TRANSVERSITY AND THE POLARIZED 
DRELL-YAN PROCESS IN $p\bar{p} \rightarrow \mu^+\mu^-X$ *

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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 probabilistic quark-parton model developed earlier.

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 $f_1^q(x)$, helicity $g_1^q(x)$, and transversity $h_1^q(x)$ distribution. Owing to its chirally odd nature $h_1^q(x)$ escapes measurement in deeply inelastic scattering experiments which are the main source of information on the chirally even $f_1^q(x)$ and $g_1^q(x)$. 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 to access $h_1^q(x)$ in connection with a fragmentation function describing a possible spin dependence of the fragmentation process, see also [3] and references therein. Recent and/or future data from semi-inclusive deeply inelastic scattering (SIDIS) experiments at HERMES [4], CLAS [5] and COMPASS [6] could be (partly) understood in terms of this effect [7, 8, 9]. Other processes to access $h_1^q(x)$ have been suggested as well, see the review [10]. However, in all these processes $h_1^q(x)$ 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 $h_1^q(x)$.

The first attempt to study $h_1^q(x)$ by means of the Drell-Yan process is planned at RHIC [11]. Dedicated estimates, however, indicate that at RHIC the access of $h_1^q(x)$ by means of the Drell-Yan process is very difficult [12, 13]. This is partly due to the kinematics of the experiment. The main reason, however, is that the observable double spin asymmetry $A_{TT}$ 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 [14] which puts a bound on $h_1^q(x)$ in terms of the better known $f_1^q(x)$ and $g_1^q(x)$.

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This problem can be circumvented by using an antiproton beam instead of a proton beam. Then \( A_{TT} \) 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 \( A_{TT} \) 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 [15]. 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 \( A_{TT} \) in the kinematics of the PAX experiment. For that we shall stick to the description of the process at LO QCD. NLO corrections for \( A_{TT} \) have been shown to be small [12, 16, 17]. Similar estimations were done earlier [18, 19] using different models for the transversity distribution. Here for transversity distribution we shall use the result of the covariant probabilistic model developed earlier [21, 22]. In this model the quarks are represented by quasifree fermions on mass shell and their intrinsic motion, which has spherical symmetry and is related to the orbital momentum, is consistently taken into account. It was shown, that the model nicely reproduces some well-known sum rules. The calculation was done from the input on unpolarized valence quark distributions \( q \) and it was shown, that assuming \( SU(6) \) symmetry, a very good agreement with experimental data on the proton spin structure functions \( g_1 \) and \( g_2 \) can be obtained.

## 2 Transversity and the dilepton transverse spin asymmetry

In the paper [22] we discussed the transversity distribution in the mentioned quark-parton (QPM) model. This model, in the limit of massless quarks, implies the relation between the transversity and the corresponding valence quark distribution:

\[
\delta q(x) = \kappa \cos \eta_q \left( q_V(x) - x^2 \int_x^1 \frac{q_V(y)}{y^3} dy \right). \tag{1}
\]

The factors \( \cos \eta_q \) represent relative contributions to the proton spin from different quark flavors, which for the assumed \( SU(6) \) symmetry means, that \( \cos \eta_u = 2/3 \) and \( \cos \eta_d = -1/3 \). The factor \( \kappa \) depends on the way, in which the transversity is calculated:

\( i) \) Interference effects are attributed to the quark level only, then \( \kappa = 1 \). In this approach the relation between the transversity and the usual polarized distribution is obtained

\[
\delta q(x) = \Delta q(x) + \int_x^1 \frac{\Delta q(y)}{y} dy, \tag{2}
\]

which means, that the resulting transversity distribution is roughly twice as large as the usual \( \Delta q \). The signs of both the distributions are simply correlated. Soffer inequality in this approach is violated for the case of large negative quark polarization, when \( \cos \eta_q < -1/3 \), which means that the proton \( d-\)quarks in the \( SU(6) \) scheme are just on the threshold of violation.
ii) Interference effects at parton-hadron transition stage are included in addition, but the result represents only upper bound for the transversity. This bound is more strict than the Soffer one and roughly speaking, our bound is more restrictive for quarks with a greater proportion of intrinsic motion and/or smaller (or negative) portion in the resulting polarization. No simple correspondence between the signs of actual transversity and $\Delta q$ follows from this approach. In this scenario: $\kappa = \cos^2(\eta_q/2) / \cos \eta_q$.

Following the papers [18, 19], the transversity can be measured from the Drell-Yan process $q\bar{q} \rightarrow l^+ l^-$ in the transversely polarized $p\bar{p}$ collisions in the proposed PAX experiment. The transversity can be extracted from the double transverse spin asymmetry

$$A_{TT}(y, Q^2) = \frac{\sum_q e_q^2\delta g(x_1, Q^2)\delta g(x_2, Q^2)}{\sum_q e_q^2g(x_1, Q^2)g(x_2, Q^2)}; \quad x_{1/2} = \sqrt{Q^2/s} \exp(\pm y),$$

where, using momenta $P_1, P_2$ of the incoming proton–antiproton pair and the momenta $k_1, k_2$ of the outgoing lepton pair, one defines the physical observables

$$s = (P_1 + P_2)^2, \quad Q^2 = (k_1 + k_2)^2, \quad y = \frac{1}{2} \ln \frac{P_1(k_1 + k_2)}{P_2(k_1 + k_2)}.$$

The variable $y$ can be interpreted as the rapidity of lepton pair. The asymmetry $A_{TT}$ is obtained from the cross sections corresponding to the different combinations of transverse polarizations in the incoming $p\bar{p}$ pair

$$A_{TT}(y, Q^2) = \frac{1}{\hat{a}_{TT}} \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}}; \quad \hat{a}_{TT} = \frac{\sin^2 \theta}{1 + \cos^2 \theta} \cos(2\varphi),$$

where the last expression corresponds to the double spin asymmetry in the QED elementary process, $q\bar{q} \rightarrow l^+ l^-$. So using the above formulas, one can calculate the double spin asymmetry (3) from the valence quark distribution according to the relation (1). In Fig. 1 the result of the calculation is shown.

The normalized input on the proton valence quark distribution was taken from Ref. [23], which corresponds to $Q^2 = 4 GeV^2$ and the energy squared of $p\bar{p}$ system is taken $45 GeV^2$ in an accordance with the assumed PAX kinematics. In the same figure the curve obtained at $Q^2 = 5 GeV^2$ from the calculation [19] based on the chiral quark-soliton model [24] is shown for a comparison. All curves in this figure are based on the same parameterization [20] of the distribution functions $q(x, Q^2)$ appearing in the denominator in Eq. (3). Obviously, our calculation gives a lower estimate of the $A_{TT}$ and one of possible reasons can be the effect of quark intrinsic motion, which, as we have shown, can play role not only for the

Figure 1: Double spin asymmetry at $Q^2 = 4 GeV/c$ is calculated using two transversity approaches: Interference effects are attributed to quark level only (solid line). Interference effects at parton-hadron transition stage are included in addition (dashed line), this curve represents upper bound only. Dotted curve corresponds to the calculation based on chiral quark-soliton model [19].
spin function $g_1$[21], but also for the transversity $\delta q$ [22]. In an accordance with [18], the motion of the lepton pair can be described alternatively with the using the variable

$$x_F = \frac{2q_L}{\sqrt{s}} = x_1 - x_2 = 2\sqrt{\frac{Q^2}{s}} \sinh y.$$  \hspace{1cm} (6)$$

In the Fig. 2 the estimation of asymmetry obtained in the cited paper for $Q^2 = 4$GeV$^2$ and at $s = 45$GeV$^2$ is compared with our curves from Fig. 1, in which the variable $y$ is replaced by the $x_F$, whereas both the variables are related by the transformation (6).

Apparently, for $x_F \leq 0.5$ the curve from [18] is quite compatible with our results.

So, in both the figures we have the set of curves resulting from different assumptions and the experiment should decide, which one gives the best fit to the data. How many events is necessary for discriminating among the displayed curves? After integrating over angular variables one gets

$$A_{TT} = \frac{n_+ - n_-}{n_+ + n_-},$$  \hspace{1cm} (7)$$

then

$$\Delta A_{TT} = \sqrt{\left( \frac{\partial A_{TT}}{\partial n_+} \Delta n_+ \right)^2 + \left( \frac{\partial A_{TT}}{\partial n_-} \Delta n_- \right)^2} = 2\sqrt{\frac{n_+ n_-}{n_+ + n_-}}.$$  \hspace{1cm} (8)$$

which implies

$$\Delta A_{TT} = \frac{1 - A_{TT}^2}{N_{ev}}; \quad N_{ev} = n_+ + n_-.$$  \hspace{1cm} (9)$$

So for approximate estimate of the statistical error we obtain

$$\Delta A_{TT} \lesssim \frac{1}{\sqrt{N_{ev}}},$$  \hspace{1cm} (10)$$

where $N_{ev}$ is number of events related to the bin or interval of $y$ or $x_F$ in which the curves are compared. For example, if one requires $\Delta A_{TT} \leq 1\%$, which is error allowing to separate the curves in presented figures, then roughly $10^4$ should be the number of events in the considered bin or interval. Of course, this estimation assumes full polarization of the colliding proton and antiproton. Since the expected polarization of antiprotons at the PAX will hardly be better than $(5 - 10)\%$, the minimum number of events will be correspondingly higher.
3 Summary

The covariant probabilistic QPM, which takes into account intrinsic quark motion, was applied to the calculation of transverse spin asymmetry of dileptons produced in the $p\bar{p}$ collisions in the conditions, which are expected for the recently proposed experiment PAX. This asymmetry is directly related to the transversity distributions of quarks inside the proton. In our asymmetry calculation the two approaches for the transversity, which differ in accounting for the interference effects, were applied. Our obtained results are compared with the prediction based on the quark-soliton model. One can observe, that quite different approaches give the similar results, but both our curves are lower than that obtained from the quark-soliton model. Our results for $x_F \leq 0.5$ are also well compatible with the recent estimate [18].

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