$ are relevant combinations of (axial-)vector couplings (for later use: $c_3 = 2 g_A g_V$).

4 Electroweak $\ell H \to \ell' h X$

During this conference we have heard that high energy experiments reach the precision where effects from electroweak currents have to be considered\(^a\). We have calculated the differential cross section for one-hadron inclusive lepton-hadron scattering thereby taking into account

- the exchange of a photon or a $Z$ boson (including interference terms)
- polarized beam/target/final state hadron (spin-1/2)
- dependence on the transverse momentum of the produced hadron.

The full results will be presented elsewhere\(^b\). Here we give some examples in form of weighted cross sections listed in Table 1. The electromagnetic part in the cross section of the first line is the asymmetry discussed in Sec. 2. Additionally, from the interference term there is a $\cos(\phi_\ell + \phi_S)$ dependence involving the same combination of distribution and fragmentation functions (second line). In principle, it provides an independent piece of information for a flavor decomposition. But since, the term is probably difficult to measure accurately, one may think of a more modest usage. Together with the simplifying assumption of only one flavor contributing dominantly to the fragmentation, e.g. $u$-quark fragmenting to a $\pi^+$ in the region of large $x_B$ and large $z_h$, this may be used for an independent cross-check on $h_1(x) H_1^{±(1)}$.

The electromagnetic part of the cross-section in the third line was discussed before\(^c\). Also here we find an orthogonal angular dependence resulting from the interference of electromagnetic and weak interaction (fourth line).

Particularly interesting is the possibility of non-zero “naive time-reversal odd” distribution functions, which would show up in a weighted cross section like in the fifth line. The electromagnetic term was discussed by Boer and Mulders\(^d\).

\(^a\)Strictly, this gives information for the quantities only at the scale of the $Z$ mass; evolution has to be taken into account for usage in other hard processes at a different scale.
\[ W \cdot \left[ -\frac{4\pi a_s^2}{Q^2} |S_T| (1-y)x_B \right]^{-1} \]

\begin{align*}
\frac{Q^2}{M_a} \sin(\phi_h^0 + \phi_S^0) & \sum_{a,a} \left( e_a^2 + 8 g_V^2 e_a g_V^0 \chi_1 + 16 c_1^2 c_2^\perp \chi_2 \right) \\
\times & h_1^q(x_B) H_{1}^{(1)a} (z_h)
\end{align*}

\begin{align*}
\frac{Q^2}{M_a} \cos(\phi_h^0 + \phi_S^0) & \sum_{a,a} 8 g_V^2 e_a g_V^0 \chi_1 \frac{\Gamma_Z^2 M_a^2}{Q^2 - M_a^2} h_1^q(x_B) H_{1}^{(2)a} (z_h)
\end{align*}

\begin{align*}
\frac{Q^2}{6 M^2 T_h} \sin(3\phi_h^0 - \phi_S^0) & \sum_{a,a} \left( e_a^2 + 8 g_V^2 e_a g_V^0 \chi_1 + 16 c_1^2 c_2^\perp \chi_2 \right) \\
\times & h_{1T}^{(2)a} (x_B) H_{1}^{(1)a} (z_h)
\end{align*}

\begin{align*}
\frac{Q^2}{6 M^2 T_h} \cos(3\phi_h^0 - \phi_S^0) & \sum_{a,a} \left( 2 - \frac{y(2-y)}{2-2y} \left( e_a^2 + 8 g_V^2 e_a g_V^0 \chi_1 + 16 c_1^2 c_2^\perp \chi_2 \right) \right) \\
\times & h_{1T}^{(2)a} (x_B) D_{1a}^T (z_h)
\end{align*}

\[ \chi_1 = \frac{1}{16\pi a_s^2_{u,v}} \frac{Q^2 (Q^2 - M_Z^2)}{(Q^2 - M_Z^2)^2 + \Gamma_Z^2 M_a^2} \]
\[ \chi_2 = \frac{1}{16\pi a_s^2_{u,v}} \frac{Q^2}{Q^2 - M_Z^2} \chi_1 \]

Table 1: Weighted cross sections in semi-inclusive DIS.

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