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Polarized antiquark flavor asymmetry in Drell–Yan pair production

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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 $M^2 = M_W^2$.

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 [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 $\sim 1\,\mathrm{GeV}$ and relies on fine-tuning of the parameters of the model; see [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 [4–6]. 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].

A distinctive difference of the two mechanisms is the degree of polarization of the antiquark flavor asymmetry, $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ [7]. In the pion cloud models polarization is absent [8]. There have been some attempts to generate polarization by including spin–1 resonances in this picture [9], which, however, presents severe conceptual difficulties[1]. 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 [4,7] and unpolarized [5] antiquark flavor asymmetries obtained in this approach are shown in Fig.1 at a scale of $\mu^2 = (5\,\mathrm{GeV})^2$.] 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) do not allow to distinguish between the large value of $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ predicted by the large-N_c limit, and zero [7]. The purpose of this paper is to study

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[1] Pions play a special role as the Goldstone bosons of spontaneously broken chiral symmetry. In contrast, there is nothing special about exchanges of spin–1 resonances compared to, say, tensor, b_1, h_1, ρ_3, a_4 *etc.* mesons. Moreover, Regge recurrences are likely to lead to strong cancellations between contributions from different resonances. Also, the quark and gluon degrees of freedom already partly account for the mesonic degrees of freedom, so one faces the problem of double counting. See [7] for a critical discussion

if DY pair and $W^\pm$ production in polarized pp collisions, which will be possible at RHIC [10–13], could discriminate 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 [4,7] on spin asymmetries in longitudinally polarized DY pair production.

Predictions for the spin asymmetries in polarized DY pair production (see e.g. [12]) have so far been made on the basis of present experimental information about the polarized parton distributions in the nucleon, which comes mostly from inclusive DIS [14,15]. 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 [14,15]. On the other hand, the polarized antiquark flavor asymmetry contributes to DY spin asymmetries at leading order in QCD [16]. A quantitative understanding of these effects is a prerequisite for any attempt to extract the polarized gluon distribution from NLO analyses of the data [17].

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 $x_1 = (Q^2/s)^{1/2} e^{y}$, $x_2 = (Q^2/s)^{1/2} e^{-y}$, where y is the photon rapidity[2]. In the case of DY pair production through a virtual photon one is interested in the double spin asymmetry of the cross section [12,13]

$$A_{LL}^{\gamma} = \frac{\sigma_{++}^{\gamma} - \sigma_{+-}^{\gamma}}{\sigma_{++}^{\gamma} + \sigma_{+-}^{\gamma}}, \tag{1}$$

where the subscripts $+,-$ denote the longitudinal polarization of nucleons 1 and 2. In QCD in leading–log approximation this ratio is given by [12,13]

$$A_{LL}^{\gamma}(y; s, M^2) = \frac{\sum_a e_a^2\, \Delta q_a(x_1, M^2)\, \Delta q_{\bar{a}}(x_2, M^2)}{\sum_a e_a^2\, q_a(x_1, M^2)\, q_{\bar{a}}(x_2, M^2)}, \tag{2}$$

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,

$$A_L^{W\pm} = \frac{\sigma_+^{W\pm} - \sigma_-^{W\pm}}{\sigma_+^{W\pm} + \sigma_-^{W\pm}}, \tag{3}$$

[2] For questions concerning the reconstruction of the partonic initial state from the event data, see e.g. [10]

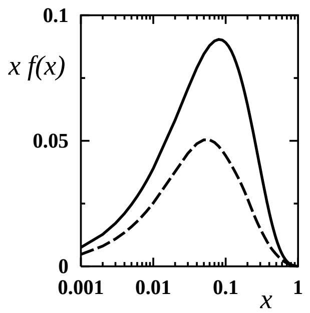

Fig. 1. The polarized and unpolarized antiquark flavor asymmetries obtained in model calculations in the large–N_c limit (chiral quark–soliton model), evolved (LO) from the low normalization point of $\mu^2 = (600\,\mathrm{MeV})^2$ to a scale of $\mu^2 = (5\,\mathrm{GeV})^2$. *Dashed line:* Unpolarized flavor asymmetry, $x[\bar{d}(x) - \bar{u}(x)]$, see [5]. *Solid line:* Polarized flavor asymmetry, $x[\Delta\bar{u}(x) - \Delta\bar{d}(x)] \equiv x\Delta_3(x)$, see [4,7]

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 [12,13]

$$A_L^{W\pm}(y; s, M^2) = \frac{\Delta u(x_1, M^2)\, \bar{d}(x_2, M^2) - \Delta\bar{d}(x_1, M^2)\, u(x_2, M^2)}{u(x_1, M^2)\, \bar{d}(x_2, M^2) + \bar{d}(x_1, M^2)\, u(x_2, M^2)}, \tag{4}$$

for W^- one should exchange $u \leftrightarrow d, \bar{u} \leftrightarrow \bar{d}$ everywhere here. Equation (4) includes only u– and d–quarks, even for values of M^2 of the order of the W–boson mass. Contributions from c–s transitions are negligible because of the comparative smallness of the product of c and s distributions, while contributions of type u–s and c–d are small because of Cabbibo suppression; see [18] for a more detailed discussion.

Our aim is to study the effect of the large flavor asymmetry of the polarized antiquark distributions, obtained in the model calculations of [4,7] based on the large–N_c limit, on the spin asymmetries A_{LL}^{γ} and $A_L^{W\pm}$, (2) and (4). In order to make maximum use of the direct experimental information on the polarized parton distributions available from DIS we proceed as follows. The individual polarized light quark and antiquark distributions $\Delta u(x), \Delta\bar{u}(x), \Delta d(x), \Delta\bar{d}(x), \Delta s(x)$, and $\Delta\bar{s}(x)$, figuring in the numerators in (2) and (4) can be expressed in terms of the six combinations

$$\Delta_u(x) \equiv \Delta u(x) + \Delta\bar{u}(x), \quad \text{(analogously for } \Delta_d, \Delta_s), \tag{5}$$

$$\Delta_0(x) \equiv \Delta\bar{u}(x) + \Delta\bar{d}(x) + \Delta\bar{s}(x), \tag{6}$$

$$\Delta_3(x) \equiv \Delta\bar{u}(x) - \Delta\bar{d}(x), \tag{7}$$

$$\Delta_8(x) \equiv \Delta\bar{u}(x) + \Delta\bar{d}(x) - 2\Delta\bar{s}(x). \tag{8}$$

The combinations $\Delta_u(x), \Delta_d(x)$ and $\Delta_s(x)$, (5), are measured directly in inclusive polarized DIS, so we evaluate them using the GRSV95 leading–order (LO) parametrization ("standard scenario"), which was obtained by fits

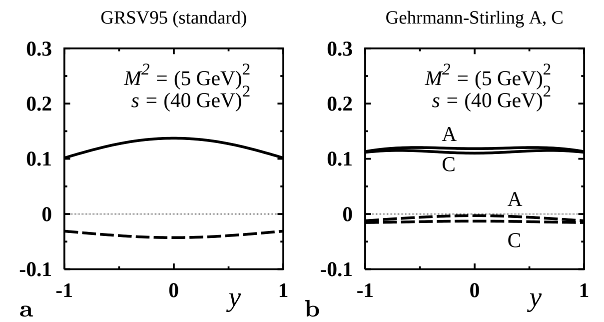

Fig. 2a,b. The longitudinal double spin asymmetry in DY pair production through a virtual photon, A_{LL}^{γ}, in proton–proton collisions, as a function of the photon rapidity, y. Shown are the results for $s = (40\,\text{GeV})^2$ and $M^2 = (5\,\text{GeV})^2$. **a**: *Dashed line:* Result obtained for zero flavor asymmetry of the polarized antiquark distributions, $\Delta_3(x) = \Delta_8(x) = 0$, using the GRSV95 LO parametrizations [14] for $\Delta_u(x), \Delta_d(x), \Delta_s(x)$ and $\Delta_0(x)$. *Solid line:* Result 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]. **b**: Same as **a**, but using instead of GRSV95 the Gehrmann–Stirling A and C parametrizations [15]

to inclusive DIS data [14][3]. The flavor–singlet antiquark distribution, $\Delta_0(x)$, (6), we also take from the GRSV95 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 GRSV95 parametrization for $\Delta_0(x)$ is in good agreement with the result of model calculations in the large–N_c limit [19]. For the polarized flavor asymmetries of the antiquark distribution, $\Delta_3(x)$ and $\Delta_8(x)$, (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 [4,7], evolved in LO from the low normalization point of $\mu^2 = (600\,\text{MeV})^2$ to the experimental scale, M^2. The result for $\Delta_3(x)$ is shown in Fig.1 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 [7] 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 (2) and (4) we use the GRV94 parametrization of the unpolarized parton distributions.

In Fig. 2a we compare the double spin asymmetries, A_{LL}^{γ}, 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 line), with what one obtains for $\Delta_3(x) = \Delta_8(x) = 0$ (dashed line). Here we show the results for $s = (40\,\text{GeV})^2$ and $M^2 = (5\,\text{GeV})^2$, which is in the kinematical region of the proposed fixed target experiment using the HERA proton beam [20]. One sees that the flavor asymmetry of the antiquark distribution has a dramatic effect on the spin asymmetry, reversing even its sign compared to the case with $\Delta_3(x) = \Delta_8(x) = 0$. We note that this effect persists also at the higher values of M^2 and s accessible in the RHIC experiment $[s > (50\,\text{GeV})^2]$.

The results for the double spin asymmetry, A_{LL}^{γ}, 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 Δ_0, which provide fits to the inclusive data with widely different assumptions about the shape of the input polarized gluon distributions [15]. The resulting asymmetries A_{LL}^{γ} 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.2b. One sees that the changes of A_{LL}^{γ} 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}^{γ} 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 Δ_0 without affecting the fits to inclusive data. It is expected that the spin asymmetry A_{LL}^{γ} 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, (2) [21]; however, this claim has been debated in [17]. In any case, since the inclusion of the polarized antiquark flavor asymmetry has a very large effect on A_{LL}^{γ} 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}^{γ} 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 [17].

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 [10,11]. Figures 3a,b show the results obtained using the GRSV95 parametrization without antiquark flavor asymmetry (dashed lines), and including the contributions from $\Delta_3(x)$

[3] 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 $SU(3)$ symmetry arguments

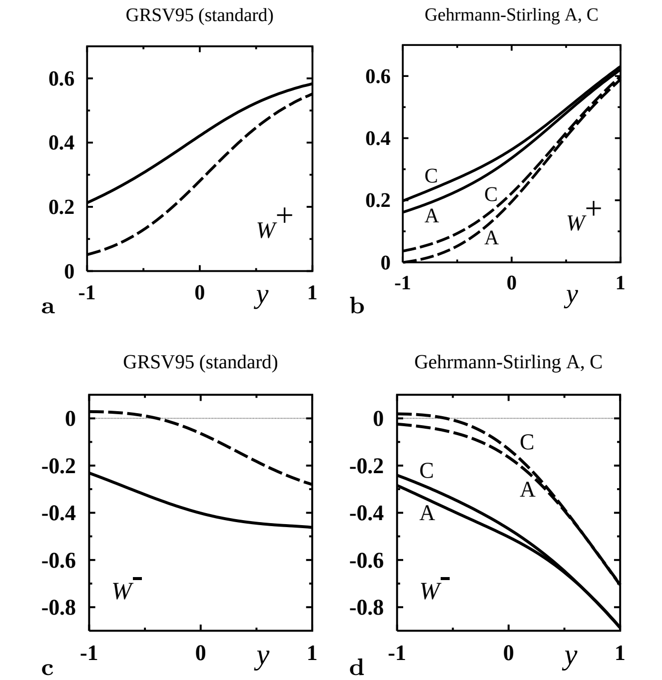

Fig. 3a–d. The longitudinal single spin asymmetry in lepton pair production through W^+ and W^- bosons, A_L^{W+} and A_L^{W-}, in proton–proton collisions, as a function of the photon rapidity, y, for $M^2 = M_W^2 = (80.3\,\mathrm{GeV})^2$ and $s = (500\,\mathrm{GeV})^2$. **a**, **c**: *Dashed lines:* Result obtained for zero flavor asymmetry of the polarized antiquark distributions, $\Delta_3(x) = \Delta_8(x) = 0$, using the GRSV95 LO parametrizations [14] 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]. **b**, **d**: Same as **a** and **c**, but using instead of GRSV95 the Gehrmann–Stirling A and C parametrizations [15]

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.3c,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 [22] will certainly be sufficient to observe an effect of the magnitude predicted.

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