Polarized antiquark flavor asymmetry in Drell–Yan pair production

B. Dressler\textsuperscript{a,1}, K. Goeke\textsuperscript{a,2}, M.V. Polyakov\textsuperscript{a,b,3}, P. Schweitzer\textsuperscript{a,4}, M. Strikman\textsuperscript{c,5,*}, and C. Weiss\textsuperscript{a,6}

\textsuperscript{a}Institut für Theoretische Physik II, Ruhr–Universität Bochum, D–44780 Bochum, Germany
\textsuperscript{b}Petersburg Nuclear Physics Institute, Gatchina, St.Petersburg 188350, Russia
\textsuperscript{c}Pennsylvania State University, University Park, PA 16802, U.S.A.

Abstract

We investigate the role of the flavor asymmetry of the nucleon’s polarized antiquark distributions in Drell–Yan lepton pair production in polarized nucleon–nucleon collisions at HERA (fixed–target) and RHIC energies. It is shown that the large polarized antiquark flavor asymmetry predicted by model calculations in the large–$N_c$ limit (chiral quark–soliton model) has a dramatic effect on the double spin asymmetries in high mass lepton pair production, as well as on the single spin asymmetries in lepton pair production through $W^\pm$–bosons at $M^2 = M_W^2$. 

\textsuperscript{1}E-mail: birgitd@tp2.ruhr-uni-bochum.de
\textsuperscript{2}E-mail: goeke@tp2.ruhr-uni-bochum.de
\textsuperscript{3}E-mail: maximp@tp2.ruhr-uni-bochum.de
\textsuperscript{4}E-mail: peterw@tp2.ruhr-uni-bochum.de
\textsuperscript{5}E-mail: strikman@physics.psu.edu
\textsuperscript{6}E-mail: weiss@tp2.ruhr-uni-bochum.de
\* Alexander–von–Humboldt–Forschungspreisträger
Drell–Yan (DY) lepton pair production in pp or pn collisions offers one of the most direct ways to measure the antiquark distributions in the nucleon. In particular, such experiments have recently established a significant flavor asymmetry of the unpolarized antiquark distributions, $\bar{u}(x) - \bar{d}(x)$, see Ref. [1] for a review. Since the amount of $\bar{u}(x) - \bar{d}(x)$ generated perturbatively is very small, this provides unambiguous evidence for an important role of nonperturbative effects in generating the sea distributions. Other evidence is the large suppression of the strange sea compared to the nonstrange one for $Q^2$ of the order of a few GeV$^2$. It appears natural to invoke the chiral degrees of freedom for the explanation of these effects. Two competing mechanisms are currently being discussed. One is due to scattering off pions generated via virtual processes $N \to N + \pi$, $N \to \Delta + \pi$, or $q \to q + \pi$ [2]. With this mechanism one can in principle generate a significant value of $\bar{u}(x) - \bar{d}(x)$, although this requires one to consider virtual pion momenta up to $\sim 1$ GeV and relies on fine-tuning of the parameters of the model; see Ref. [3] for a discussion. Another mechanism emerges within the large--$N_c$ limit of QCD, where the nucleon can be described as a chiral soliton [4, 5, 6]. This approach allows for a fully quantitative description of the antiquark distributions essentially without free parameters, and preserves all fundamental qualitative properties of the distribution functions, such as positivity, sum rules etc. It describes well the data for $\bar{u}(x) - \bar{d}(x)$ [6].

It was pointed out in Ref. [7] that a distinctive difference of the two mechanisms is the degree of polarization of the antiquark flavor asymmetry, $\Delta \bar{u}(x) - \Delta \bar{d}(x)$. In the pion cloud models polarization is absent [3]. There have been some attempts to generate polarization by including spin–1 resonances in this picture [4], which, however, presents severe conceptual difficulties. In contrast to the pion cloud model the large–$N_c$ approach predicts that $\Delta \bar{u}(x) - \Delta \bar{d}(x)$ is much larger than the unpolarized $\bar{u}(x) - \bar{d}(x)$; in fact, it is parametrically enhanced by a factor of $N_c$. [The numerical results for the polarized [4] and unpolarized [5] antiquark flavor asymmetries obtained in this approach are shown in Fig. 1 at a scale of $\mu^2 = (5 \text{ GeV})^2$.] Thus, measurements of $\Delta \bar{u}(x) - \Delta \bar{d}(x)$ would provide a decisive test of the different approaches to include the chiral degrees of freedom in the nucleon.

We have recently demonstrated that the current data on hadron production in semi-inclusive deep–inelastic scattering (DIS) are not sensitive to the value of $\Delta \bar{u}(x) - \Delta \bar{d}(x)$ [7]. The purpose of this letter is to study if DY pair and $W^\pm$ production in polarized pp collisions, which will be possible at RHIC, allow to distinguish between the two options. Specifically, we investigate the role of the large polarized antiquark flavor asymmetries obtained in the large–$N_c$ model calculation of Ref. [4, 7] on spin asymmetries in longitudinally polarized DY pair production.

Predictions for the spin asymmetries in polarized DY pair production (see e.g. Ref. [10]) have so far been made on the basis of present experimental information about the polar-
ized parton distributions in the nucleon, which comes mostly from inclusive DIS \cite{11,12}. However, DIS probes directly only the sum of quark– and antiquark distributions, while the separation in quarks and antiquarks, as well as the gluon distribution, have to be determined indirectly through scaling violations. The flavor asymmetry of the polarized antiquark distribution is practically not constrained by the DIS data \cite{11,12}. On the other hand, the polarized antiquark flavor asymmetry contributes to DY spin asymmetries at leading order in QCD \cite{13}. A quantitative understanding of these effects is a prerequisite for any attempt to extract the polarized gluon distribution from NLO analyses of the data \cite{14}.

The cross section for DY pair production is a function of the center–of–mass energy of the incoming hadrons, \(s = (p_1 + p_2)^2\), and the invariant mass of the produced lepton pair, \(M^2\), which is equal to the virtuality of the exchanged gauge boson. At the partonic level this process is described by the annihilation of a quark and an antiquark originating from the two hadrons, carrying, respectively, longitudinal momenta \(x_1 p_1\) and \(x_2 p_2\), with \(x_1 x_2 = Q^2/s\). One can parametrize the momentum fractions as \(\frac{Q^2/2}{s} e^y\), \(\frac{Q^2/2}{s} e^{-y}\), where \(y\) is called rapidity. In the case of DY pair production through a virtual photon one is interested in the double spin asymmetry of the cross section

\[
A_{\gamma}^{LL} = \frac{\sigma_{++}^\gamma - \sigma_{+-}^\gamma}{\sigma_{++}^\gamma + \sigma_{+-}^\gamma},
\]

where the subscripts \(+,−\) denote the longitudinal polarization of nucleons 1 and 2. In QCD in leading–log approximation this ratio is given by \cite{10,15}

\[
A_{\gamma}^{LL}(\gamma; s, M^2) = \frac{\sum a e_a^2 \Delta q_a(x_1, M^2) \Delta \bar{q}_a(x_2, M^2)}{\sum a e_a^2 q_a(x_1, M^2) \bar{q}_a(x_2, M^2)},
\]

where the sum runs over all species of light quarks and antiquarks in the two nucleons, \(a = \{u, \bar{u}, d, \bar{d}, s, \bar{s}\}\); we neglect the small contributions due to heavy flavors. The relevant scale here for the parton distribution functions is the virtuality of the photon, \(M^2\). When the lepton pair is produced instead by exchange of a charged weak gauge boson, \(W^\pm\), due to the parity–violating nature of the weak interaction the cross section exhibits already a single spin asymmetry,

\[
A_{\pm}^{W} = \frac{\sigma_{++}^{W} - \sigma_{--}^{W}}{\sigma_{++}^{W} + \sigma_{--}^{W}},
\]

where now the subscripts \(+,−\) denote the longitudinal polarization of nucleon 1; the polarization of nucleon 2 is averaged over. In QCD in leading–log approximation one has \cite{10,15}

\[
A_{\pm}^{W}(\pm; s, M^2) = \frac{\Delta u(x_1, M^2) \bar{d}(x_2, M^2) - \Delta \bar{d}(x_1, M^2) u(x_2, M^2)}{u(x_1, M^2) \bar{d}(x_2, M^2) + d(x_1, M^2) u(x_2, M^2)},
\]

for \(W^−\) one should exchange \(u \leftrightarrow d, \bar{u} \leftrightarrow \bar{d}\) everywhere here. Eq.(4) includes only \(u–\) and \(d–\)quarks, even for values of \(M^2\) of the order of the \(W–\)boson mass. Contributions from
In DIS with proton or nuclear targets one is able to measure directly only two flavor combinations of these three distributions; however, the third one can be inferred using \( SU(3) \) symmetry arguments.

\[ \Delta_3(x) = \Delta_8(x) = 0 \]

The combinations \( \Delta_u(x), \Delta_d(x) \) and \( \Delta_s(x) \), Eq.(5), are measured directly in inclusive polarized DIS, so we evaluate them using the GRV95 leading–order (LO) parametrization ("standard scenario"), which was obtained by fits to inclusive DIS data \([4, 7]\). The flavor–singlet antiquark distribution, \( \Delta_0(x) \), Eq.(3), we also take from the GRV95 parametrization; this distribution is known only from the study of scaling violations in inclusive DIS and depends to some extent on the assumptions made about the polarized gluon distribution; however, the GRV95 parametrization for \( \Delta_0(x) \) is in good agreement with the result of model calculations in the large–\( N_c \) limit \([7]\). For the polarized flavor asymmetries of the antiquark distribution, \( \Delta_3(x) \) and \( \Delta_8(x) \), Eqs.(7) and (8), which are not constrained by DIS data, we use the results of the model calculation in the large–\( N_c \) limit of Refs.\([4, 7]\), evolved in LO from the low normalization point by \( \mu^2 = (600 \text{ MeV})^2 \) to the experimental scale, \( M^2 \). The result for \( \Delta_3(x) \) is shown in Fig.\( 4 \) at a scale of \( (5 \text{ GeV})^2 \). The other non–singlet combination, \( \Delta_8(x) \), is obtained from \( \Delta_3(x) \) at the low normalization point by the \( SU(3) \) relation

\[ \Delta_8(x) = [(3F - D)/(F + D)]\Delta_3(x), \]

where we use \( F/D = 5/9 \), see Ref.\([4]\) for details. Note that \( \Delta_3(x) \) and \( \Delta_8(x) \) do not mix with the other distributions under LO evolution. The “hybrid” polarized quark and antiquark distributions thus obtained, by construction, fit all the inclusive polarized DIS data in LO, while at the same time incorporating the polarized antiquark flavor asymmetry obtained in the model calculation in the large–\( N_c \) limit. Finally, to evaluate the denominators in Eqs.(2) and (4) we use the GRV94 parametrization of the unpolarized parton distributions.

In Fig.\( 2 \)(a) and (b) we compare the double spin asymmetries, \( A_{LL}^c \), obtained with the “hybrid” distributions incorporating the antiquark flavor asymmetries, \( \Delta_3(x) \) and \( \Delta_8(x) \), calculated in the large–\( N_c \) limit (solid lines), with what one obtains for \( \Delta_3(x) = \Delta_8(x) = 0 \) (dashed lines). We show the results in two different kinematical regions, (a): \( s = (40 \text{ GeV})^2 \)

\([^2\text{Actually, in DIS with proton or nuclear targets one is able to measure directly only two flavor combinations of these three distributions; however, the third one can be inferred using } SU(3) \text{ symmetry arguments.}\]
and \( M^2 = (5 \text{ GeV})^2 \), corresponding to a proposed fixed target experiment using the HERA proton beam \( [18] \), and (b): \( s = (500 \text{ GeV})^2 \) and \( M^2 = M_W^2 = (80.3 \text{ GeV})^2 \), which can be reached in the RHIC experiment. One sees that in both cases the flavor asymmetry of the antiquark distribution has a dramatic effect on the spin asymmetry, reversing even its sign compared to the case with \( \Delta_3(x) = \Delta_8(x) = 0 \).

The results for the double spin asymmetry, \( A_{LL}^\gamma \), depend in principle also on the assumptions made about the polarized gluon distribution in the nucleon, which mixes with the singlet quark distribution under evolution, and which is practically not constrained by the present data. In order to estimate the sensitivity of our results to the polarized gluon distribution we have repeated the above comparison using instead of GRSV95 the Gehrmann–Stirling LO “A” and “C” parametrizations for \( \Delta_u, \Delta_d, \Delta_s \) and \( \Delta_0 \), which provide fits to the inclusive data with widely different assumptions about the shape of the input polarized gluon distributions \( [12] \). The resulting asymmetries \( A_{LL}^\gamma \) obtained without polarized flavor asymmetry, \( \Delta_3(x) = \Delta_8(x) = 0 \) (dashed lines), and including the large–\( N_c \) model results for \( \Delta_3(x) \) and \( \Delta_8(x) \) (solid lines) are shown in Fig.2 (c) and (d). One sees that the changes of \( A_{LL}^\gamma \) due to the inclusion of the flavor asymmetry (differences between corresponding solid and dashed curves) are much larger than the differences due to changes of the input gluon distribution (differences between the two dashed curves). It is not an exaggeration to say that \( A_{LL}^\gamma \) measures the polarized flavor asymmetry of the antiquark distribution, and not the polarized gluon distribution.

Our comparison of asymmetries calculated with and without inclusion of a polarized antiquark flavor asymmetry refers explicitly to the leading–logarithmic (LO) approximation, since only at this level the flavor asymmetries \( \Delta_3(x) \) and \( \Delta_8(x) \), evolve separately and can be combined with parametrizations for \( \Delta_u, \Delta_d, \Delta_s \) and \( \Delta_0 \) without affecting the fits to inclusive data. It is expected that the spin asymmetry \( A_{LL}^\gamma \) is less sensitive to NLO corrections than the polarized and unpolarized DY cross sections individually, since the \( K \)–factors partially cancel between numerator and denominator in the ratio, Eq.(2) \( [19] \); however, this claim has been debated in Ref.\( [14] \). In any case, since the inclusion of the polarized antiquark flavor asymmetry has a very large effect on \( A_{LL}^\gamma \) already at LO level, it is unlikely that higher–order corrections will reverse this situation. At least, the differences between our LO results for \( A_{LL}^\gamma \) obtained with and without flavor asymmetry are much larger than those between the LO and NLO results in the case of zero flavor asymmetry quoted in Ref.\( [14] \).

The single spin asymmetries in lepton pair production through \( W^\pm \), \( A_L^{W^\pm} \), for proton–proton scattering are shown in Fig.3 for \( s = (500 \text{ GeV})^2 \) and \( M^2 = M_W^2 = (80.3 \text{ GeV})^2 \), which can be reached at RHIC. Figs.3 (a) and (b) show the results obtained using the GRSV95 parametrization without antiquark flavor asymmetry (dashed lines), and including the contributions from \( \Delta_3(x) \) and \( \Delta_8(x) \) obtained in the large–\( N_c \) model estimate \( [4, 7] \) (solid lines). One sees that also in this case the inclusion of the antiquark flavor asymmetry has a qualitative effect on the spin asymmetry. Again, in the case of the Gehrmann–Stirling parametrizations, Fig.3 (c) and (d), the differences due to changes in the gluon distribution are negligible compared to the effect of the flavor asymmetry of the antiquark distribution.
To summarize, we have shown that the large flavor asymmetries of the polarized antiquark distributions predicted by model calculations in the large–$N_c$ limit (chiral quark–soliton model), have a pronounced effect on the spin asymmetries in Drell–Yan pair production through photons or $W^\pm$ bosons at HERA or RHIC energies. In particular, the effect of the antiquark flavor asymmetry on the spin asymmetries is much larger than their uncertainties due to the lack of knowledge of the degree of gluon polarization in the nucleon. The expected accuracy of the RHIC measurements \cite{20} will certainly be sufficient to observe an effect of the magnitude predicted.

We are grateful to S. Heppelmann and P.V. Pobylitsa for useful discussions. This investigation was supported in part by the Deutsche Forschungsgemeinschaft (DFG), by a joint grant of the DFG and the Russian Foundation for Basic Research, by the German Ministry of Education and Research (BMBF), and by COSY, Jülich. The work of M. Strikman was supported in part by a DOE grant, and by the Alexander–von–Humboldt Foundation.

References

\[1\] P.L. McGaughey, J.M. Moss, and J.C. Peng, Report LA-UR-99-850, hep-ph/9905409.

\[2\] A.W. Thomas, Phys. Lett. 126 B (1983) 97.
L.L. Frankfurt, L. Mankiewicz, and M.I. Strikman, Z. Phys. A 334 (1989) 343.
E.M. Henley and G.A. Miller, Phys. Lett. B 251 (1990) 453.
W.Y.P. Hwang, J. Speth, and G.E. Brown, Z. Phys. A 339 (1991) 383.
W. Melnitchouk and A.W. Thomas, Phys. Rev. D 47 (1993) 3794.
H. Holtmann, N.N. Nikolaev, J. Speth, and A. Szczurek Z. Phys. A 353 (1996) 411.
H. Holtmann, A. Szczurek, and J. Speth, Nucl. Phys. A 596 (1996) 397, ibid. 631.

\[3\] W. Koepf, L.L. Frankfurt, and M. Strikman, Phys. Rev. D 53 (1996) 2586.

\[4\] D.I. Diakonov, V.Yu. Petrov, P.V. Pobylitsa, M.V. Polyakov and C. Weiss, Nucl. Phys. B 480 (1996) 341; Phys. Rev. D 56 (1997) 4069.

\[5\] P.V. Pobylitsa, M.V. Polyakov, K. Goeke, T. Watabe, and C. Weiss, Phys. Rev. D 59 (1999) 034024.

\[6\] B. Dressler, K. Goeke, P.V. Pobylitsa, M.V. Polyakov, T. Watabe, and C. Weiss, Proceedings of the 11th International Conference on Problems of Quantum Field Theory, Dubna, Russia, Jul. 13–17, 1998, hep-ph/9809487.

\[7\] B. Dressler, K. Goeke, M.V. Polyakov, and C. Weiss, Report RUB-TPII-12/99, hep-ph/9909541.

\[8\] V.R. Zoller, Z. Phys. C 53 (1992) 443; C 60 (1993) 141.

\[9\] R.J. Fries and A. Schäfer, Phys. Lett. B 443 (1998) 40.
K.G. Boreskov, A.B. Kaidalov, Eur. Phys. J. C 10 (1999) 143.
[10] J. Soffer and J.–M. Virey, Nucl. Phys. B 509 (1998) 297.

[11] M. Glück, E. Reya, M. Stratmann and W. Vogelsang, Phys. Rev. D 53 (1996) 4775.

[12] T. Gehrmann and W.J. Stirling, Phys. Rev. D 53 (1996) 6100.

[13] S. Kumano and M. Miyama, Report SAGA-HE-150-99, hep-ph/9909432.

[14] T. Gehrmann, Nucl. Phys. B 498 (1997) 245.

[15] B. Kamal, Phys. Rev. D 57 (1998) 6663.

[16] A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne, Report DTP-99-64, hep-ph/9907231.

[17] M. Wakamatsu and T. Kubota, Phys. Rev. D 60 (1999) 034020.

[18] M. Anselmino et al., Proceedings of the Workshop “Future Physics at HERA”, 1995/96, ed. G. Ingelman, A. DeRoeck and G. Klanner, DESY, Hamburg (1996), p.837.

[19] P. Ratcliffe, Nucl. Phys. B 223 (1982) 45.

[20] S. Heppelmann, in Proceedings of SPIN’96, Amsterdam, Sep. 10–14, 1996.
Figure 1: The polarized and unpolarized antiquark flavor asymmetries obtained in model calculations in the large–$N_c$ limit (chiral quark–soliton model), evolved (LO) from the low normalization point of $\mu^2 = (600 \text{ MeV})^2$ to a scale of $\mu^2 = (5 \text{ GeV})^2$. Dashed line: Unpolarized flavor asymmetry, $x[\bar{d}(x) - \bar{u}(x)]$, see Ref.\[3\]. Solid line: Polarized flavor asymmetry, $x[\Delta \bar{u}(x) - \Delta \bar{d}(x)] \equiv x \Delta_3(x)$, see Refs.\[4, 7\].
Figure 2: The longitudinal double spin asymmetry in DY pair production through a virtual photon, $A_{LL}^γ$, in proton–proton collisions, as a function of the rapidity, $y$. Shown are the results for two different kinematical regions: $s = (40 \text{ GeV})^2, M^2 = (5 \text{ GeV})^2$ (HERA proton beam fixed–target experiment) and $s = (500 \text{ GeV})^2, M^2 = M_W^2 = (80.3 \text{ GeV})^2$ (RHIC). (a), (b): Dashed lines: Results obtained for zero flavor asymmetry of the polarized antiquark distributions, $\Delta_3(x) = \Delta_8(x) = 0$, using the GRSV95 LO parametrizations [11] for $\Delta_u(x), \Delta_d(x), \Delta_s(x)$ and $\Delta_0(x)$. Solid lines: Results obtained including in addition the antiquark flavor asymmetries, $\Delta_3(x)$ and $\Delta_8(x)$, obtained in model calculations in the large–$N_c$ limit [4, 7]. (c), (d): same as (a) and (b), but using instead of GRSV95 the Gehrmann–Stirling A and C parametrizations [12].
Figure 3: The longitudinal single spin asymmetry in lepton pair production through $W^+$ and $W^-$ bosons, $A_{L}^{W^+}$ and $A_{L}^{W^-}$, in proton–proton collisions, as a function of the rapidity, $y$, for $M^2 = M_{W}^2 = (80.3 \text{ GeV})^2$ and $s = (500 \text{ GeV})^2$. (a), (b): Dashed lines: Results obtained for zero flavor asymmetry of the polarized antiquark distributions, $\Delta_3(x) = \Delta_8(x) = 0$, using the GRSV95 LO parametrizations [11] for $\Delta_u(x)$, $\Delta_d(x)$, $\Delta_s(x)$ and $\Delta_0(x)$. Solid lines: Results obtained including in addition the antiquark flavor asymmetries, $\Delta_3(x)$ and $\Delta_8(x)$, obtained in model calculations in the large–$N_c$ limit [4]. (c), (d): same as (a) and (b), but using instead of GRSV95 the Gehrmann–Stirling A and C parametrizations [12].