Twist-3 Effects in Polarized Drell-Yan and Semi-Inclusive DIS

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Two twist-3 processes are discussed. We first present a simple estimate of the longitudinal-transverse spin asymmetry in the polarized Drell-Yan process. We next derive a cross section for the semi-inclusive production of a polarized spin-1/2 baryon in the DIS of an unpolarized electron off the polarized nucleon.

Spin dependent processes in high energy scatterings provide us with a possibility to extract twist-3 distribution and fragmentation functions which represent quark-gluon correlations inside the hadrons. A well known example is the nucleon's transverse spin-structure function $g_2(x, Q^2)$. In this report, we discuss two other processes in which twist-3 distribution functions reveal themselves as a leading contribution with respect to the inverse power of the hard momentum Q. The first one is the longitudinal (L) and the transverse (T) spin asymmetry A_{LT} in the nucleon-nucleon polarized Drell-Yan process. We present a simple estimate for A_{LT} in comparison with A_{LL} and A_{TT}.[1] The second one is the semi-inclusive production of a polarized spin-1/2 baryon in the deep inelastic scattering from a polarized nucleon. A formula for the cross section is presented.

In LO QCD, the double spin asymmetries in the nucleon-nucleon polarized Drell-Yan process are given by [2]

$$A_{LL}N = \Sigma_a e_a^2 g_1^a(x_1, Q^2) g_1^{\bar{a}}(x_2, Q^2), \tag{1}$$

$$A_{TT}N = a_{TT}\Sigma_a e_a^2 h_1^a(x_1, Q^2) h_1^{\bar{a}}(x_2, Q^2), \tag{2}$$

$$A_{LT}N = a_{LT}\Sigma_a e_a^2 \left[g_1^a(x_1, Q^2) x_2 g_T^{\bar{a}}(x_2, Q^2) + x_1 h_L^a(x_1, Q^2) h_1^{\bar{a}}(x_2, Q^2) \right], \tag{3}$$

where $N = \Sigma_a e_a^2 f_1^a(x_1, Q^2) f_1^{\bar{a}}(x_2, Q^2)$, Q^2 is the virtuality of the photon, e_a represent the electric charge of the quark-flavor a and the summation is over all quark and anti-quark flavors: $a = u, d, s, \bar{u}, \bar{d}, \bar{s}$, ignoring heavy quark contents $(c, b, \cdots)$ in the nucleon. The variables x_1 and x_2 refer to the momentum fractions of the partons coming from the two nucleons "1" and "2", respectively. In (2) and (3), a_{TT} and a_{LT} represent the asymmetries in the parton level defined as $a_{TT} = \sin^2\theta \cos 2\phi/(1+\cos^2\theta)$ and $a_{LT} = (M/Q)(2\sin 2\theta \cos\phi)/(1+\cos^2\theta)$, where θ and ϕ are, respectively, the polar and azimuthal angle of the lepton momentum with respect to the beam direction and the transverse spin. We note that A_{LL} and A_{TT} receive contribution only from the twist-2 distributions, while A_{LT} is proportional to the twist-3 distributions and hence a_{LT} is suppressed by a factor $1/Q$.

The twist-3 distributions g_T and h_L can be decomposed into the twist-2 contribution and the "purely twist-3" contribution (at $m_q = 0$):

$$g_T(x, \mu^2) = \int_x^1 dy \frac{g_1(y, \mu^2)}{y} + \widetilde{g}_T(x, \mu^2),$$

$$h_L(x, \mu^2) = 2x \int_x^1 dy \frac{h_1(y, \mu^2)}{y^2} + \widetilde{h}_L(x, \mu^2). \tag{4}$$

The purely twist-3 pieces $\widetilde{g}_T$ and $\widetilde{h}_L$ can be written as quark-gluon-quark correlators on the light-cone. In the following we call the first terms in (4) $g_T^{WW}(x, \mu^2)$ and $h_L^{WW}(x, \mu^2)$ (Wandzura-Wilczek parts).

For the present estimate of A_{LT}, we have used the LO parametrization by Glück-Reya-Vogt for f_1 [3], the LO parametrization (standard scenario) by Glück-Reya-Stratmann-Vogelsang (GRSV) and the LO model-A by Gehrmann and Stirling for g_1 [4]. For h_1, g_T and h_L no experimental data is available up to now and we have to rely on some theoretical postulates. Here we assume $h_1(x, \mu^2) = g_1(x, \mu^2)$ at a low energy scale ($\mu^2 = 0.23$ GeV^2) as has been suggested by a low energy nucleon model [2]. These assumptions also fix g_T^{WW} and h_L^{WW}. For the purely twist-3 parts $\widetilde{g}_T$ and $\widetilde{h}_L$ we employ the bag model results at a low energy scale, assuming the bag scale is $\mu_{bag}^2 = 0.081$ and 0.25 GeV^2. For the Q^2 evolution of $\widetilde{g}_T(x,Q^2)$ and $\widetilde{h}_L(x,Q^2)$, we apply the large-N_c evolution[5]: In the $N_c \to \infty$ limit, their evolution equation is reduced to a simple DGLAP form similarly to the twist-2 distibution and a correction due to the finite value of N_c is of $O(1/N_c^2) \sim 10$ % level.

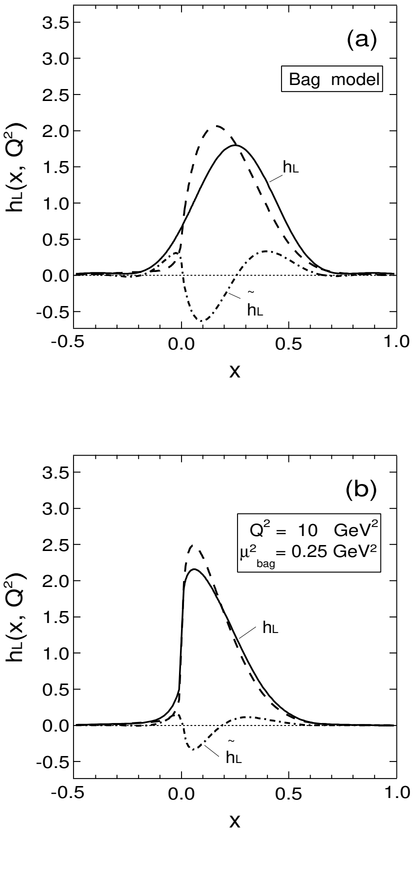

Figure 1. Bag model calculation of $h_L(x)$. The full, dashed, and dash-dot lines, respectively, denote h_L, h_L^{WW}, and $\widetilde{h}_L$.

To see the characteristics of the Q^2 evolution of the twist-3 distributions, we show in Fig. 1 the bag model result for h_L and the one at $Q^2 = 10$ GeV ^{2} obtained by assuming that the bag scale is $\mu_{bag}^2 = 0.25\ GeV^2$ [6]. One sees clearly that even though $\widetilde{h}_L(x,Q^2)$ is of the same order as $h_L^{WW}(x,Q^2)$ at a low energy scale, $h_L(x,Q^2)$ is dominated by $h_L^{WW}(x,Q^2)$ at a high energy scale. This feature is common to $g_T(x,Q^2)$ and has a following general ground not peculiar to the bag model calculation:

- The anomalous dimensions for $\widetilde{h}_L(x,Q^2)$ and $\widetilde{g}_T(x,Q^2)$ are larger than those for $h_1(x,Q^2)$ and $g_1(x,Q^2)$, hence faster Q^2 evolution for the former.
- $\widetilde{h}_L(x,Q^2)$ has a node. This is due to the sum rule $\int_{-1}^{1} dx\, \widetilde{h}_L(x,Q^2) = 0$ and $\int_{-1}^{1} dx\, \widetilde{g}_T(x,Q^2) = 0$, which is known as the Burkhardt and Cottingham sum rule for $g_T(x,Q^2)$.

In Ref.[1], we have calculated the asymmetries normalized by the partonic asymmetries, $\widetilde{A}_{LL} = -A_{LL}$, $\widetilde{A}_{TT} = -A_{TT}/a_{TT}$, $\widetilde{A}_{LT} = -A_{LT}/a_{LT}$, at the center of mass energy $\sqrt{s} = 50$ and 200 GeV and the virtuality of the photon $Q^2 = 8^2$ and 10^2 (GeV)^2, which are within or close to the planned RHIC and HERA-$\vec{N}$ kinematics. (50 GeV $< \sqrt{s} <$ 500 GeV for RHIC, and $\sqrt{s} = 40$ GeV for HERA-$\vec{N}$.) Although the GRSV and GS distributions give quite different result, the following common features are observed:

- $\widetilde{A}_{LT}$ is approximately 5 to 10 times smaller than $\widetilde{A}_{LL}$ and $\widetilde{A}_{TT}$. This is largely due to the factor x_1 and x_2 in (3), either of which takes quite small values in the whole kimematic range considered ($-0.5 < x_F = x_1 - x_2 < 0.5$).
- The contribution from $\widetilde{h}_L$ and $\widetilde{g}_T$ is almost negligible compared with the Wandzura-Wilczek part, which is due to the peculiar Q^2 evolution shown in Fig.1. Larger bag scale μ_{bag}^2 would not make the former contribution appreciably larger.

From these results, extraction of the effect of the quark-gluon correlation in $\widetilde{h}_L$ and $\widetilde{g}_T$ would be very challenging in the future polarized Drell-Yan experiment.

Next we discuss briefly the semi-inclusive production of a polarized spin-1/2 baryon (mass M_B) in the DIS of an unpolarized electron from the polarized nucleon (mass M).[7] In this process one can measure the following combination of the quark distribution and the fragmentation functions:

$$G_1(x,z) = e_a^2 g_1^a(x)\hat{g}_1^a(z),$$
$$G_T(x,z) = e_a^2\left(g_T^a(x)\hat{g}_1^a(z) + \frac{M_B h_1^a(x)\hat{h}_L^a(z)}{Mxz}\right),$$
$$H_1(x,z) = e_a^2 h_1^a(x)\hat{h}_1^a(z),$$
$$H_L(x,z) = e_a^2\left(h_L^a(x)\hat{h}_1^a(z) + \frac{M_B g_1^a(x)\hat{g}_T^a(z)}{Mxz}\right),$$

where the summation over quark flavors is implied. Consider the cross section in the target rest frame. We take the cordinate system in which the lepton beam defines the z-axis and the x-z plane contains the nucleon polarization vector which has a polar angle α. The scattered lepton has polar and azimuthal angle (θ,ϕ). The cross section for the production of the longitudinally polarized spin-1/2 baryon is

$$\frac{d\Delta\sigma}{dxdydzd\phi} = \frac{\alpha_{em}^2}{Q^2}\left[-\cos\alpha\frac{1+(1-y)^2}{y}G_1(x,z) + \sin\alpha\cos\phi\sqrt{(\kappa-1)(1-y)} \times\left\{\frac{1+(1-y)^2}{y}G_1(x,z) - \frac{2(2-y)}{y}G_T(x,z)\right\}\right].$$

Here $x = Q^2/2P\cdot q$, $y=(E-E')/E$, $\kappa = 1+(4M^2x^2/Q^2)$, $z = P\cdot P_B/P\cdot q$, where $P = (M,0)$, P_B, q are the 4-momenta of the initial nucleon, the produced baryon, and the virtual photon, and E and E' are the energies of the initial and the scattered leptons, respectively. Note the appearence of the factor $\sqrt{\kappa-1}\sim O(1/Q)$ in the second term which characterizes twist-3 effect. Even at $\alpha=\pi/2$, the nucleon's polarization vector is not completely orthogonal to the virtual photon's momentum and the cross section receives the contribution from $G_1(x,z)$, which can be extracted by setting $\alpha=0$.

Similarly, the cross section for the production of the transversely polarized baryon is

$$\frac{d\Delta\sigma}{dxdydzd\phi} = \frac{\alpha_{em}^2}{Q^2}\left[-2\sin\alpha\cos(\phi-\phi')\frac{1-y}{y}H_1(x,z) + \cos\alpha\cos\phi'\sqrt{(\kappa-1)(1-y)} \times\left\{-\frac{2(1-y)}{y}H_1(x,z) + \frac{2(2-y)}{y}H_L(x,z)\right\}\right],$$

where ϕ' is the azimuthal angle between the polarization vector of the produced baryon $\vec{S}_B$ and the momentum of the outgoing lepton $\vec{k}'$.

These semi-inclusive processes and the polarized Drell-Yan are complementary to each other to extract twist-3 distribution functions.

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