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Transversity distribution function in hard scattering of polarized protons and antiprotons in the PAX experiment

A.V. Efremov[1], K. Goeke[2], P. Schweitzer[2]

[1] Joint Institute for Nuclear Research, Dubna, 141980 Russia
[2] Institut für Theoretische Physik II, Ruhr-Universität Bochum, 44780 Bochum, Germany

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Abstract. Estimates are given for the double spin asymmetry in lepton-pair production from collisions of transversely polarized protons and antiprotons for the kinematics of the recently proposed PAX experiment at GSI on the basis of predictions for the transversity distribution from the chiral quark soliton model.

1 Introduction

The leading structures of the nucleon in deeply inelastic scattering processes are described in terms of three twist-2 parton distribution functions – the unpolarized $f_1^a(x)$, helicity $g_1^a(x)$, and transversity $h_1^a(x)$ distribution. Owing to its chirally odd nature $h_1^a(x)$ escapes measurement in deeply inelastic scattering experiments which are the main source of information on the chirally even $f_1^a(x)$ and $g_1^a(x)$. The transversity distribution function was originally introduced in the description of the process of dimuon production in high energy collisions of transversely polarized protons [1].

Alternative processes have been discussed. Let us mention here the Collins effect [2] which, in principle, allows one to access $h_1^a(x)$ in connection with a fragmentation function describing a possible spin dependence of the fragmentation process; cf. also [3] and references therein. Recent and/or future data from semi-inclusive deeply inelastic scattering experiments at HERMES [4], CLAS [5] and COMPASS [6] could be (partly) understood in terms of this effect [7–9]. Other processes to access $h_1^a(x)$ have been suggested as well; c.f. the review [10]. However, in all these processes $h_1^a(x)$ enters in connection with some unknown fragmentation function. Moreover, these processes involve the introduction of transverse parton momenta, and for none of them a strict factorization theorem could be formulated so far. The Drell–Yan process remains up to now the theoretically cleanest and safest way to access $h_1^a(x)$.

The first attempt to study $h_1^a(x)$ by means of the Drell–Yan process is planned at RHIC [11]. The STAR Collaboration has already delivered data on the single spin asymmetry in the process $pp^\uparrow \to \pi X$ [12] in which $h_1^a(x)$ may be involved.[1] Dedicated estimates, however, indicate that at RHIC the access of $h_1^a(x)$ by means of the Drell–Yan process is very difficult [16, 17]. This is partly due to the kinematics of the experiment. The main reason, however, is that the observable double spin asymmetry $A_{\rm TT}$ is proportional to a product of transversity quark and antiquark distributions. The latter are small, even if they were as large as to saturate the Soffer inequality [18], which puts a bound on $h_1^a(x)$ in terms of the better known $f_1^a(x)$ and $g_1^a(x)$.

This problem can be circumvented by using an antiproton beam instead of a proton beam. Then $A_{\rm TT}$ is proportional to a product of transversity quark distributions from the proton and transversity antiquark distributions from the antiproton (which are connected by charge conjugation). Thus in this case $A_{\rm TT}$ is due to valence quark distributions, and one can expect sizeable counting rates. The challenging program how to polarize an antiproton beam has been recently suggested in the polarized antiproton experiment (PAX) at GSI [19]. The technically realizable polarization of the antiproton beam of about (5–10)% and the large counting rates – due to the use of antiprotons – make the program promising.

In this note we shall make quantitative estimates for the Drell–Yan double spin asymmetry $A_{\rm TT}$ in the kinematics of the PAX experiment. In order to do this we shall stick to the description of the process at LO QCD. NLO corrections have been shown to be of order (10–30)% [16, 20] which is, however, a sufficient accuracy for our purposes at the present stage. We also will estimate the recently suggested analog double spin asymmetry in J/Ψ production [21]. For the transversity distribution we shall use predictions from the chiral quark soliton model [24, 25] which have also been used among the first attempts [9] to interpret and/or predict single spin effects at HERMES, CLAS and COMPASS [4–6].

[1] The STAR data confirm earlier observations by the FNAL-E704 collaboration [13] at substantially higher energies. Assuming factorization one finds that $h_1^a(x)$ contributes to this process; however, in convolution with the equally unknown Collins fragmentation function and in competition with other mechanisms [14, 15].

2 Lepton pair production in collisions of transversely polarized $p\bar{p}$

The process $p\bar{p} \to \mu^+\mu^- X$ can be characterized by the following invariants: Mandelstam variable $s = (p_1 + p_2)^2$ and dilepton invariant mass $Q^2 = (k_1 + k_2)^2$, where $p_{1/2}$ and $k_{1/2}$ are the momenta of respectively the incoming proton–antiproton pair and the outgoing lepton pair, and the rapidity

$$y = \frac{1}{2} \ln \frac{p_1(k_1 + k_2)}{p_2(k_1 + k_2)} . \qquad (1)$$

Let us denote by $\uparrow$ ($\downarrow$) the relative orientation of the transverse polarization of protons and antiprotons. The double spin asymmetry in Drell–Yan lepton-pair production with transversely polarized protons and antiprotons is given by

$$\frac{N^{\uparrow\uparrow} - N^{\uparrow\downarrow}}{N^{\uparrow\uparrow} + N^{\uparrow\downarrow}} = D_P \; f(\theta, \phi) \; A_{\rm TT}(y, Q^2) . \qquad (2)$$

The factor D_P takes into account depolarization effects. (Detector acceptance effects will not be considered.) The function $f(\theta, \phi)$ is given by

$$f(\theta, \phi) = \frac{\sin^2\theta}{1 + \cos^2\theta} \; \cos 2\phi, \qquad (3)$$

where θ is the emission angle of one lepton in the dilepton rest frame and ϕ its azimuth angle around the collision axis counted from the polarization plane of the hadron whose spin is not flipped in (2). Finally $A_{\rm TT}$ is given by

$$A_{\rm TT}(y, Q^2) = \frac{\sum_a e_a^2 h_1^a(x_1, Q^2) h_1^a(x_2, Q^2)}{\sum_b e_b^2 f_1^b(x_1, Q^2) f_1^b(x_2, Q^2)} \; , \qquad (4)$$

where the parton momenta $x_{1/2}$ in (4) are fixed in terms of s, Q^2 and y as

$$x_{1/2} = \sqrt{\frac{Q^2}{s}} \, {\rm e}^{\pm y} \; . \qquad (5)$$

The sum goes over all quark and antiquark flavors $a = u$, $\bar{u}$, d, $\bar{d}$, ... etc. In (4) use was made of the charge conjugation invariance which relates distributions in the nucleon and antinucleon as, e.g.,

$$h_1^{u/p}(x) = h_1^{\bar{u}/\bar{p}}(x) . \qquad (6)$$

Distribution functions without explicit indication of the hadron refer to the proton, i.e. $f_1^u(x) \equiv f_1^{u/p}(x)$, etc. Equation (4) corresponds to LO QCD. It is modified at NLO [20].

In the PAX experiment an antiproton beam with energies in the range (15–25) GeV could be available, which yields an $s = (30\text{–}50)\,\text{GeV}^2$ for a fixed proton target. For this kinematics the "safe region" [22] for Drell–Yan experiments, i.e. above the region $Q \geq 4\,\text{GeV}$ dominated by lepton pairs from leptonic decays of charmed vector mesons, would mean that one would probe parton distribution functions in the large x region, $x > 0.5$.

The region $1.5\,\text{GeV} < Q < 3\,\text{GeV}$, i.e. below the J/Ψ threshold but well above the region of dileptons from $\Phi(1020)$-decays (and with sufficiently large Q^2 to be in the hard scattering regime) would allow one to explore the region $x > 0.2$. However, in principle one can also address the resonance region itself – and benefit from large counting rates [21]. Whether the "Drell–Yan subprocess" proceeds via $q\bar{q} \to \gamma^* \to \mu^+\mu^-$ or via $q\bar{q} \to J/\Psi \to \mu^+\mu^-$ is irrelevant for $A_{\rm TT}$, since the unknown $q\bar{q}J/\Psi$ and $J/\Psi\mu^+\mu^-$-couplings cancel in the ratio in (2) as argued in [21].

In any case a good understanding of background processes, possible power corrections and the K-factors is required. Low dilepton mass regions (in nucleon–nucleus collisions) were studied in [23]. Keeping this in mind we shall present below estimates for $s = 45\,\text{GeV}^2$, and $Q^2 = 5\,\text{GeV}^2$, $9\,\text{GeV}^2$ and $16\,\text{GeV}^2$.

3 Chiral quark-soliton model prediction for $h_1^a(x)$

In order to make quantitative estimates for $A_{\rm TT}$ in the PAX kinematics we will use for the transversity distribution function predictions from the chiral quark soliton model. This model was derived from the instanton model of the QCD vacuum [26] and describes numerous nucleonic properties without adjustable parameters to within (10–30)% accuracy [27]. The field theoretic nature of the model allows one to consistently compute quark and antiquark distribution functions [28] which agree with parameterizations [29] to within the same accuracy. This gives us a certain confidence that the model describes $h_1^a(x)$ with a similar accuracy.

In the chiral quark soliton model we observe the hierarchy $h_1^u(x) \gg |h_1^d(x)| \gg |h_1^{\bar{u}}(x)|$, and an interesting "maximal sea quark flavor asymmetry" $h_1^{\bar{d}}(x) \approx -h_1^{\bar{u}}(x) > 0$ [25]. In Fig. 1a we show the chiral quark soliton model prediction for $h_1^a(x)$ from [25] LO-evolved from the low scale of the model of about $\mu_0^2 = (0.6\,\text{GeV})^2$ to the scale $Q^2 = 16\,\text{GeV}^2$. In order to gain some more intuition on the predictions,

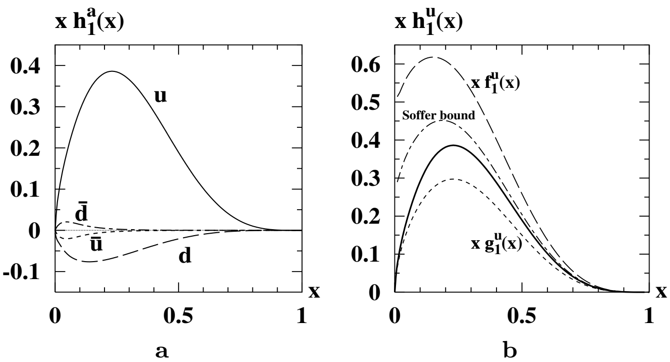

Fig. 1. a The transversity distribution function $h_1^a(x)$ versus x from the chiral quark soliton model [25]. **b** Comparison of $h_1^u(x)$ from the chiral quark soliton model (solid) to $f_1^u(x)$ (dashed) and $g_1^u(x)$ (dotted) and the Soffer bound $(f_1^u + g_1^u)(x)/2$ (dashed-dotted line) with the parameterizations of [29]. All curves in Figs. 1a,b are multiplied by x and are LO evolved to a scale of $Q^2 = 16\,\text{GeV}^2$

we compare in Fig. 1b the dominating distribution function $h_1^u(x)$ from the chiral quark soliton model to $f_1^u(x)$ and $g_1^u(x)$ from the parameterizations of [29]. It is remarkable that the Soffer inequality $|h_1^u(x)| \leq (f_1^u + g_1^u)(x)/2$ is nearly saturated – in particular in the large x region. (The Soffer bound in Fig. 1b is constructed from $f_1^u(x)$ and $g_1^u(x)$ taken at $Q^2 = 16\,\mathrm{GeV}^2$ from [29].)

For the unpolarized distribution function $f_1^a(x)$ we use the LO parameterization from [29].

4 Double spin asymmetry A_{TT} at PAX

The estimates for the double spin asymmetry A_{TT} as defined in (4) for the PAX kinematics on the basis of the ingredients discussed above is shown in Fig. 2a. The explorable rapidity range shrinks with increasing dilepton mass Q^2. Since $s = x_1 x_2 Q^2$, for $s = 45\,\mathrm{GeV}^2$ and $Q^2 = 5\,\mathrm{GeV}^2$ ($16\,\mathrm{GeV}^2$) one probes parton momenta $x > 0.3$ ($x > 0.5$). The asymmetry A_{TT} grows with increasing Q^2 where larger parton momenta x are involved, since $h_1^u(x)$ is larger with respect to $f_1^u(x)$ in the large x region; cf. Fig. 1b. The magnitude of A_{TT} can roughly be estimated by noting that at $Q^2 = 5\,\mathrm{GeV}^2$ in the model with a good accuracy $xh_1^u(x) \approx 4.0\,x(1-x)^3$ for all x, while somehow more roughly $xf_1^u(x) \approx 5.5\,x(1-x)^3$ for $x \gtrsim 0.5$. This yields $A_{\mathrm{TT}} \approx (4.0/5.5)^2 \approx 0.5$ considering u-quark dominance.

The advantage of using antiprotons is evident from Fig. 2b. The corresponding asymmetry from proton–proton collisions is an order of magnitude smaller (this observation holds also in the kinematics of RHIC [25]). At first glance this advantage seems to be compensated by the polarization factor in (2). D_P is basically the product of the antiproton beam polarization of (5–10)% and the proton target polarization of 90%, i.e. at PAX $D_P \approx 0.05$. For instance, at RHIC the polarization of each proton beam could reach 70%, yielding $D_P \approx 0.5$. However, thanks to the use of antiprotons cross sections and counting rates are more sizeable.

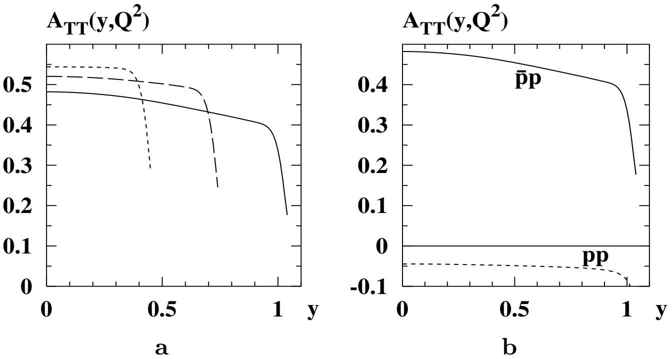

Fig. 2. **a** The asymmetry $A_{\mathrm{TT}}(y, M^2)$, cf. (4), as a function of the rapidity y for $Q^2 = 5\,\mathrm{GeV}^2$ (solid) and $9\,\mathrm{GeV}^2$ (dashed) and $16\,\mathrm{GeV}^2$ (dotted line) for $s = 45\,\mathrm{GeV}^2$. **b** Comparison of $A_{\mathrm{TT}}(y, M^2)$ from proton–antiproton (solid) and proton–proton (dotted line) collisions at PAX for $Q^2 = 5\,\mathrm{GeV}^2$ and $s = 45\,\mathrm{GeV}^2$

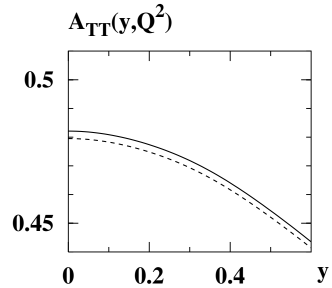

Fig. 3. The Drell–Yan double spin asymmetry A_{TT} at PAX for $s = 45\,\mathrm{GeV}^2$ and $Q^2 = 5\,\mathrm{GeV}^2$. Solid line: The full result. Dashed line: The "transversity u-quark approximation"; only $h_1^u(x)$ is considered in the numerator of A_{TT} in (4)

A precise measurement of A_{TT} in the region $Q > 4\,\mathrm{GeV}$ is very difficult, however, in the dilepton mass region below the J/Ψ threshold [19] and in the resonance region [21] A_{TT} could be measured with sufficient accuracy in the PAX experiment.

What could one learn from a measurement of the Drell–Yan double spin asymmetry A_{TT} in proton–antiproton collisions at PAX? The PAX experiment is sensitive in particular to $h_1^u(x)$. This is demonstrated by Fig. 3 where A_{TT} is compared to what one would obtain in a "transversity u-quark-only approximation", i.e. by replacing $\sum_a e_a^2 h_1^a(x_1) h_1^a(x_2) \to \frac{4}{9} h_1^u(x_1) h_1^u(x_2)$ in the numerator of A_{TT} in (4). Clearly, with good accuracy the result can be interpreted as being due to $h_1^u(x)$ only.

In the mid-rapidity region $y \approx 0$ the asymmetry $A_{\mathrm{TT}} \propto [h_1^u(x)]^2$ at $x \approx \sqrt{Q^2/s}$. A precise measurement would allow one to discriminate between different models for $h_1^a(x)$. For example, on the basis of the non-relativistic quark model motivated popular guess $h_1^a(x) \approx g_1^a(x)$ (at some unspecified low scale) one would expect an A_{TT} of about 30% [21] to be contrasted with the chiral quark soliton model estimate of about 50%; cf. Fig. 2a.

5 Summary

To summarize, in the recently proposed PAX experiment at GSI one could access the u-quark transversity distribution function in the valence x region $x > 0.2$ by means of the double spin asymmetry in Drell–Yan lepton-pair production from collisions of transversely polarized protons and antiprotons [19]. A leading order QCD estimate yields at dilepton invariant masses below the threshold of J/Ψ, but well above the background from decays of $\Phi(1020)$ and other resonances, sizeable spin asymmetries $A_{\mathrm{TT}} \approx (40–50)\%$ on the basis of predictions for $h_1^a(x)$ from the chiral quark soliton model [25]. At next-to-leading order in QCD one can expect corrections to this result which reduce somehow the asymmetry [20]. Similarly large asymmetries can also be expected in the recently suggested process of lepton-pair production via J/Ψ production [21]. In order to unambiguously interpret the result it is, however, necessary to understand well – both phenomenologically and theoretically – background processes, possible power corrections and K-factors in the dilepton mass region $Q < 4\,\mathrm{GeV}$.

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