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The Polarised Valence Quark Distribution from semi-inclusive DIS

The COMPASS Collaboration

Abstract

The semi-inclusive difference asymmetry $A^{h^+-h^-}$ for hadrons of opposite charge has been measured by the COMPASS experiment at CERN. The data were collected in the years 2002–2004 using a 160 GeV polarised muon beam scattered off a large polarised ^{6}LiD target and cover the range $0.006 < x < 0.7$ and $1 < Q^2 < 100$ (GeV/c)^2. In leading order QCD (LO) the asymmetry $A_d^{h^+-h^-}$ measures the valence quark polarisation and provides an evaluation of the first moment of $\Delta u_v + \Delta d_v$ which is found to be equal to 0.40 ± 0.07 (stat.)± 0.05 (syst.) over the measured range of x at $Q^2 = 10$ (GeV/c)^2. When combined with the first moment of g_1^d previously measured on the same data, this result favours a non-symmetric polarisation of light quarks $\Delta\overline{u} = -\Delta\overline{d}$ at a confidence level of two standard deviations, in contrast to the often assumed symmetric scenario $\Delta\overline{u} = \Delta\overline{d} = \Delta\overline{s} = \Delta s$.

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The COMPASS experiment at CERN has recently published an evaluation of the deuteron spin-dependent structure function $g_1^d(x)$ in the DIS region, based on measurements of the spin asymmetries observed in the scattering of 160 GeV longitudinally polarised muons on a longitudinally polarised ^{6}LiD target [1]. These measurements provide an accurate evaluation of the first moment of g_1 for the average nucleon N in an isoscalar target $g_1^N = (g_1^p + g_1^n)/2$

$$\Gamma_1^N(Q^2\!=\!10\ (\mathrm{GeV}/c)^2) = \int_0^1 g_1^N(x, Q^2\!=\!10\ (\mathrm{GeV}/c)^2)dx = 0.051 \pm 0.003\ (\mathrm{stat.}) \pm 0.006\ (\mathrm{syst.}) \tag{1}$$

from which the first moment of the strange quark distribution can be extracted if the value of the octet matrix element ($a_8 = 3\,F - D$) is taken from semi-leptonic hyperon decays. [1)] At LO in QCD

$$\Delta s + \Delta\overline{s} = 3\,\Gamma_1^N - \frac{5}{12}a_8 = -0.09 \pm 0.01\ (\mathrm{stat.}) \pm 0.02\ (\mathrm{syst.}) \tag{2}$$

at $Q^2 = 10\ (\mathrm{GeV}/c)^2$.

Since quarks and antiquarks of the same flavour equally contribute to g_1, inclusive data do not allow to separate valence and sea contributions to the nucleon spin. We present here additional information on the contribution of the nucleon constituents to its spin, based on semi-inclusive spin asymmetries measured on the same data as those used in Ref. [1].

The semi-inclusive spin asymmetries for positive and negative hadrons h^+ and h^- are defined by

$$A^{h^+} = \frac{\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h+}_{\uparrow\uparrow}}{\sigma^{h+}_{\uparrow\downarrow} + \sigma^{h+}_{\uparrow\uparrow}}, \qquad A^{h^-} = \frac{\sigma^{h-}_{\uparrow\downarrow} - \sigma^{h-}_{\uparrow\uparrow}}{\sigma^{h-}_{\uparrow\downarrow} + \sigma^{h-}_{\uparrow\uparrow}}, \tag{3}$$

where the arrows indicate the relative beam and target spin orientations.

The data used in the present analysis were collected by the COMPASS collaboration at CERN during the years 2002–2004. The event selection requires a reconstructed interaction vertex defined by the incoming and scattered muons and located inside one of the two target cells [2]. The energy of the beam muon is required to be in the interval $140 < E_\mu < 180$ GeV and its extrapolated trajectory is required to cross entirely the two cells in order to equalise the fluxes seen by each of them. DIS events are selected by cuts on the photon virtuality ($Q^2 > 1\ (\mathrm{GeV}/c)^2$) and on the fractional energy of the virtual photon ($0.1 < y < 0.9$). The hadrons used in the analysis are required to originate from the interaction vertex and to be produced in the current fragmentation region. The latter requirement is satisfied by selecting hadrons with fractional energy $z > 0.2$. In addition an upper limit $z < 0.85$ is imposed in order to suppress hadrons from exclusive diffractive processes and to avoid contamination from wrongly identified muons. The resulting sample contains 30 and 25 million of positive and negative hadrons, respectively. The hadron identification provided by the RICH detector is not used in the present analysis.

The target spins are reversed at regular intervals of 8 hours during the data taking. The spin asymmetries are obtained from the numbers of hadrons collected from each target cell during consecutive periods before and after reversal of the target spins, following the same procedure as for inclusive asymmetries [3]. They are listed in Table 1 and also shown in Fig. 1 as a function of x, in comparison with the SMC [4, 5] and HERMES [6] results. The results from the three experiments are consistent. The COMPASS results show a large gain in statistical precision with respect to SMC, especially in the low x region ($x < 0.04$), while at larger x the COMPASS errors are comparable to those of HERMES. The systematic errors, shown by the bands at the bottom of the figure, result from different sources. The uncertainty on the various factors entering in the asymmetry calculation (beam and target polarisation, depolarisation factor and dilution factor) leads to a relative error of 8% on the asymmetry when combined in quadrature. The uncertainty due to radiative corrections is smaller than in the inclusive case due to the selection of hadronic

[1)] At the precision of the experiment the value of Γ_1^N is unchanged when the evolution of the measured values $g_1(x_i, Q_i^2)$ to a common Q^2 is done at LO or at NLO in QCD.

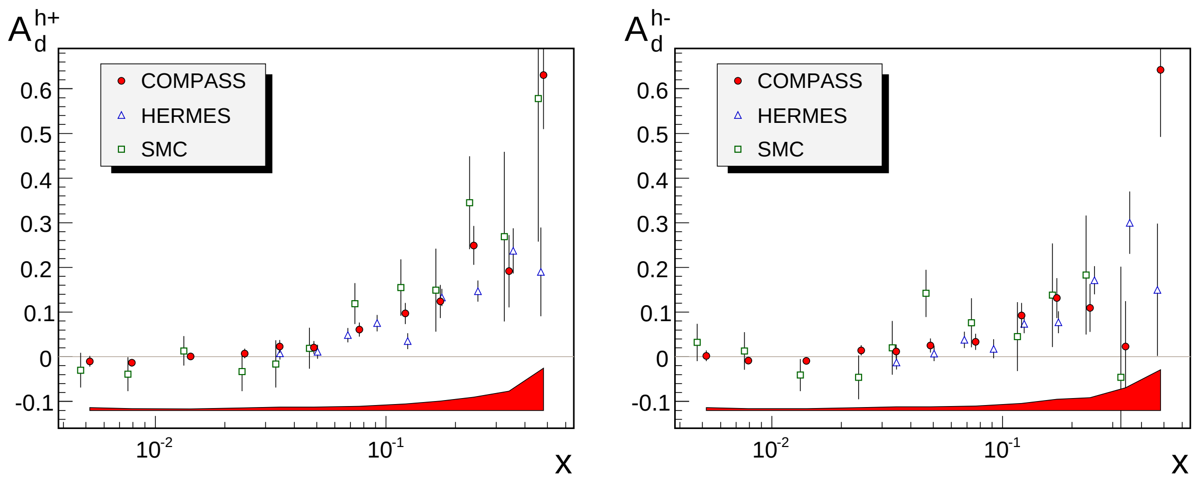


Figure 1: Hadron asymmetries A_d^{h+} (left) and A_d^{h-} (right) measured by COMPASS, SMC [5] and HERMES [6] experiments. The bands at the bottom of the figures show the systematic errors of the COMPASS measurements.

$\langle x\rangle$	$\langle Q^2\rangle$ $(\mathrm{GeV}/c)^2$	A_d^{h+}	A_d^{h-}	$A_d^{h^+-h^-}$
0.0052	1.17	$-0.010 \pm 0.012 \pm 0.006$	$0.002 \pm 0.012 \pm 0.006$	–
0.0079	1.45	$-0.013 \pm 0.008 \pm 0.004$	$-0.008 \pm 0.008 \pm 0.004$	$-0.081 \pm 0.138 \pm 0.070$
0.0141	2.06	$0.000 \pm 0.007 \pm 0.003$	$-0.009 \pm 0.007 \pm 0.004$	$0.070 \pm 0.067 \pm 0.034$
0.0244	2.99	$0.007 \pm 0.011 \pm 0.005$	$0.014 \pm 0.012 \pm 0.006$	$-0.027 \pm 0.077 \pm 0.039$
0.0346	4.03	$0.023 \pm 0.015 \pm 0.008$	$0.012 \pm 0.016 \pm 0.008$	$0.070 \pm 0.090 \pm 0.045$
0.0486	5.56	$0.021 \pm 0.014 \pm 0.007$	$0.025 \pm 0.016 \pm 0.008$	$0.006 \pm 0.076 \pm 0.038$
0.0764	8.29	$0.061 \pm 0.016 \pm 0.009$	$0.033 \pm 0.018 \pm 0.009$	$0.138 \pm 0.070 \pm 0.037$
0.121	12.6	$0.097 \pm 0.024 \pm 0.014$	$0.092 \pm 0.028 \pm 0.016$	$0.107 \pm 0.087 \pm 0.044$
0.172	17.7	$0.124 \pm 0.037 \pm 0.021$	$0.132 \pm 0.045 \pm 0.025$	$0.109 \pm 0.121 \pm 0.061$
0.239	25.3	$0.249 \pm 0.044 \pm 0.029$	$0.109 \pm 0.054 \pm 0.028$	$0.478 \pm 0.130 \pm 0.075$
0.341	42.6	$0.192 \pm 0.081 \pm 0.043$	$0.023 \pm 0.101 \pm 0.051$	$0.429 \pm 0.217 \pm 0.114$
0.482	60.2	$0.630 \pm 0.121 \pm 0.078$	$0.643 \pm 0.150 \pm 0.091$	$0.616 \pm 0.291 \pm 0.186$

Table 1: Values of $A_d^{h^+}$, $A_d^{h^-}$ and $A_d^{h^+-h^-}$ with their statistical and systematical errors as a function of x with the corresponding average value of Q^2.

events and does not exceed 10^{-3} in any x bin. The presence of possible false asymmetries due to time-dependent apparatus effects has been studied in the same way as for the inclusive asymmetries: the data sample has been divided into a large number of subsamples, each of them collected in a small time interval. The observed dispersion of the asymmetries obtained for these subsamples has been found compatible with the value expected from their statistical error. This allows to set an upper limit for this type of false asymmetries at about half of the statistical error. Asymmetries, obtained with different settings of the microwave frequency used for dynamic nuclear polarisation of the target, have also been compared and did not reveal any systematic difference. In order to avoid possible (x, z) correlated acceptance effects, the asymmetries have also been calculated in three different intervals of z for each bin of x. No significant z dependence is observed and the weighted averages in each bin of x are consistent with the quoted values.

In the present analysis we use the “difference asymmetry” which is defined as the spin asymmetry for the difference of the cross sections for positive and negative hadrons:

$$A^{h^+-h^-} = \frac{(\sigma_{\uparrow\downarrow}^{h+} - \sigma_{\uparrow\downarrow}^{h-}) - (\sigma_{\uparrow\uparrow}^{h+} - \sigma_{\uparrow\uparrow}^{h-})}{(\sigma_{\uparrow\downarrow}^{h+} - \sigma_{\uparrow\downarrow}^{h-}) + (\sigma_{\uparrow\uparrow}^{h+} - \sigma_{\uparrow\uparrow}^{h-})}. \tag{4}$$

The difference asymmetry approach for the extraction of helicity distributions was introduced in [7] and further discussed in [8]. For the first time it was used by SMC [4]. In LO QCD, under the assumption of isospin symmetry and charge conjugation symmetry, fragmentation functions cancel out from $A^{h^+-h^-}$. In addition, in the case of an isoscalar target the difference asymmetries for pions and kaons are both equal to the valence quark polarisation

$$A_N^{h^+-h^-} = A_N^{\pi^+-\pi^-} = A_N^{K^+-K^-} = \frac{\Delta u_v + \Delta d_v}{u_v + d_v}\,, \tag{5}$$

where we introduce the valence quark distributions $q_v = q - \bar{q}$. Since kaons contribute to the asymmetry in the same way as pions, the use of hadron identification is not needed, allowing to reduce the statistical errors. It is worth noting that the difference asymmetry for (anti)protons, $A_N^{p-\overline{p}}$, has the same value under slightly more restrictive assumptions. At higher order in QCD the difference asymmetries still determine the valence quark polarisation without any assumption on the sea and gluon densities [8]. Fragmentation functions no longer cancel out but their effect is expected to be small [9].

The relation between the difference asymmetries of Eq. (4) and the single hadron asymmetries of Eq. (3) is

$$A^{h^+-h^-} = \frac{1}{1-r}(A^{h^+} - rA^{h^-})\,, \quad \text{with} \quad r = \frac{\sigma_{\uparrow\downarrow}^{h-} + \sigma_{\uparrow\uparrow}^{h-}}{\sigma_{\uparrow\downarrow}^{h+} + \sigma_{\uparrow\uparrow}^{h+}} = \frac{\sigma^{h-}}{\sigma^{h+}}. \tag{6}$$

The ratio of cross sections for negative and positive hadrons, r, depends on the event kinematics and is obtained as the product of the corresponding ratio of the number of observed hadrons N^-/N^+ by the ratio of the geometrical acceptances a^+/a^-:

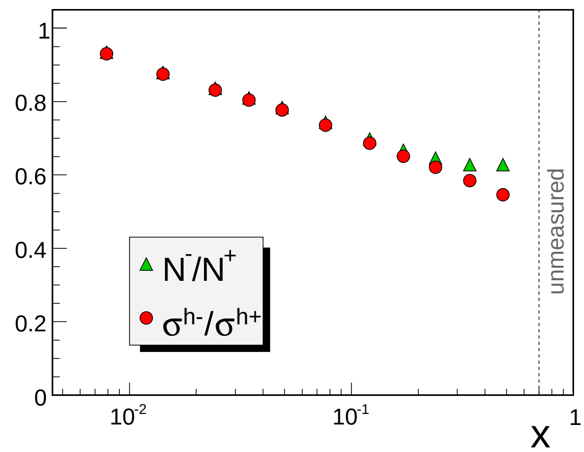
$$r = \frac{\sigma^{h-}}{\sigma^{h+}} = \frac{N^-}{N^+} \cdot \frac{a^+}{a^-}. \tag{7}$$

Figure 2 (left) shows the ratio of the number of negative to positive hadrons which decreases with increasing x. This ratio is subject to acceptance corrections because positive and negative hadrons, produced at the same angle, cross different regions of the spectrometer. To this end LEPTO generated Monte Carlo events have been processed through the program simulating the COMPASS spectrometer performance [2] and reconstructed in the same way as the data. The acceptances a^+ and a^- are indeed found to be different: the ratio a^-/a^+ which is about 1.0 at low x, increases for $x > 0.1$ reaching $\sim$1.12 in the highest x bin. The corrected cross section ratio $\sigma^{h^-}/\sigma^{h^+}$ is also shown in Fig. 2.

The resulting values of the difference asymmetry $A_d^{h^+-h^-}$ as a function of x are shown in Fig. 2 (right) and listed with their statistical and systematic errors in Table 1. The statistical correlation between $A_d^{h^+}$ and $A_d^{h^-}$ which is approximately 0.20 over the measured range of x, is taken into account in the evaluation of the error of $A_d^{h^+-h^-}$. As can be seen from Eq. (6), a singularity appears when the cross section ratio becomes close to one, leading to infinite statistical errors. For this reason, we discard the lowest x bin used in the inclusive g_1 analysis [1] and take $x = 0.006$ as lower limit for the present analysis. The increase of $A_d^{h^+-h^-}$ for $x > 0.1$ illustrates the increasing polarisation of valence quarks carrying a larger fraction of the nucleon momentum.

The polarised valence quark distribution $\Delta u_v + \Delta d_v$ is obtained by multiplying $A_d^{h^+-h^-}$ by the unpolarised valence distribution of MRST04 at LO [10]. Here two corrections are applied, one accounting for the fact that although $R(x, Q^2) = 0$ at LO, the unpolarised parton distribution functions (pdfs) originate from F_2's in which $R = \sigma_L/\sigma_T$ was different from zero [11], the other one accounting for deuteron D-state contribution ($\omega_D = 0.05 \pm 0.01$ [12]):

$$\Delta u_v + \Delta d_v = \frac{(u_v + d_v)_{\text{MRST}}}{(1+R)(1-1.5\omega_D)} A_d^{h^+-h^-}. \tag{8}$$



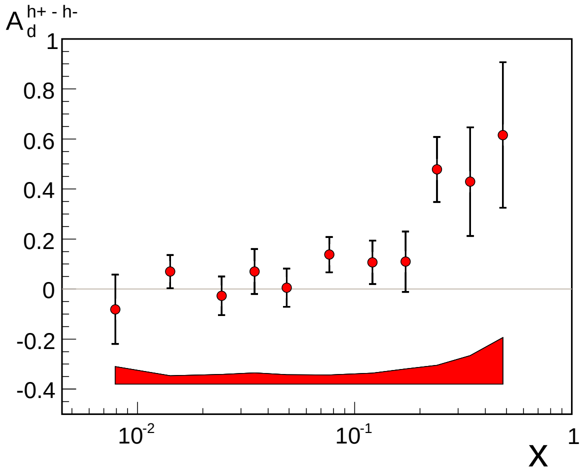


Figure 2: Left: The ratio $\sigma^{h^-}/\sigma^{h^+}$ before (triangles) and after acceptance corrections (circles). Right: The difference asymmetry, $A_d^{h^+-h^-}$, for unidentified hadrons of opposite charges, as a function of x at the Q^2 of each measured point.

The LO parameterisation of the DNS fit[13] has been used to evolve all values of $\Delta u_v + \Delta d_v$ to a common Q^2 fixed at 10 $(\mathrm{GeV}/c)^2$. The DNS analysis includes all DIS g_1 data prior to COMPASS, the partial COMPASS data on g_1 from Ref. [3] as well as the SIDIS data from SMC [5] and HERMES [6]. Two parameterisations of polarised pdfs are provided at LO, corresponding to two different choices of fragmentation functions, KRE [14] and KKP [15]. We have checked that the x dependence of the ratio $\sigma^{h^-}/\sigma^{h^+}$ (Fig. 2) is fairly well reproduced by the LO MRST04 pdfs and the KKP fragmentation functions whereas the KRE parameterisation leads to a much weaker x dependence. For this reason we choose the fit with the KKP parameterisation. The resulting values are shown in Fig. 3 (left). The DNS fit, also shown in the figure, is basically defined by the SMC and HERMES semi-inclusive asymmetries. Its good agreement with the COMPASS values ($\chi^2 = 7.7$ for 11 data points) illustrates the consistency between the three experiments.

The sea contribution to the unpolarised structure function F_2 decreases rapidly with increasing x and becomes smaller than 0.1 for $x > 0.3$. Due to the positivity conditions $|\Delta q| \leq q$ and $|\Delta \overline{q}| \leq \overline{q}$, the polarised sea contribution to the nucleon spin also becomes negligible in this region. In view of this, the evaluation of the valence spin distribution of Eq. (8) can be replaced by a more accurate one obtained from inclusive interactions, indeed at LO

$$\Delta u_v + \Delta d_v \;=\; \frac{36}{5}\frac{g_1^d}{(1-1.5\omega_D)} - \Big(2(\Delta\bar{u}+\Delta\bar{d}) + \frac{2}{5}(\Delta s + \Delta\bar{s})\Big). \tag{9}$$

The values obtained by taking only the first term on the r.h.s. for $x > 0.3$ are also shown in Fig. 3. They agree very well with the DNS curve, which is based on previous experiments where the same procedure had been applied [5, 6]. The neglected sea quark contributions are taken into account in the systematic error.

The first moment of the polarised valence distribution, truncated to the measured range of x

$$\Gamma_v(x_{min}) = \int_{x_{min}}^{0.7} (\Delta u_v(x) + \Delta d_v(x))dx, \tag{10}$$

derived from the difference asymmetry for $x < 0.3$ and from g_1^d for $0.3 < x < 0.7$, is shown in Fig. 3 (right). Practically no dependence on the lower limit is observed for $x_{min} < 0.03$. We obtain for the full measured range of x

$$\Gamma_v(0.006 < x < 0.7) = 0.40 \pm 0.07\ (\mathrm{stat.}) \pm 0.05\ (\mathrm{syst.}) \tag{11}$$

	x-range	Q^2 $(\mathrm{GeV}/c)^2$	$\Delta u_v + \Delta d_v$ Exp.Value	DNS	$\Delta\bar{u} + \Delta\bar{d}$ Exp.Value	DNS
SMC	0.003–0.7	10	$0.26 \pm 0.21 \pm 0.11$	0.386	$0.02 \pm 0.08 \pm 0.06$	-0.009
HERMES	0.023–0.6	2.5	$0.43 \pm 0.07 \pm 0.06$	0.363	$-0.06 \pm 0.04 \pm 0.03$	-0.005
COMPASS	0.006–0.7	10	$0.40 \pm 0.07 \pm 0.05$	0.385	–	-0.007
	0–1		$0.41 \pm 0.07 \pm 0.05$	–	$0.0 \pm 0.04 \pm 0.03$	–

Table 2: Estimates of the first moments $\Delta u_v + \Delta d_v$ and $\Delta\bar{u} + \Delta\bar{d}$ from the SMC [5], HERMES [6], COMPASS data and also from the DNS fit at LO [13] truncated to the range of each experiment (lines 1–3). The SMC results were obtained with the assumption of a $SU(3)_f$ symmetric sea: $\Delta\bar{u} = \Delta\bar{d} = \Delta\bar{s}$. The last line shows the COMPASS results for the full range of x.

at $Q^2 = 10$ $(\mathrm{GeV}/c)^2$, with contributions of 0.26 ± 0.07 and 0.14 ± 0.01 for $x < 0.3$ and $x > 0.3$, respectively. It should be noted that removing the factor $(1 + R)$ in Eq. (8) would increase the value of Γ_v to $0.42 \pm 0.08 \pm 0.06$. Our value of Γ_v confirms the HERMES result obtained at $Q^2 = 2.5$ $(\mathrm{GeV}/c)^2$ over a smaller range of x and is also consistent with the SMC result which has three times larger errors (Table 2). The factor $(1 + R)$ was also used in the previous experiments.

The difference between our measured value of $\Gamma_v(0.006 < x < 0.3)$ and the integral of g_1^N over the same range of x gives a global measurement of the polarised sea. Indeed, re-ordering Eq. (9) we obtain

$$\int_{0.006}^{0.30} \Big((\Delta\overline{u} + \Delta\overline{d}) + \frac{1}{5}(\Delta s + \Delta\overline{s}) \Big) dx = -0.02 \pm 0.03 \text{ (stat.)} \pm 0.02 \text{ (syst.)}, \tag{12}$$

where the correlation between inclusive and semi-inclusive asymmetries has been taken into account in the statistical error. This result is compatible with zero but also consistent with the strange quark contribution of Eq. (2) and a vanishing contribution from the light quarks. It should be kept in mind that moments of sea quarks evaluated at LO have to be taken with caution because their values are small and thus comparable to the NLO corrections.

The unmeasured contribution to Γ_v for $x > 0.7$ estimated from the LO DNS parameterisation of Ref. [13] is 0.004 at $Q^2 = 10$ $(\mathrm{GeV}/c)^2$. Its upper limit corresponding to the assumption $A_d^{h^+-h^-} = 1$ for $x > 0.7$ is 0.007 according to the MRST04 parameterisation.

The unmeasured low x contribution to Γ_v is expected to be negligible since the integral shows not significant variation when its lower limit is varied between 0.006 and 0.02. We thus estimate the first moment

$$\Gamma_v(0 < x < 1) = 0.41 \pm 0.07 \text{ (stat.)} \pm 0.05 \text{ (syst.)}. \tag{13}$$

The assumption of a fully flavour symmetric sea $\Delta\overline{u} = \Delta\overline{d} = \Delta s = \Delta\overline{s}$ obviously leads to $\Gamma_v(0 < x < 1) = a_8$. As shown in Fig. 3 (right), our experimental value is two standard deviations below the value of $a_8 = 3\,F - D = 0.58 \pm 0.03$ derived from hyperon β decays [16]. It has been suggested that a value of the valence contribution Γ_v smaller than a_8 (as expected from the constituent quark models) could be a hint that a so far unmeasured part of the nucleon's spin resides at $x = 0$ [17].

An estimate of the light sea quark contribution to the nucleon spin can be obtained by combining the values of Γ_v (Eq. (13)), Γ_1^N (Eq. (1)) and a_8

$$\Delta\overline{u} + \Delta\overline{d} = 3\Gamma_1^N - \frac{1}{2}\Gamma_v + \frac{1}{12}a_8 \tag{14}$$

and the result is found to be zero (Table 2). Possible deviations from the nominal value of a_8 due to $SU(3)_f$ symmetry violation in hyperon decays are generally assumed to be of the order of 10% [18] and are included in the systematic error. The zero value of $\Delta\overline{u} + \Delta\overline{d}$ is in contrast with

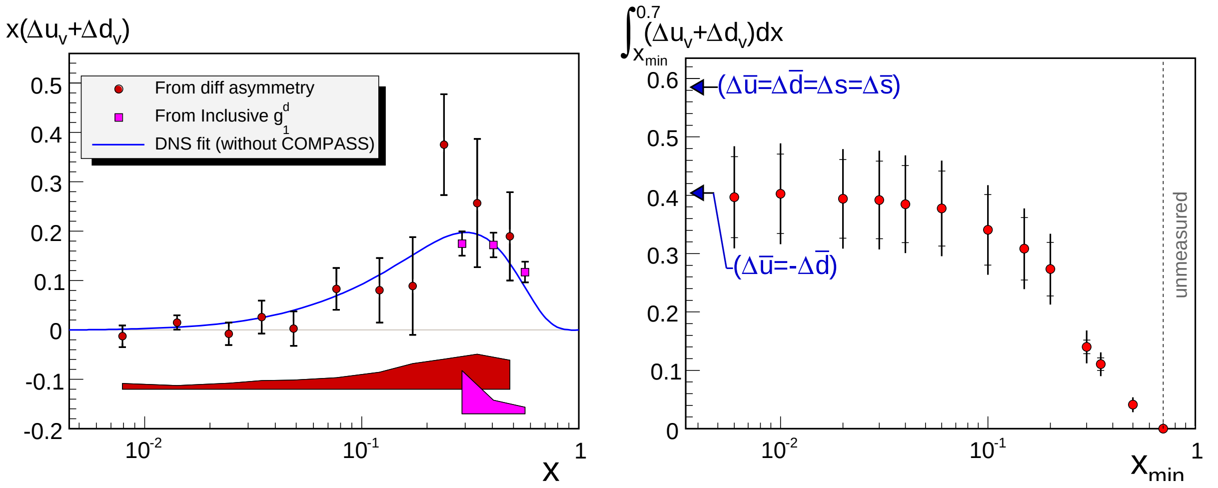


Figure 3: Left: Polarised valence quark distribution $x(\Delta u_v(x) + \Delta d_v(x))$ evolved to $Q^2 = 10$ (GeV/c)^2 according to the DNS fit at LO [13]. The line shows the DNS fit which does not include the present COMPASS data. Three additional points at high x are obtained from g_1^d [1]. Right: The integral of $\Delta u_v(x)+\Delta d_v(x)$ over the range $0.006 < x < 0.7$ as the function of the low x limit of integration x_{min}, evaluated at $Q^2 = 10$ (GeV/c)^2. SIDIS data are used in the interval $0.006 < x < 0.3$ and inclusive g_1^d data from Ref. [1] in the interval $0.3 < x < 0.7$.

the non-zero value obtained for $\Delta s + \Delta\overline{s}$ (Eq. (2)) and suggests that $\Delta\overline{u}$ and $\Delta\overline{d}$, if different from zero, must be of opposite sign. Previous estimates by SMC and HERMES, also given in Table 2, are compatible with this hypothesis. The DNS parameterisation finds a positive $\Delta\overline{u}$ and a negative $\Delta\overline{d}$, about equal in absolute value. Opposite signs of $\Delta\overline{u}$ and $\Delta\overline{d}$ are also obtained in the statistical model of Ref. [19]. Forthcoming COMPASS data on a proton target will provide separate determinations of $\Delta\overline{u}$ and $\Delta\overline{d}$.

In conclusion, we have determined at LO QCD the polarised valence quark distribution from the difference asymmetry for oppositely charged hadrons in DIS of muons on a polarised isoscalar target. Its first moment at $Q^2 = 10$ (GeV/c)^2 over the measured range of x (0.006–0.7) is found to be 0.40 ± 0.07 (stat.) ± 0.05 (syst.). This value disfavours at a two σ level the assumption of a flavour symmetric polarised sea and suggest that $\Delta\overline{u}$ and $\Delta\overline{d}$ are most likely of opposite sign.

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