A study on Δu and Δd in charged current events using polarized beams at HERA

J. G. Contreras[a], A. De Roeck[b], M. Maul[c]

[a] *Universität Dortmund, Institut für Physik, D–44221 Dortmund, Germany*

[b] *Deutsches Elektronen–Synchrotron DESY, Notkestraße 85, D–22603 Hamburg, Germany*

[c] *Institute for Theoretical Physics, Universität Regensburg, 93053 Regensburg, Germany*

Abstract

Charged current events are studied at HERA with polarized beams, using a Monte Carlo event generator and taking into account detector smearing effects. The observed asymmetries are used to study the extraction of the polarized structure function g_5 and the polarized parton distributions Δu and Δd in the proton.

1 Introduction

The flavour decomposition of the polarized quark distributions in the proton is important information for our understanding of the spin structure of the proton. At present fixed target experiments the asymmetries measured in semi-inclusive data [1] have been exploited for this purpose, a method which can also be used at HERA with polarized beams [2]. This option for HERA has been proposed in [3], and leads to collisions of 27.5 GeV polarized electrons on 820 GeV polarized protons. The high center of mass energy of HERA ($\sqrt{s} = 300$ GeV) allows in addition to study charged current (CC) events which probe different combinations of spin-dependent quark distribution functions compared to neutral current interactions. In particular, CC interactions distinguish quark from anti-quark flavours.

This paper is a continuation of the analytical calculations reported in [4], and is based on a Monte Carlo study of CC events. For this purpose the Monte Carlo event generator PEPSI 6.5 [5, 6] was upgraded to contain the full electroweak structure at tree level for lepton-proton scattering. It was used to generate event samples which were tracked through a detector program to study detector smearing effects. PEPSI is a version of the program LEPTO [7], extended for polarized beams and targets. It contains leading order QCD matrix elements, supplemented with parton showers to approximate higher order effects. The hadronization in PEPSI is based on the Lund string fragmentation model [8]. The cross section results of PEPSI have been checked with the analytical calculations reported in [4], and were found to be in agreement.

The sensitivity of the CC cross section to the polarized quark distributions is shown in the following. The hadronic scattering tensor for lepton-nucleon interactions can be decomposed in three unpolarized and five polarized structure functions. The latter (g_1 to g_5) are not independent. Assuming $g_4 \sim 0$, which is strictly true in the parton model, the differential cross section

for CC reactions on a longitudinally polarized target reads [4]:

$$\frac{d^2\sigma}{dxdQ^2} = \frac{G_F^2 M_W^4}{4\pi} \frac{1}{(Q^2+M_W^2)^2}([aF_1(x,Q^2) - \lambda bF_3(x,Q^2)] + [-2\lambda b g_1(x,Q^2) + a g_5(x,Q^2)]\delta), \quad (1)$$

with x being Bjorken-x, and Q^2 the four-momentum transfer squared in the deep inelastic scattering process. G_F is the Fermi constant, and M_W is the W-Boson mass; λ is $-1(+1)$ for the e^- (e^+); δ denotes the longitudinal polarization of the nucleon to be anti-parallel $(+1)$ or parallel (-1) to the polarization of the lepton; $a = 2(y^2 - 2y + 2)$ and $b = y(2-y)$, with y the usual inelasticity variable. The asymmetry is defined by

$$A^{W\mp} = \frac{d\sigma^{W\mp}_{\uparrow\downarrow} - d\sigma^{W\mp}_{\uparrow\uparrow}}{d\sigma^{W\mp}_{\uparrow\downarrow} + d\sigma^{W\mp}_{\uparrow\uparrow}} = \frac{\pm 2b g_1^{W\mp} + a g_5^{W\mp}}{a F_1^{W\mp} \pm b F_3^{W\mp}}, \quad (2)$$

where in leading order

$$\begin{array}{ll} g_1^{W^-} = \Delta u + \Delta c + \Delta\bar{d} + \Delta\bar{s}, & g_1^{W^+} = \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{c}, \\ g_5^{W^-} = \Delta u + \Delta c - \Delta\bar{d} - \Delta\bar{s}, & g_5^{W^+} = \Delta d + \Delta s - \Delta\bar{u} - \Delta\bar{c}, \\ F_1^{W^-} = u + c + \bar{d} + \bar{s}, & F_1^{W^+} = d + s + \bar{u} + \bar{c}, \\ F_3^{W^-} = 2(u + c - \bar{d} - \bar{s}), & F_3^{W^+} = 2(d + s - \bar{u} - \bar{c}). \end{array} \quad (3)$$

Here Δq denotes the polarized parton distribution which is the difference between the probability to find a parton in the longitudinally polarized proton whose spin is aligned minus the one whose spin is anti-aligned, and q is the unpolarized parton distribution.

To evaluate the measurability and quality of the spin asymmetries for CC events several systematic studies have been performed. A total luminosity of 500 pb^{-1} and a total polarization of 0.5 (0.7 for each beam) was assumed and generated with PEPSI, compatible with the expectations for HERA [3]. The polarized parton distributions GS–A [9] and the unpolarized parton distributions GRV [10] have been used throughout this analysis. The available luminosity was distributed in equal parts for incoming electron and positron beams, and for parallel or antiparallel polarizations; i.e., for each case 125 pb^{-1} was used. However, since the proton has roughly two times more up than down quarks, it could be better to assign two thirds of the luminosity to the W^+ case to obtain results with equal statistical significance. Since this does not interfere with other polarized measurements such a scenario should be considered for future measurements and studies.

2 Detector Effects and Simulation

To investigate the measurability of the spin asymmetries a fast simulation of a HERA type of detector [11, 12] has been implemented [13] (for more details see for example [14]). The experimental characteristic of charged current interactions at HERA is a high p_t neutrino in the final state leading to large missing transverse momentum for the detected event. The corresponding selection of the events relies essentially on the calorimetric measurement of the hadronic final state. For this study we based the simulation on the calorimeter of the H1 experiment. The simulation parameters have been tuned to real data, and some details will be given in the following.

A calorimeter with a separate backward and central/forward part was considered. Backward here means the electron direction. The calorimeter covers the polar angle θ (defined with respect to direction of the incoming proton) from 4° to 177°. The central/forward and backward parts

are separated at 152°. An optional acceptance in the range $10° < \theta < 170°$ was implemented to take into account the planned luminosity upgrade of HERA [15], which would reduce the acceptance as a result of machine magnets which are installed close to the interaction point. The complete range in azimuthal angle ϕ is covered.

The influence of the inactive material in front of the calorimeter, and of losses due to the calorimeter edges and in the region between the central/forward and backward part was modeled with a set of efficiency factors which depend on the polar angle of the simulated particle.

The smearing of the energy and reconstructed angle of the detected particles was applied as follows. The energy resolution of the backward part is taken to be $\sigma_{back}/E = 0.56$, and of the central part $\sigma_{cent}/E = 0.46/\sqrt{E} \oplus 0.73/E \oplus 0.026$, where the energy is given in GeV. For the angular resolutions $\sigma_\theta = 50$ and $\sigma_\phi = 90$ (in mrad) was used.

Further, a Gaussian smearing (with RMS 11 cm) of the interaction vertex position along the beam line, consistent with current HERA operation, was included in the simulation.

The efficiency to trigger and select charged current events was set to 85±3% in accordance with current estimates [16] for charged current events. The background of photoproduction events, cosmic rays and production of $W^\pm$ or Z^0 Bosons is very small in the present analyses at HERA and was ignored in the following [16, 17].

We will study the asymmetries as a function of Bjorken-x. The bin size in x as used in the following was chosen taking into account statistics and event migration due to detector effects. For each bin we have a purity[1] and an efficiency[2] bigger than 80%.

3 Results

3.1 Kinematics

The H1 collaboration selects CC events requiring a minimal missing transverse momentum, P_{Tmiss}, of the hadronic final state to be larger than 25 GeV and presents results with a minimal Q^2 of 625 GeV^2 [16]. The ZEUS collaboration on the other hand has recently published an analysis of CC events with the selection criteria of $P_{Tmiss} > 11$ GeV and $Q^2 > 200$ GeV^2 [17]. The lower cut allows to extent the reach in kinematics from $\log_{10}(x) \approx -1.5$ to $\log_{10}(x) \approx -2.0$.

For the studies presented in this contribution $P_{Tmiss} > 15$ GeV and $Q^2 > 225$ GeV^2 have been used, which seem a reasonable assumption based on the present day experience at HERA. The results for the asymmetries, including detector effects, are shown on the left side of figure 1. The error bars indicate the statistical precision of the measurement. The asymmetries are very large, as noticed before in [4], so that the data allow for a significant measurement. The solid line is the result of the analytical calculation of the asymmetry using the formulae of section 1, and the same parton distributions as used for the PEPSI generated events. It shows that the detector smeared asymmetries are in good agreement with the true ones.

Note that in our kinematic domain we have $a >> b$, thus the asymmetry to a good approximation directly measures the structure function ratio g_5/F_1:

$$A^{W^\pm} \approx \frac{g_5^{W^\pm}}{F_1^{W^\pm}} \tag{4}$$

[1] number of events generated and simulated in a bin divided by the number of simulated events in the same bin

[2] number of events generated and simulated in a bin divided by the number of generated events in the same bin

The structure functions $F_1^{W^\pm}$ will be already precisely measured by the time the analysis of polarized data from HERA can be performed. This makes it possible to extract the structure functions $g_5^{W^\pm}$ from the measured asymmetries. Here we multiply the asymmetry with $F_1^{W^\pm}$ as calculated from the GRV distributions. The results are presented on the right side of Fig. 1 and compared with the asymmetries from the analytical calculation for g_5. It shows that this approximation works well (to the 10-20% level) in our kinematic range.

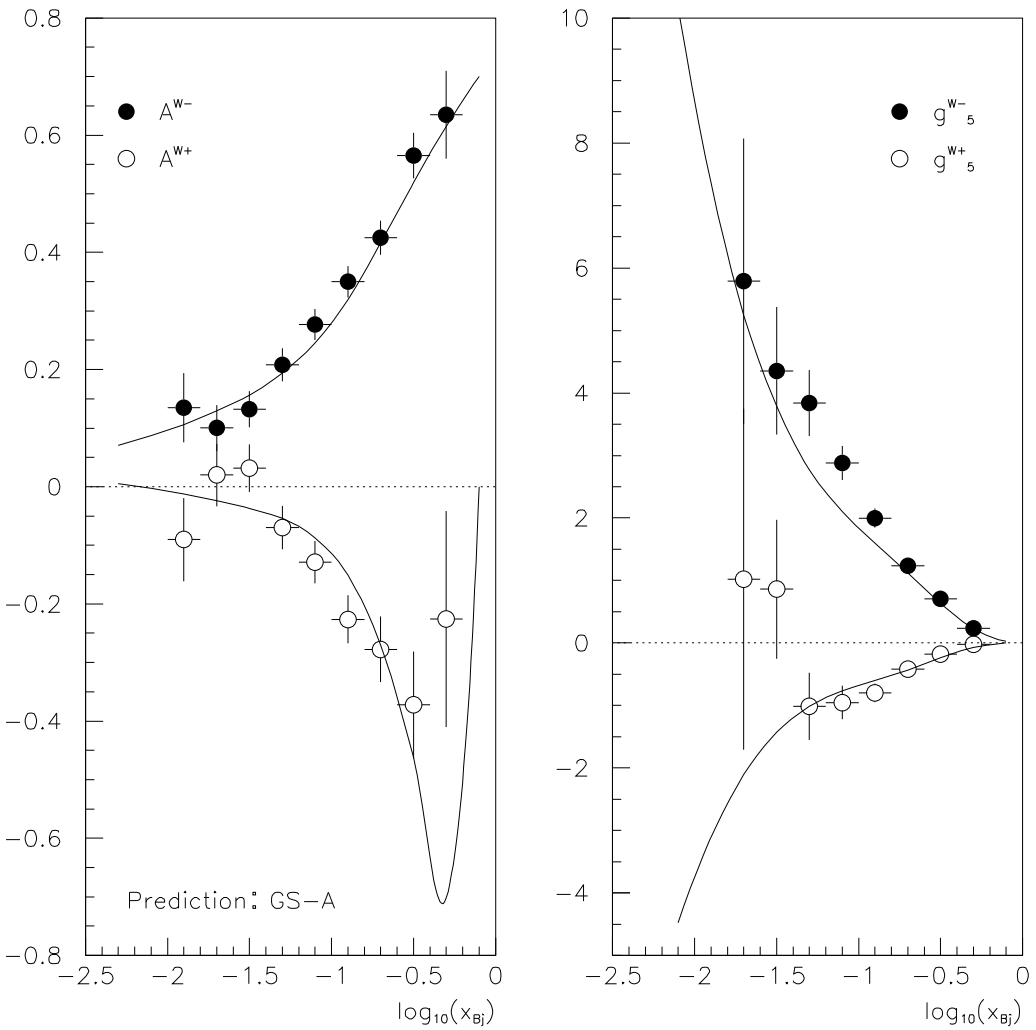

Figure 1: Spin asymmetries A^{W^-} (full symbols, left side) and A^{W^+} (open symbols, left side) for CC events are presented for a total luminosity of 500 pb^{-1}. Also shown are the structure functions $g_5^{W^\pm}$ (right side) extracted from the asymmetries. The parton densities GS–A from [9] were used. The error bars represent the statistical uncertainty of the measurement.

3.2 Energy scale of the calorimeter

The selection and measurement of CC events depends strongly on the calorimeters of the detector. This implies that one of the dominant sources of systematic uncertainty of the measurement is

the precision on the knowledge of the energy scale of the calorimeters. The electromagnetic energy scale will be rather well determined for the complete detector, to better than 1%, but the uncertainty on the hadronic energy scale will be larger.

To study this effect the energy scale of the calorimeters was changed in the simulation program by ± 10% in the backward part and by ± 4% in the central/forward region. These values are in agreement with those currently used by the H1 experiment and thus represent a somewhat pessimistic scenario. We find that the effect of varying the energy scales on the asymmetries and the structure function g_5 is within the statistical fluctuations of the measurement, shown in Fig. 2. Hence, it turns out that the effect of the energy scale uncertainty largely cancels in the measured ratio of cross sections (see eqn. 2).

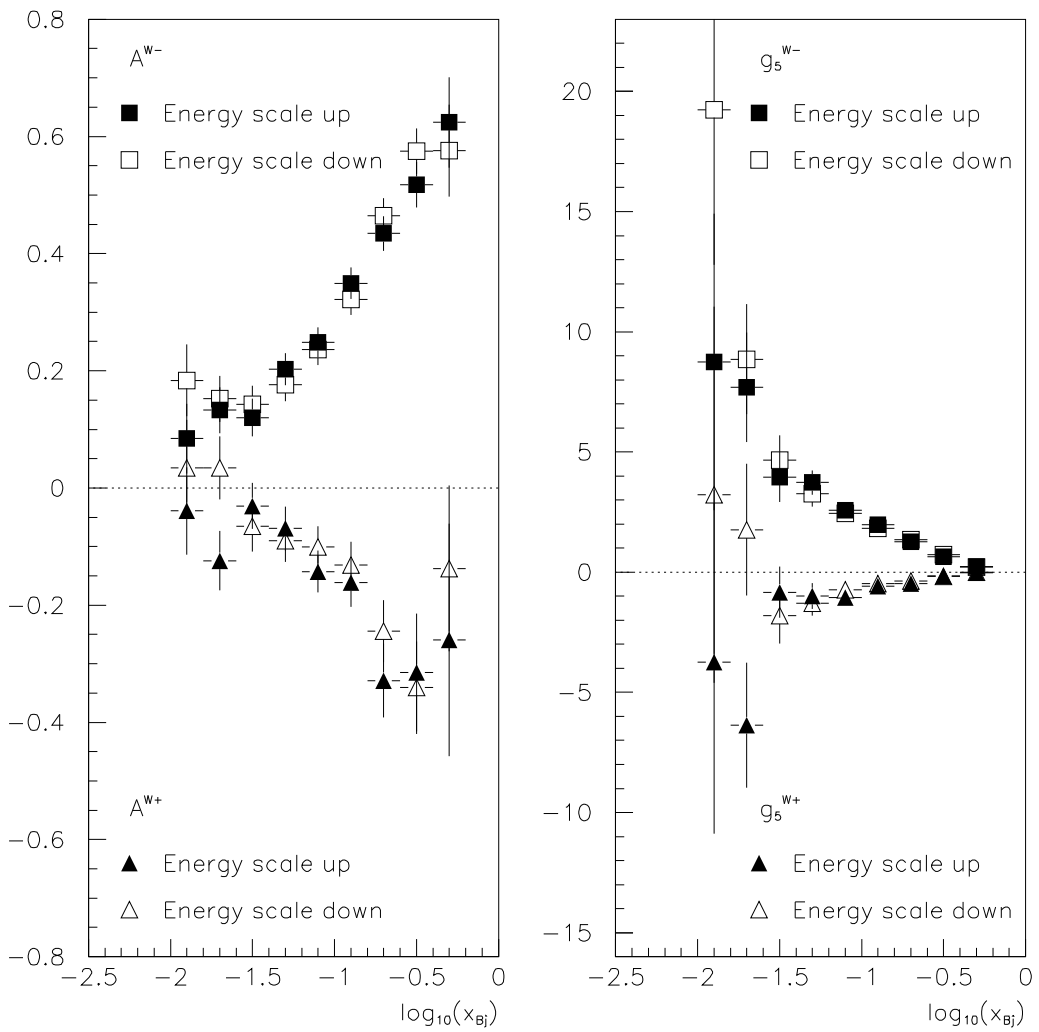

Figure 2: Effect on $A^{W^\pm}$ (right) and $g_5^{W^\pm}$ (left) of the variation of the absolute energy scale of the central/forward and backward calorimeters.

3.3 Acceptance of the detector

Currently the geometrical acceptance of the central detectors at the HERA collider is about 4° − 177° in polar angle θ. This will be reduced by the high luminosity upgrade of HERA. For this upgrade it is planned to install magnets within the detectors, close to the interaction point, tightly surrounding the beam pipe [15]. Apart from a reduced angular acceptance, the large amount of material added close to the interaction point will result in an area in the calorimeter which will be strongly affected by secondary interactions and backscattering. This area will have to be excluded from the analysis for CC event studies. We took a fiducial region of the calorimeter, which amounts to approximately 10° to 170° in polar angle, considered to be usable for the CC analysis. To study the effect of the reduced acceptance, the simulation program was changed accordingly (but the possible remaining influence of backscattering due to the magnets inside the detectors has not been included). The results show however that the quality of the measurement of $A^{W^\pm}$ is not significantly affected by the reduced acceptance, and is compatible within statistics with the result of Fig.1, using the full acceptance.

3.4 Influence of the parton density functions

The studies presented so far have used the parton densities of GS set A. Here results for GS set C and the parton densities of reference [18] for the standard version in leading order approximation (labelled GRSV–S–LO) are shown in Fig. 3 for $A^{W^\pm}$ and $g_5^{W^\pm}$. It appears that the predictions are very similar. This is due to the limited flavour separation possibilities in extracting these parton densities (from QCD fits to g_1 measurements), and in the overall normalization imposed by the g_1 measurements. However, only future measurements will show whether the present assumptions are in agreement with reality.

To extract $g_5^{W^\pm}$ (right side of the figure) the GRV parton densities were used in all three cases to calculate $F_1^{W^\pm}$.

4 Extraction of Δu and Δd

As mentioned in section 1, we have in leading order

$$\begin{aligned} g_5^{W^-} &= \Delta u + \Delta c - \Delta\bar{d} - \Delta\bar{s} \\ g_5^{W^+} &= \Delta d + \Delta s - \Delta\bar{u} - \Delta\bar{c} \end{aligned}$$

In all three parametrizations of the polarized parton densities used in this analysis Δc has been neglected. Also the following assumptions are made: $\Delta\bar{u} = \Delta s$ and $\Delta\bar{d} = \Delta\bar{s}$. With these assumptions the extraction of $g_5^{W^+}$ is equivalent to the extraction of Δd. Furthermore, $g_5^{W^-}$ is close to Δu. This is demonstrated in Fig. 4 where the ratio of Δu to $g_5^{W^-}$ for the three parametrizations used in this analysis is shown. It is seen that for the kinematic range accessible to this measurement ($\log_{10}(x) > -2$) all three Δu distributions account for more than 85% of $g_5^{W^-}$. Hence the extraction of Δu can be done with a precision comparable to the $g_5^{W^-}$ extraction shown in the preceding sections.

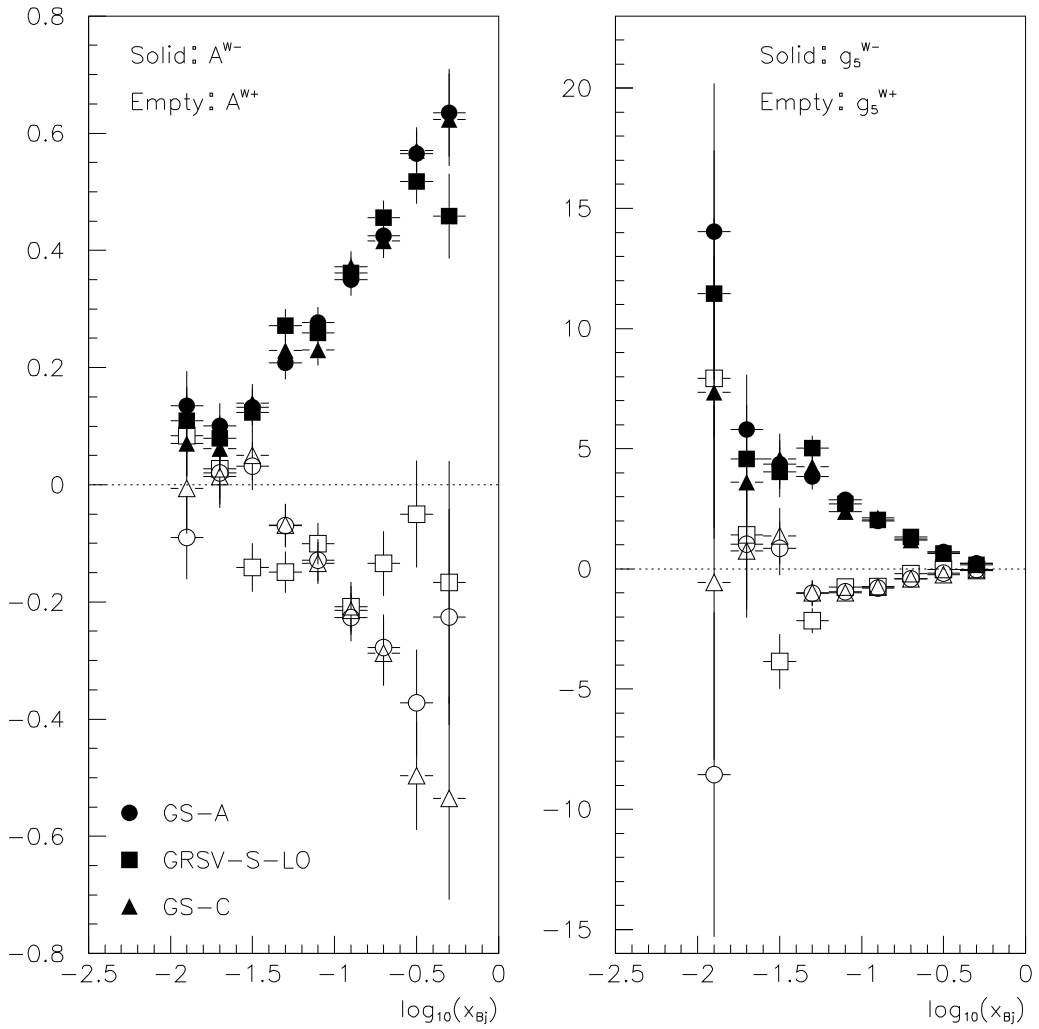

Figure 3: Asymmetries $A^{W^\pm}$ (right) and structure functions $g_5^{W^\pm}$ (left) for three different parton densities. In all three cases GS–A was used to calculate $F_1^{W^\pm}$, needed to extract $g_5^{W^\pm}$ from $A^{W^\pm}$.

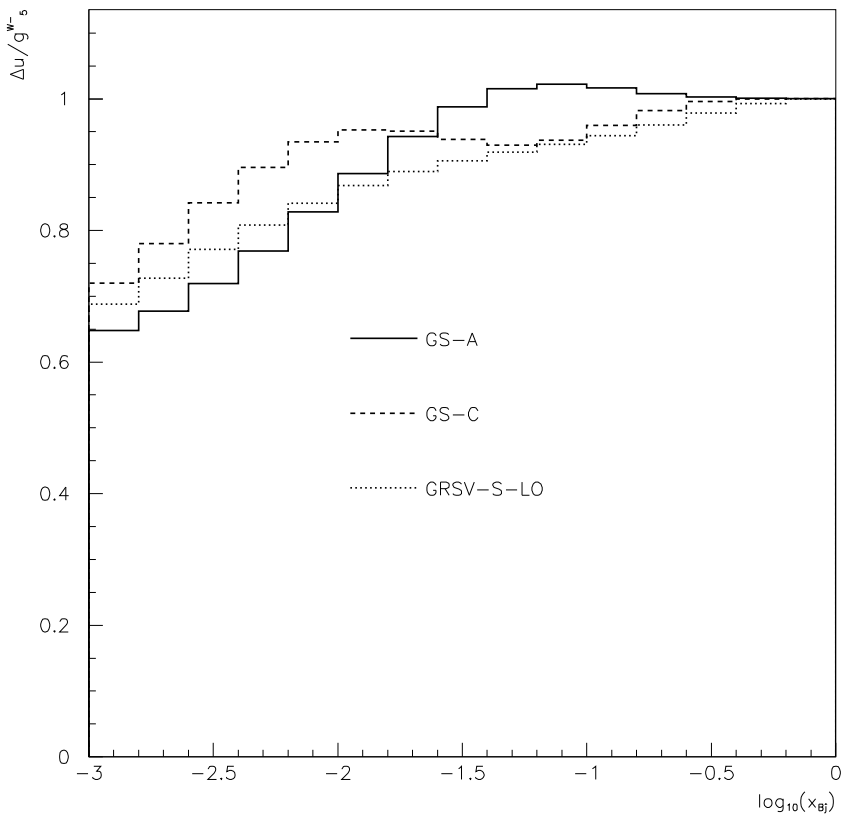

Figure 4: Ratio of the Δu polarized parton distribution to the $g_5^{W^-}$ structure function for three sets of polarized parton distributions considered in this analysis.

5 Conclusions

Charged current events, generated with the PEPSI Monte Carlo program, have been studied for a polarized HERA. Detector effects were taken into account. Charged current events allow a precise extraction of the structure functions $g_5^{W^\pm}$ in the region of Bjorken-x larger than 0.01. Systematic effects of the calorimeter energy scale, parton distributions and detector acceptance were studied, with data samples corresponding to a total statistics of 500 pb^{-1}. The measurable asymmetries remain very prominent and survive the detector effects. With simplistic assumptions these structure functions are directly related to the polarized quark distributions Δu and Δd. Hence the study of asymmetries allows to extract information on these quantities at a Q^2 scale of $O(1000)$ GeV^2. Although present parton density parametrizations do not predict large differences, mainly due to the limited information presently available for extracting these densities, this measurement is unique and will provide vital data on the flavour decomposition of the polarized quark densities. It will be also of interest to check the evolution of these densities at low Q^2 as measured by SMC and HERMES [19] to the kinematic region of HERA.

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