Spin asymmetries from charged current events

M. Anselmino[a], J. Blümlein[b] P. Gambino[c], J. Kalinowski[d], N. Kochelev[e], M. Maul[f], A. Schäfer[f], and T. Yamanishi[g]

[a] Università di Torino and INFN, Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy
[b] DESY-Zeuthen, Platanenallee 6, D–15735 Zeuthen, Germany
[c] MPI für Physik, Föhringer Ring 6, D-80805 München, Germany
[d] Warsaw University, Institute of Theoretical Physics, Ul. Hoza 69, Pl-00681 Warsaw, Poland
[e] Bogoliubov Laboratory for Theoretical Physics, JINR, ul. Joliot–Curie 6, RU–141980 Dubna, Russia
[f] Institut für Theoretische Physik, Universität Frankfurt, D-60054 Frankfurt, Germany
[g] Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka, 567, Japan

Abstract: Charged currents reactions offer the possibility to measure combinations of polarized distribution functions which are linearly independent from those appearing in $g_1^{\mathrm{p,n}}(x, Q^2)$. It turns out that the expected accuracy for an effective luminosity of 100 pb^{-1} is quite good. Also neutral current interactions offer in principle new information on the internal nucleon spin structure, however it is very difficult to extract such information due to the dominance of electromagnetic contributions. Also semi-inclusive D-production, which is a direct signal for the polarized s-quark distribution is investigated. For practical measurements one needs for this observable, however, a very high luminosity, of the order 1000 pb^{-1}. To make full use of the possibilities offered by CC reactions requires electron as well as positron beams.

A polarized proton beam at DESY would allow for the investigation of spin effects in charged current (CC) reactions (and less favourably neutral current (NC) reactions), where the outgoing neutrino is detected by its missing momentum. CC events probe a different combination of spin-dependent quark-distribution functions than electromagnetic processes, thus allowing to extract new information on the flavor decomposition of the polarized quark distribution functions. These experiments would yield results similar to those expected from semi-inclusive fixed target experiments [1, 2]. The most important property of CC reactions is that they distinguish quark and antiquark flavours, allowing to extract the polarized valence quark distributions Δu_V, Δd_V as well as the strange ones $\Delta s, \Delta \overline{s}$. The latter two are usually assumed to be identical. If a difference between them were observed this could be related to the fact that the virtual coupling of p to e.g. (K^+ + baryon) is stronger than to (K^-+baryon). Including deep inelastic weak interaction processes, but neglecting lepton and quark masses the hadronic scattering tensor can be decomposed into eight structure functions [3]:

$$
\begin{aligned}
\frac{1}{2m_N}W_{\mu\nu} &= -\frac{g_{\mu\nu}}{m_N}F_1(x,Q^2) + \frac{p_\mu p_\nu}{m_N p\cdot q}F_2(x,Q^2) \\
&\quad + \frac{i\epsilon_{\mu\nu\alpha\beta}}{2p\cdot q}\left[\frac{p^\alpha q^\beta}{m_N}F_3(x,Q^2) + 2q^\alpha S^\beta g_1(x,Q^2) - 4xp^\alpha S^\beta g_2(x,Q^2)\right] \\
&\quad - \frac{p_\mu S_\nu + S_\mu p_\nu}{2p\cdot q}g_3(x,Q^2) + \frac{S\cdot q}{(p\cdot q)^2}p_\mu p_\nu g_4(x,Q^2) + \frac{S\cdot q}{p\cdot q}g_{\mu\nu}g_5(x,Q^2) \quad . \qquad (1)
\end{aligned}
$$

Here the twist–2 contributions to g_2 and g_3 are related to the structure functions g_1 and g_5, respectively. The former relation is due to Wandzura and Wilczek [4]

$$
g_2(x) = -g_1(x) + \int_x^1 \frac{dy}{y} g_1(y), \tag{2}
$$

whereas the latter was only found recently in ref. [5]

$$
g_3(x) = 4x \int_x^1 \frac{dy}{y} g_5(y). \tag{3}
$$

Furthermore, in the definition of polarized structure functions introduced in eq. (1) Dicus' relation [6] reads

$$
g_4(x) = 4x \int_x^1 \frac{dy}{y} g_5(y) - 2xg_5(x), \tag{4}
$$

i.e. both $g_3(x)$ and $g_4(x)$ do not vanish in general. The structure functions g_1 to g_5 are compared numerically in figure 1 [7] for the case of charged current interactions.

Clearly the structure functions $\hat{g}_3(x,Q^2) = -g_3(x,Q^2)$ and $\hat{g}_4(x,Q^2) = g_4(x,Q^2) - g_3(x,Q^2)$ are small quantities if compared to g_1 and g_5. They vanish at small x and do not exhibit strong (LO) scaling violations being non–singlet structure functions. In the present analysis their contribution to the asymmetries is suppressed due to kinematical reasons. However, they yield equally important contributions in transverse polarization asymmetries. Particularly the structure function $\hat{g}_3$ would be interesting to measure since it contains aside of its twist 2 contribution given in eq. (3) a twist–3 contribution [7].

To a good approximation one may assume $g_4 \approx 0$ (in the parton model $g_4 = 0$), for which eq. (4) results into $2xg_5(x) = g_3(x)$ [5, 6, 9, 10, 11] in the subsequent treatment. Contracted with the leptonic scattering tensor the differential cross section reads for the CC reactions with longitudinally polarized targets [12, 13]

$$
\frac{d^2\sigma}{dxdQ^2} = \frac{G_F^2 M_W^4}{4\pi}\Big([aF_1 - \lambda bF_3] + [-\lambda 2bg_1 + ag_5]\delta\Big)\frac{1}{(Q^2+M_W^2)^2} \quad , \tag{5}
$$

where G_F is Fermi's constant and M_W the W-Boson mass. λ is -1 for e^- and $+1$ for e^+, and δ denotes the longitudinal polarization of the nucleon antiparallel $(+1)$ or parallel (-1) to the polarization of the lepton. The y dependence is absorbed in the two constants $a = 2(y^2-2y+2)$ and $b = y(2-y)$.

The asymmetry is defined by

$$
A := \frac{d\sigma_{\uparrow\downarrow} - d\sigma_{\uparrow\uparrow}}{d\sigma_{\uparrow\downarrow} + d\sigma_{\uparrow\uparrow}} \quad , \tag{6}
$$

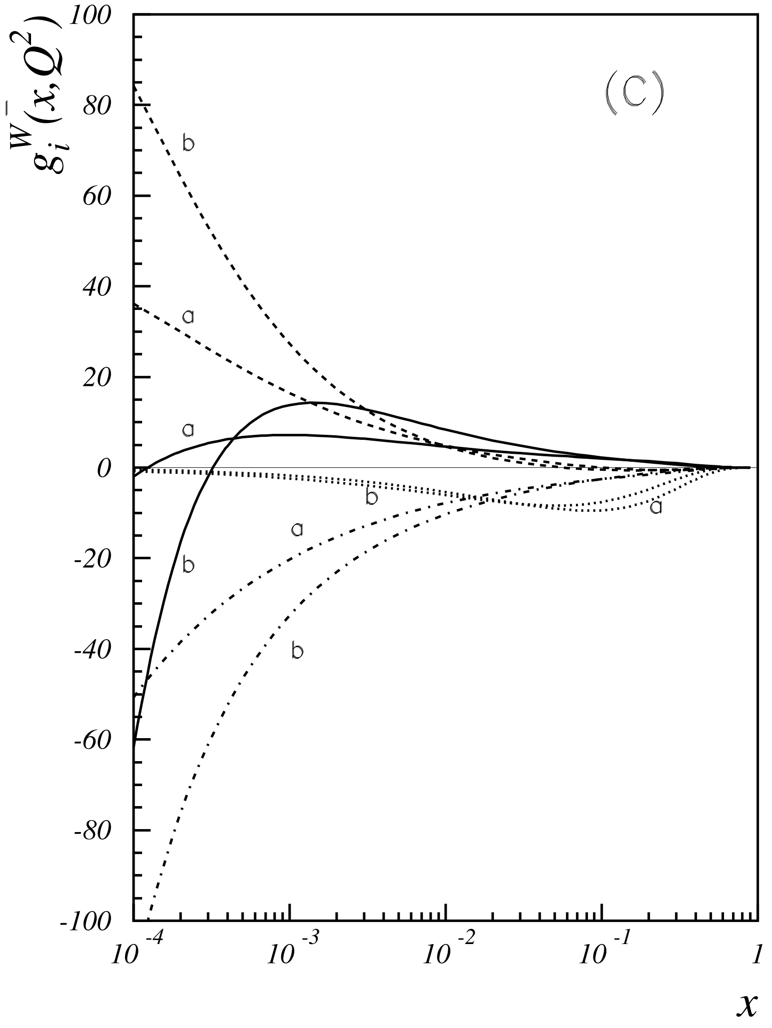

Figure 1: *x and Q^2 dependence of the charged current structure functions $g_i^{W^-}|_{i=1}^{5}(x)$. The lines correspond to: (a) $Q^2 = 10$ GeV^2 and (b) $Q^2 = 10^4$ GeV^2. Full lines: g_1; dashed lines: g_2; dotted lines: $-10 \cdot g_3$; dash–dotted lines: $-g_5$. The structure function g_4 obeys the relation $g_4 = g_3 - 2xg_5$. The structure functions $g_{1,5}(x, Q^2)$ were parametrized using the parton densities of ref. [8].*

which leads to

$$A^{W^-} = \frac{2bg_1 + ag_5}{aF_1 + bF_3}\ ; \qquad A^{W^+} = \frac{-2bg_1 + ag_5}{aF_1 - bF_3} \quad . \tag{7}$$

It is interesting to note that for relatively low Q^2 ($\approx 10^3$ GeV^2) and in the kinematically allowed region, $a \gg b$, so that the asymmetries are dominated by the parity violating form factor g_5. This hints to the possibility of a direct extraction of this interesting quantity from the asymmetry. In the framework of the quark parton model the eight combinations of distribution functions tested by CC asymmetries read:

$$
\begin{array}{rlrl}
F_1^{W-} = u + c + \overline{d} + \overline{s} & , & F_1^{W+} = d + s + \overline{u} + \overline{c} & , \\
F_3^{W-} = 2(u + c - \overline{d} - \overline{s}) & , & F_3^{W+} = 2(d + s - \overline{u} - \overline{c}) & , \\
g_1^{W-} = \Delta u + \Delta c + \Delta\overline{d} + \Delta\overline{s} & , & g_1^{W+} = \Delta d + \Delta s + \Delta\overline{u} + \Delta\overline{c} & , \\
g_5^{W-} = \Delta u + \Delta c - \Delta\overline{d} - \Delta\overline{s} & , & g_5^{W+} = \Delta d + \Delta s - \Delta\overline{u} - \Delta\overline{c} & .
\end{array} \tag{8}
$$

Rewriting (4) in terms of the parton distributions we get for the inclusive asymmetries:

$$
\begin{aligned}
A^{W^-} &= \frac{\Delta u + \Delta c - [(y-1)^2][\Delta\overline{s} + \Delta\overline{d}]}{u + c + [(y-1)^2][\overline{s} + \overline{d}]} \quad , \\
A^{W^+} &= \frac{[(y-1)^2][\Delta s + \Delta d] - \Delta\overline{u} - \Delta\overline{c}}{[(y-1)^2][s + d] + \overline{u} + \overline{c}} \quad .
\end{aligned} \tag{9}
$$

In figure 2 [13] we show the expected asymmetries for HERA energies ($E_l = 27.6$ GeV, $E_n = 820$ GeV) with integrated cross sections in the Q^2 range $600 - 1000$ $(\mathrm{GeV})^2$ and 1000 $(\mathrm{GeV})^2$ – maximum. We split the data into these two Q^2 ranges, because it might not be obvious, that the detection of missing momentum in the range $\sqrt{600}$ GeV – $\sqrt{1000}$ GeV is absolutely reliable. (Usually already $Q^2 \geq 600$ $(\mathrm{GeV})^2$ is regarded as safe). Fig. 2 shows that the low-Q^2 data do not dominate the statistics. So even if one would be very restrictive on the criteria for identifying CC events our conclusions would be hardly affected. Probably one can safely combine all data down to $Q^2 \approx 400$ GeV^2 to improve the statistics. For the polarized parton distributions we use the set "standard scenario, LO" given in [8], for the unpolarized ones those of [14]. The error bars are calculated according to

$$
\Delta A = \sqrt{\frac{1 - A^2}{2\mathcal{L}\Delta x \Delta Q^2 d^2\sigma/dx dQ^2}} \quad , \tag{10}
$$

where $\mathcal{L}$ denotes the effective luminosity. $d\sigma$ is the unpolarized cross section. We assumed $\mathcal{L}$ = 200 pb^{-1} (100 pb^{-1} per relative polarization) and fully polarized beams. We notice that the CC asymmetry is proportional to the degree of polarization of the proton only, while the statistical error scales as $1/\sqrt{1/2(1 - P_e)}$. The remarkable features of our results are that the asymmetries are sizable in the range $x \in [0.01, 1]$ and that even for 100 pb^{-1} the expected statistical accuracy for W^- exchange is rather good.

In figure 3 [13] we compare the contribution of the sea quarks and valence quarks to the asymmetries using two different parton distribution sets. One is again the LO standard scenario [8] the other one is LO Gluon C [15]. The main distinction between the two sets is the fact that the polarized valence quark distribution given in [8] is nearly proportional to the unpolarized valence quark contribution, whereas in [15] the fit shows larger deviations. For the parametrization of [15] the spin asymmetry is even larger than for that of [8]. Obviously the expected accuracy should allow to distinguish the two scenarios. Besides these single W boson asymmetries one can form four combinations which are determined by pure valence contributions and by valence + sea contributions:

$$
A_{(\pm)_1(\pm)_2} := \frac{(d\sigma_{\uparrow\downarrow}^{W^-} - d\sigma_{\uparrow\uparrow}^{W^-})(\pm)_1(d\sigma_{\uparrow\downarrow}^{W^+} - d\sigma_{\uparrow\uparrow}^{W^+})}{(d\sigma_{\uparrow\downarrow}^{W^-} + d\sigma_{\uparrow\uparrow}^{W^-})(\pm)_2(d\sigma_{\uparrow\downarrow}^{W^+} + d\sigma_{\uparrow\uparrow}^{W^+})} \quad . \tag{11}
$$

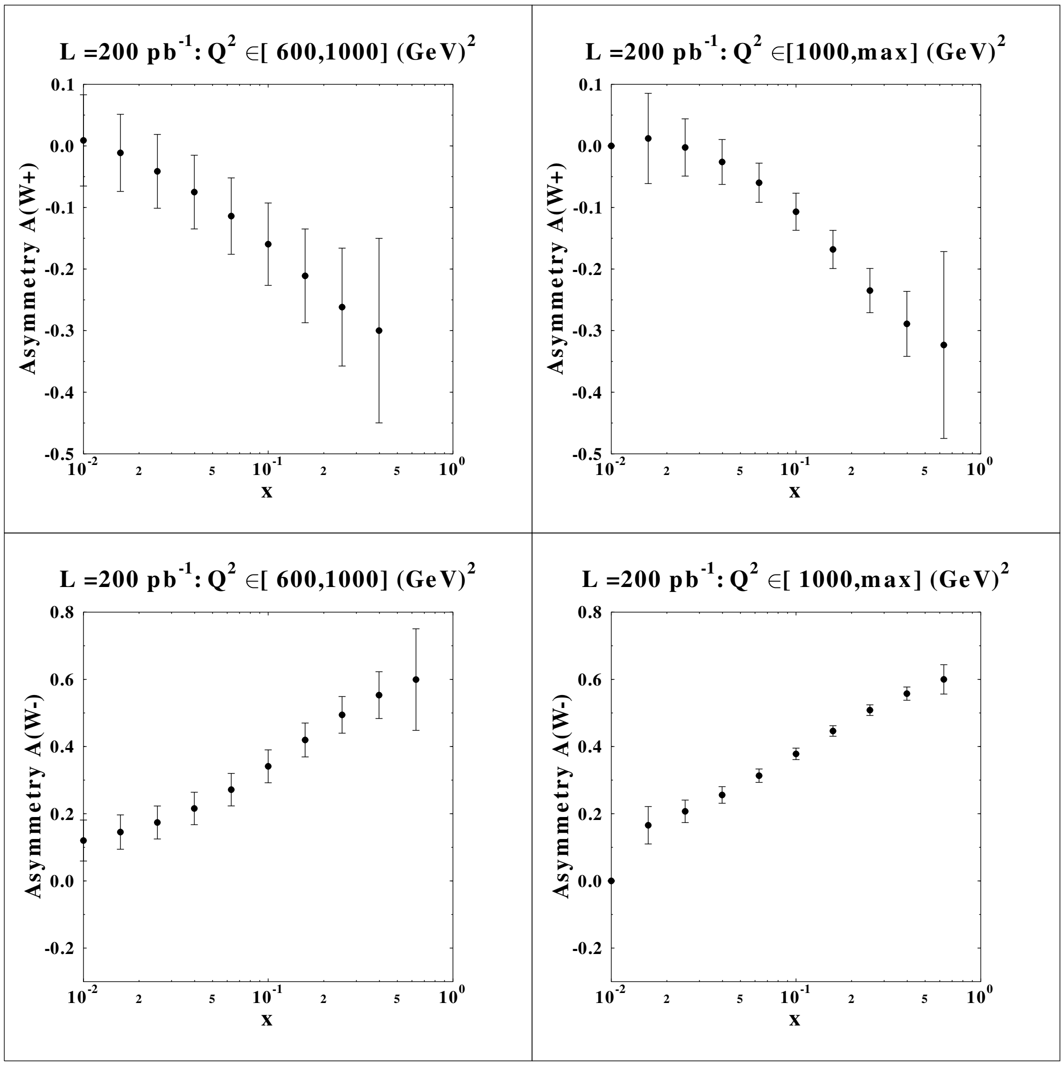

Figure 2: *Asymmetries A^{W^+} and A^{W^-} in the Q^2 range 600-1000* $(\mathrm{GeV})^2$ *and 1000- max* $(\mathrm{GeV})^2$ *for the luminosity of 200 pb^{-1}, i.e. 100 pb^{-1} per relative polarization and fully polarized beams using the parton distributions of [8].*

Here the first $\pm$ accounts for the numerator and the second for the denominator. With this definition we write:

$$
\begin{aligned}
A_{++} &= \frac{\Delta u_V + [(y-1)^2]\Delta d_V}{u_T + c_T + [(y-1)^2][s_T + d_T]} \quad , \\
A_{--} &= \frac{\Delta u_T + \Delta c_T - [(y-1)^2][\Delta s_T + \Delta d_T]}{u_V - [(y-1)^2] d_V} \quad , \\
A_{-+} &= \frac{\Delta u_T + \Delta c_T - [(y-1)^2][\Delta s_T + \Delta d_T]}{u_T + c_T + [(y-1)^2][s_T + d_T]} \quad , \\
A_{+-} &= \frac{\Delta u_V + [(y-1)^2]\Delta d_V}{u_V - [(y-1)^2] d_V} \quad .
\end{aligned} \tag{12}
$$

Here we defined for the quark distribution functions q_f

$$\Delta q_f \;=\; q_{f,\uparrow\downarrow} - q_{f,\uparrow\uparrow} \quad ,$$

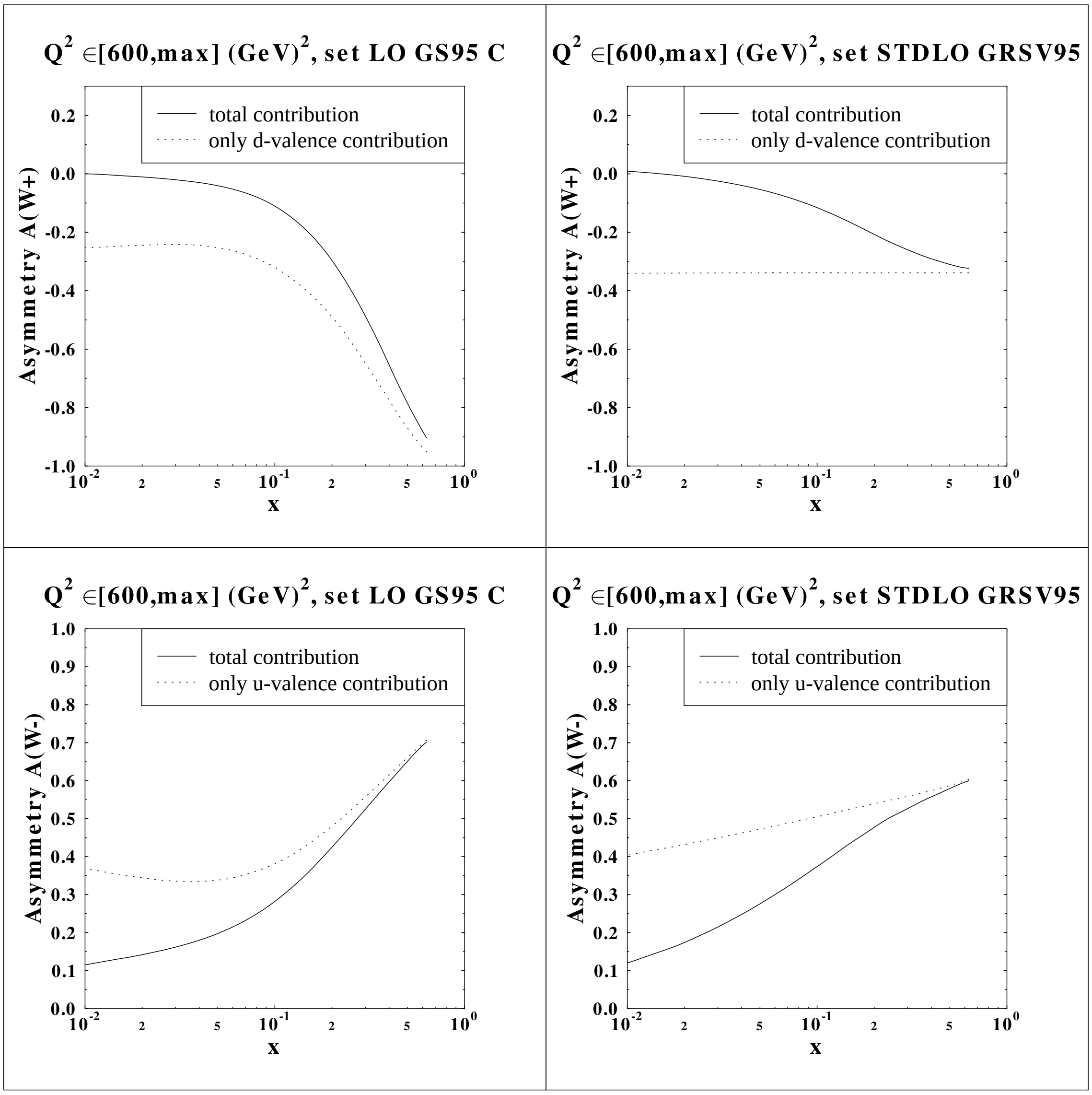

Figure 3: *Asymmetries A^{W^+} and A^{W^-} in the Q^2 range 600-max* $(\mathrm{GeV})^2$, *comparison between valence and sea quark contributions using set "Gluon C, leading order "[15], and "standard scenario, leading order " [8].*

$$
\begin{aligned}
q_{f,V} &= q_f - \overline{q}_f \quad , \\
q_{f,T} &= q_f + \overline{q}_f \quad .
\end{aligned} \tag{13}
$$

While the inclusive asymmetries are mainly sensitive to the u- and d- quark flavour it is possible to extract direct information on the strange and antistrange sea by semi-inclusive CC current measurements. As usual, we define the fragmentation function $D_f^H(z)$, which describes the probability that a quark with flavor f fragments into a hadron H which carries the fraction z of the whole energy transferred to the nucleon. The most interesting process turns out to be D-meson production. In this case the relevant fragmentation functions are

$$
D_1^D(z) \equiv D_c^D(z) \equiv D_{\overline{c}}^D(z) \quad . \tag{14}
$$

The fragmentation of any other flavour into a D meson is strongly suppressed. The only relevant contributions come from $s + W^+ \to D^+$, or D^0. Also we set

$$\int_{0.2}^{1} D_1^D(z) dz \approx 1 \tag{15}$$

because each c-quark fragments in at least one charmed hadron. Furthermore the fragmentation functions are assumed to be spin independent. The resulting formulas read [13]

$$\begin{aligned} A^D_{W^-} &:= \frac{d\sigma^{\uparrow\downarrow}_{W^-,D} - d\sigma^{\uparrow\uparrow}_{W^-,D}}{d\sigma^{\uparrow\downarrow}_{W^-,D} + d\sigma^{\uparrow\uparrow}_{W^-,D}} = -\frac{\Delta\overline{s} + t^2\Delta\overline{d}}{\overline{s} + t^2\overline{d}} \quad , \\ A^D_{W^+} &:= \frac{d\sigma^{\uparrow\downarrow}_{W^+,D} - d\sigma^{\uparrow\uparrow}_{W^+,D}}{d\sigma^{\uparrow\downarrow}_{W^+,D} + d\sigma^{\uparrow\uparrow}_{W^+,D}} = \frac{\Delta s + t^2\Delta d}{s + t^2 d} \quad , \end{aligned} \tag{16}$$

where $t = \tan^2\theta_C$ contains the Cabbibo-angle. These asymmetries are obviously a direct signal for the strange and antistrange polarization and figure 4 [13] shows that the anticipated statistical accuracy for $\mathcal{L} = 1000$ pb^{-1} should allow at least for an approximate experimental determination.

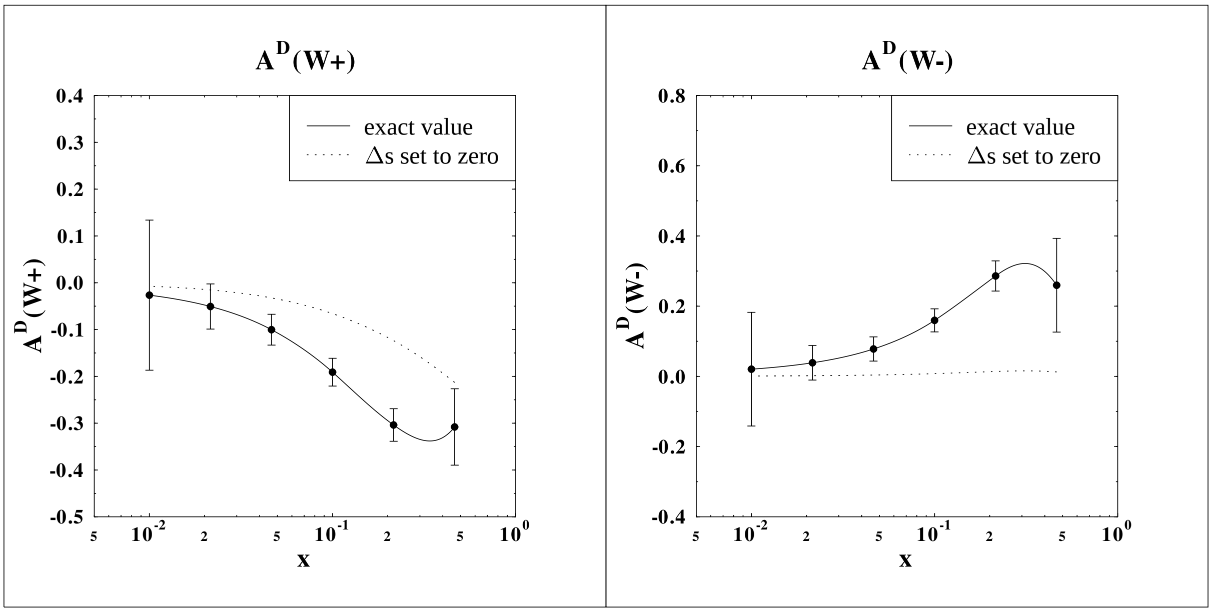

Figure 4: *Charmed asymmetries A^D_{W+}, and A^D_{W-} in the Q^2 range 600-max* $(\mathrm{GeV})^2$ *using "standard scenario, leading order" [8]. The error bars are given for the luminosity of 1000 pb^{-1}.*

In principle, one might easily extract information on parity violating polarized structure functions also by considering a single spin asymmetry in neutral current (NC) processes with longitudinally polarized protons and unpolarized leptons [10, 16]. The spin asymmetry for unpolarized electrons reads [10]

$$A_{NC}^{e^-p} = \eta^{\gamma Z}\, \frac{a\left[(2s_w^2 - \frac{1}{2})g_5^{\gamma Z} + \eta^{\gamma Z}(4s_w^4 - 2s_w^2 + \frac{1}{2})g_5^Z)\right] - b\left[g_1^{\gamma Z} + \eta^{\gamma Z}(4s_w^2 - 1)g_1^Z\right]}{a\left[F_1^{\gamma} + \eta^{\gamma Z}(2s_w^2 - \frac{1}{2})F_1^{\gamma Z}\right] - \frac{1}{2}b\,\eta^{\gamma Z}\,F_3^{\gamma Z} + \mathcal{O}[(\eta^{\gamma Z})^2]} \;, \tag{17}$$

where

$$\eta^{\gamma Z} = \frac{G M_Z^2}{2\sqrt{2}\pi\alpha} \frac{Q^2}{Q^2 + M_Z^2} \;, \tag{18}$$

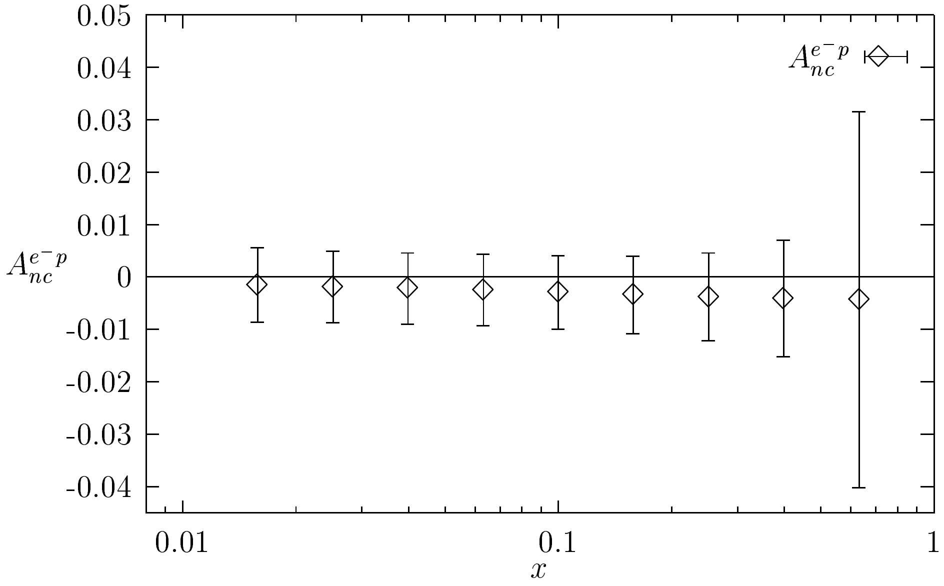

Figure 5: *Neutral current e^-p single spin asymmetry, Eq.(17) of text, for $Q^2 = 1000$ GeV^2 at HERA energies with fully polarized proton beams. The statistical errors calculated for $\mathcal{L} = 500\,pb^{-1}$ for each polarization and $\Delta Q^2 = 500$ GeV^2 are shown.*

s_w is the sine of the Weinberg angle, and we have neglected in the denominator the purely weak contributions, of $\mathcal{O}[(\eta^{\gamma Z})^2]$ and negligible in most of HERA Q^2 range where $\eta^{\gamma Z}$ is still rather small. The expression for the structure functions $g^{\gamma Z}$ and g^Z in terms of quark distributions can be found in Ref. [10].

For the numerical analysis of NC events we impose the following kinematical cuts: $0.01 < y < 0.9$, $x < 0.7$. In addition, we demand $Q^2 > 500$ GeV^2. The leading order polarized parton distributions are taken from Ref. [8] (here we use the set "standard scenario", eventually extrapolated to Q^2 values greater than 10^4 GeV^2; the "valence" set yields very similar results); the unpolarized ones are taken from Ref. [14]. We have assumed fully polarized beams, and we emphasize again that $A^{W^\mp}$ are independent of the degree of polarization of the lepton beam, and proportional to the polarization of the proton: $P_e < 1$ would only marginally decrease the available statistical precision, while $P_p < 1$ would simply reduce the asymmetries by the corresponding factor. A high degree of polarization of the proton beam, more than that of the leptons, would be a most welcome feature.

In figures 5 and 6 [12] we show the expected asymmetries as functions of x both at fixed $Q^2 = 1000$ GeV^2 and averaging over all the kinematically allowed Q^2 region, that is summing all detectable events in a given x-bin. The statistical errors shown in the figures have been calculated from Eq. (7) assuming that for each longitudinal proton polarization an integrated luminosity $\mathcal{L} = 500$ pb^{-1} can be collected. [To calculate the errors at fixed Q^2 we take $\Delta Q^2 = Q^2/2$.] For NC events the spin asymmetry is probably too small to be meaningfully measured at HERA, as an effect of the dominant parity conserving electromagnetic contribution.

In summary, we have clearly shown that measurements of charged current processes in deep inelastic scattering of longitudinally polarized or unpolarized leptons off longitudinally polarized

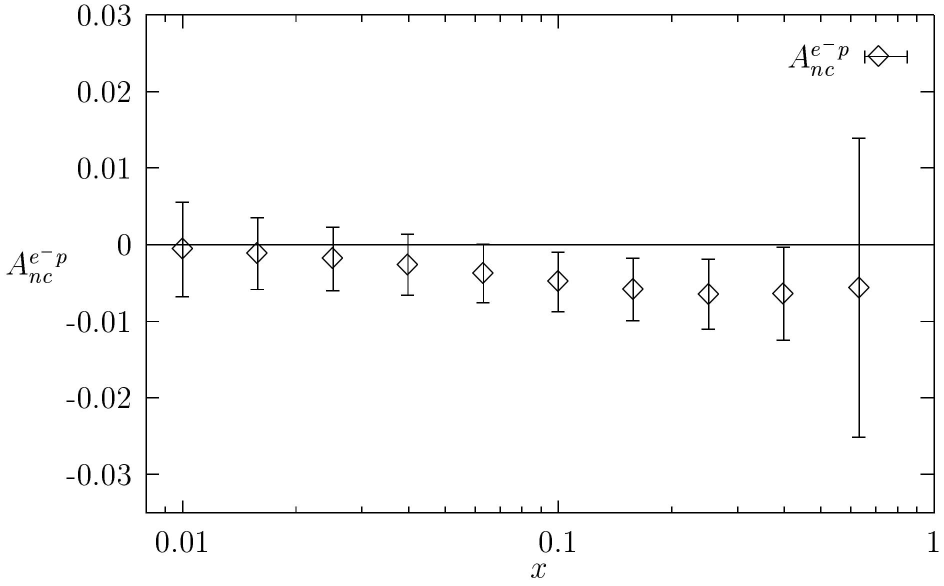

Figure 6: *Neutral current e^-p single spin asymmetry, Eq.(17) of text, averaged over the allowed Q^2 region at HERA energies with fully polarized proton beams. The statistical errors calculated for $\mathcal{L} = 500\,pb^{-1}$ for each polarization are shown.*

protons at HERA energies offer a unique and viable way of reaching more information on the quark spin content of protons.

This work has been supported by DESY, the Polish Committee for Scientific Research (J.K.), DFG, BMBF and MPI für Kernphysik (A.S.).

References

[1] M. Veltri, M. Düren, K. Rith, L. Mankiewicz, A. Schäfer, Proceedings, Physics at HERA, **vol. 1*** 447-457 (1991)

[2] L. L. Frankfurt, M. I. Strikman, L. Mankiewicz, A. Schäfer, E. Rondio, A. Sandacz, and V. Papavassiliou, Phys. Lett. **B230** 141 (1989)

[3] J. A. Bartelski, Acta Phys. Pol. **B10** 923 (1979)

[4] S. Wandzura and F. Wilczek, Phys. Lett. **B72** (1977) 195

[5] J. Blümlein and N. Kochelev, Phys. Lett. **B381** (1996) 296

[6] D. A. Dicus, Phys. Rev. **D5** 1367 (1972)

[7] J. Blümlein and N. Kochelev, DESY 96–175

[8] M. Glück, E. Reya, M. Stratmann, W. Vogelsang, Phys. Rev. **D53** 4775 (1996)

[9] B. Lampe, Phys. Lett. **B227** (1989) 469

[10] M. Anselmino, P. Gambino and J. Kalinowski, Z. Phys. **C64** 267 (1994)

[11] M. Maul, B. Ehrnsperger, E. Stein, A. Schäfer, hep-ph/9602377

[12] M. Anselmino, P. Gambino, and J. Kalinowski, preprint, hep-ph/9607427

[13] M. Maul and A. Schäfer, preprint, hep-ph/9607438

[14] M. Glück, E. Reya and A. Vogt, Z. Phys. **C67** (1995) 433

[15] T. Gehrmann, W. J. Stirling, Phys. Rev. **D53** 6100 (1996)

[16] S.M. Bilenky, N.A. Dadajan and E.H. Hristova, Sov. J. Nucl. Phys. **21** (1975) 657