Quark Helicity Distributions from Longitudinal Spin Asymmetries in Muon-Proton and Muon-Deuteron Scattering

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Abstract. We present a leading order evaluation of the helicity distributions for the three lightest quarks and anti-quarks flavours, derived from the double-spin asymmetries measured by the COMPASS collaboration. The data, obtained by scattering a 160 GeV muon beam off longitudinally polarised NH_3 and ^{6}LiD targets, cover the Bjorken variable x range $0.004 < x < 0.7$. The resulting values of the sea quark distributions are all small and do not show any sizable dependence on x in the range of the measurements. No significant difference is observed between the strange and anti-strange helicity distributions, both compatible with zero. The integrated value of the polarised flavour sea asymmetry is found to be slightly positive, about 1.5 standard deviations away from zero.

1. Introduction

Spin asymmetries measured in polarised Deep Inelastic Scattering (DIS) provide the main source of information on the spin structure of the nucleon. Semi-inclusive asymmetries, where in addition to the scattered lepton, hadrons are also detected, are sensitive to the individual quark and antiquark flavours so that the combined analysis of DIS and semi-inclusive DIS on both proton and deuteron targets leads to a simultaneous determination of the up, down and strange quark helicity distributions.

The COMPASS collaboration has presented previously a leading order (LO) evaluation of the isoscalar quark helicity distributions $\Delta u_v + \Delta d_v$, $\Delta \overline{u} + \Delta \overline{d}$ and $\Delta s + \Delta \overline{s}$ derived from the inclusive and semi-inclusive double-spin asymmetries on the deuteron [1]. In the present paper this analysis is extended by using the new COMPASS data on the proton and a full flavour decomposition is obtained.

2. Data

The COMPASS experiment at CERN has measured double-spin asymmetries for charged pions and kaons produced in deep-inelastic muon scattering off polarised ^{6}LiD and NH_3 targets. The LO evaluation of the helicity distributions for the three lightest quark and antiquark flavours is based on these asymmetries and on the previously measured inclusive double-spin asymmetries $A_{1,p}$ and $A_{1,d}$. The incident muon beam has an energy of 160 GeV and is naturally polarised to $\sim(-0.80)$. The target polarisation is about ± 0.50 for ^{6}LiD and ± 0.90 for NH_3 with dilution factors of ~ 0.37 and ~ 0.14, respectively. The target is divided into two or three cells polarised by Dynamic Nuclear Polarisation. Consecutive cells are always polarised in opposite directions and the spin orientations are reversed at regular intervals by rotation of the solenoidal magnetic field[2].

DIS events are selected by cuts on the photon virtuality, $Q^2 > 1(\mathrm{GeV/c})^2$, and the fractional energy, y, transfered to the virtual photon $0.1 < y < 0.9$. The selected event samples cover the range $0.004 < x < 0.7$. All events are required to have a primary vertex located in one of the target cells. Hadrons are identified in the RICH detector. Only hadron tracks originating from the primary vertex are considered. Their fractional energy, z, is required to be in the interval $0.2 < z < 0.85$ in order to select hadrons produced in the beam fragmentation region and to suppress possible contributions from diffractive processes. In addition the momentum range is restricted to the interval $10 < p < 50$ (GeV/c) where pions and kaons can both be identified by the RICH detector. The purity of the samples selected by the RICH detector is larger than 0.98 over the full range of x for pions while for kaons it varies from $0.75 - 0.80$ at low x to about 0.92 at $x \geq 0.03$. The unfolding correction applied to account for the fraction of misidentified hadrons has only a minor effect on the pion and kaon asymmetries.

Spin asymmetries are evaluated from the number of hadrons originating from cells with opposite spin orientations collected before and after a target field rotation so that flux and acceptance factors cancel out. The inclusive and semi-inclusive asymmetries for the deuteron and proton data can be found in Refs.[1] and [3], respectively. They are corrected for QED radiative effects [4], for the admixture of ^{7}Li in the ^{6}LiD material and for the ^{14}N polarisation in NH$_3$ [5]. These corrections are small (≤ 0.020) for all values of the Bjorken variable x and for all types of hadrons.

The systematic errors on the spin asymmetries contain a multiplicative part resulting from uncertainties on the beam and target polarisations, on the dilution factor and on the ratio $R = \sigma_L/\sigma_T$. Added in quadrature these uncertainties amounts to 8% and 6% for the ^{6}LiD and NH$_3$ data, respectively. In addition an important contribution to the systematic error arises from possible false asymmetries generated by random instabilities in the experimental setup. The upper limits for these errors are found to be $0.4\sigma_{\mathrm{stat}}$ for the deuteron sample and $0.56\sigma_{\mathrm{stat}}$ for the proton sample at the level of one standard deviation.

3. Polarised PDFs

At LO in QCD, under the assumption of independent quark fragmentation, the spin asymmetry for hadrons h produced in the current fragmentation region can be written as a sum of products of the quark and antiquark helicity distributions Δq ($\Delta\overline{q}$) times the fragmentation functions D_q^h ($D_{\overline{q}}^h$):

$$A^h(x,z) \quad = \quad \frac{\sum_q e_q^2(\Delta q(x) D_q^h(z) + \Delta\overline{q}(x) D_{\overline{q}}^h(z))}{\sum_q e_q^2(q(x) D_q^h(z) + \overline{q}(x) D_{\overline{q}}^h(z))} \,. \tag{1}$$

In the present analysis, we neglect the Q^2 dependence of the asymmetries and assume all measurements to be valid at $Q_0^2 = 3$ (GeV/c)^2, an assumption supported by the consistency of the COMPASS asymmetries with those obtained by HERMES at much lower Q^2 values [6]. For the unpolarised parton distributions (PDFs) we use the LO parameterisation of MRST [7] with three quark flavours and for the fragmentation functions the LO parameterisation of DSS [8]. As in previous analyses[9, 1], the unpolarised PDFs which are extracted from cross sections assuming non-zero values of R are corrected by a factor $(1 + R(x, Q_0^2))$[10] to take into account the fact that R is assumed to be zero at LO. The four semi-inclusive asymmetries on the proton, the four on the deuteron and the two inclusive asymmetries thus provide a system of ten equations with six unknowns (Δu, Δd, $\Delta\overline{u}$, $\Delta\overline{d}$, Δs and $\Delta\overline{s}$) which is solved by a least-square fit, independently in each bin of x. The analysis is limited to $x \leq 0.3$ because the antiquark distributions become insignificant above this limit.

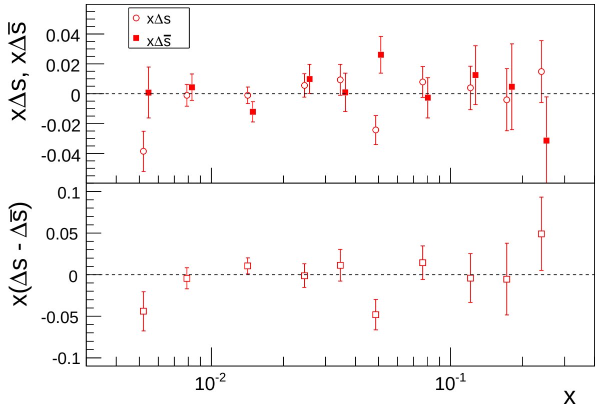

Figure 1. Comparison of $x\,\Delta s$ (open circles) and $x\,\Delta\overline{s}$ (squares) at $Q_0^2 = 3$ (GeV$/c)^2$ (top) and corresponding values of the difference $x(\Delta s - \Delta\overline{s})$ (bottom).

The fit results for the Δs and $\Delta\overline{s}$ distributions and for their difference are displayed in Fig. 1. In the measured x range both distributions are flat and compatible with zero. The same observation can be made for their difference, $\Delta s - \Delta\overline{s}$; only one point out of ten is outside two standard deviations (2.7 σ at $x = 0.0487$). We have checked that the vanishing values of $\Delta s - \Delta\overline{s}$ are not artificially generated by the MRST parameterisation of the unpolarised PDFs where $s(x) = \overline{s}(x)$ is assumed. The $s(x)$ and $\overline{s}(x)$ distributions were scaled simultaneously by factors 2 and 0.5 and allowed to differ in any interval of x by a factor of 2. The values of $\Delta s(x)$ and $\Delta\overline{s}(x)$ were found to be nearly independent of these modifications. We conclude that there is no significant difference between $\Delta s(x)$ and $\Delta\overline{s}(x)$ in the x-range covered by the data. This conclusion remains valid when the DSS fragmentation functions used in the fit are replaced by those derived by EMC [11]. The results on $\Delta s(x)$ and $\Delta\overline{s}(x)$ are at variance with the SU(3) Chiral Quark-Soliton model prediction $|\Delta s(x)| \gg |\Delta\overline{s}(x)|$ [12] but are compatible with statistical models predicting that $\Delta s(x) - \Delta\overline{s}(x)$ should be zero [13] or small [14].

From here on the distributions of Δs and $\Delta\overline{s}$ will be assumed to be equal. This assumption reduces the number of unknowns to five and improves the statistical precision of the fit results at least by a factor 1.5. The average χ^2-probability of the fits is equal to 55%. Within their statistical precision the COMPASS data are thus compatible with the factorisation formula of Eq. (1).

The results for the quark helicity distributions Δu, Δd, $\Delta\overline{u}$, $\Delta\overline{d}$, and Δs ($\Delta s = \Delta\overline{s}$) are shown in Fig. 2. In the range $0.3 < x < 0.7$ three additional values of Δu and Δd, derived under the assumption $\Delta\overline{q} = 0$, are also displayed. The dominant contribution to the systematic errors on Δu and Δd comes from the uncertainty of the beam polarisation, which affects all data in the same way and leads to an uncertainty of 5% for all fitted values. The systematic error on the antiquarks and strange quarks distributions is mainly due to possible false asymmetries generated by time dependent effects on the detector acceptance. The curves show the results of the DSSV fit at Next-to-Leading Order (NLO) [17]. The comparison with the experimental results derived at LO is thus only qualitative. Nevertheless, the curves reproduce fairly well the x dependence of Δu and Δd.

The anti-quark distributions, $\Delta\overline{u}$ and $\Delta\overline{d}$, do not show any significant variation in the x range of the data, the former being consistent with zero, the latter being slightly negative. The values of the strange quark helicity distribution confirm with slightly reduced errors the results obtained from the deuteron data alone[1] and with the same fragmentation functions (DSS): no significant variation of $\Delta s(x)$ is observed in the range of the data. Only the first point at low x shows a small deviation from zero ($\approx 2.5\sigma$).

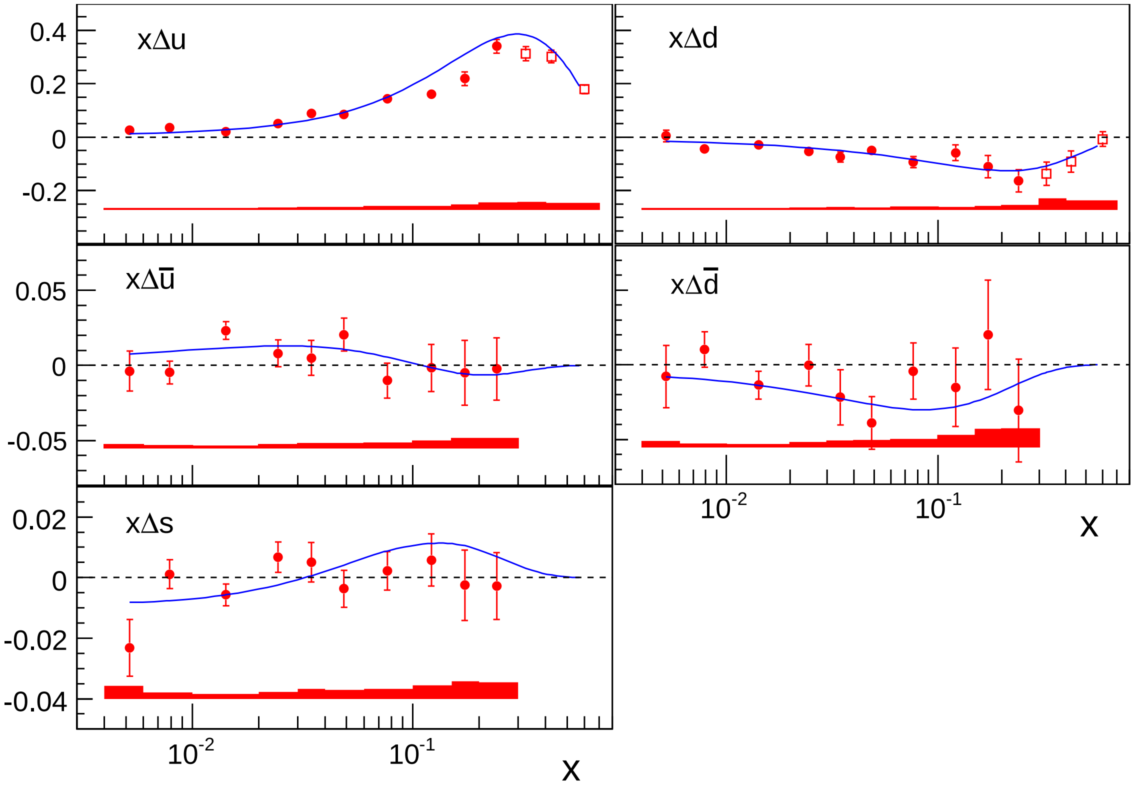

Figure 2. The quark helicity distributions $x\,\Delta u$, $x\,\Delta d$, $x\,\Delta\overline{u}$, $x\,\Delta\overline{d}$, and $x\,\Delta s$ at $Q_0^2 = 3$ $(\mathrm{GeV}/c)^2$ as a function of x. The values for $x < 0.3$ (dots) are derived at LO from the COMPASS spin asymmetries using the DSS fragmentation functions [8]. Those at $x > 0.3$ (open squares) are derived from the values of the polarised structure functions $g_1^p(x)$ and $g_1^d(x)$ quoted in [15, 16] assuming $\Delta\overline{q} = 0$. The bands at the bottom of each plot show the systematic errors. The curves show the predictions of the DSSV fit calculated at NLO[17].

The flavour asymmetry of the helicity distribution of the sea, $\Delta\overline{u} - \Delta\overline{d}$, is shown in Fig.3. Although compatible with zero, the values indicate a slightly positive distribution. The DSSV fit at NLO[17] and the unpolarised asymmetry $\overline{d} - \overline{u}$ are shown for comparison. The first moment $\Delta\overline{u} - \Delta\overline{d}$, truncated to the range $0.004 < x < 0.3$, is $0.06 \pm 0.04(\mathrm{stat.}) \pm 0.02(\mathrm{syst.})$. It is worth noting that the polarised first moment is about one standard deviation smaller than the unpolarised one truncated to the same range (≈ 0.10 for the MRST parameterisation[7]). The data thus disfavour models predicting $\Delta\overline{u} - \Delta\overline{d} \gg \overline{d} - \overline{u}$ (see Refs.[19, 21] and references therein). Three model predictions are shown in Fig.3. The statistical model of Ref.[20] and the SU(3) version of the Chiral Quark-Soliton model of Ref.[12] both predict positive distributions, while the Meson Cloud model of Ref.[18] predicts a slightly negative distribution. Within the statistical errors, the COMPASS data are compatible with all three predictions.

4. First moments of polarised PDFs

4.1. Results

Two evaluations of the first moments of the helicity distributions are listed in Table 1. In the first one the contributions from the unmeasured region at low x are obtained by linear extrapolations of the data while in the second one they are taken from the DSSV parameterisations[17]. A significant difference only appears for Δs where DSSV assumes a large negative contribution for $x < 0.004$.

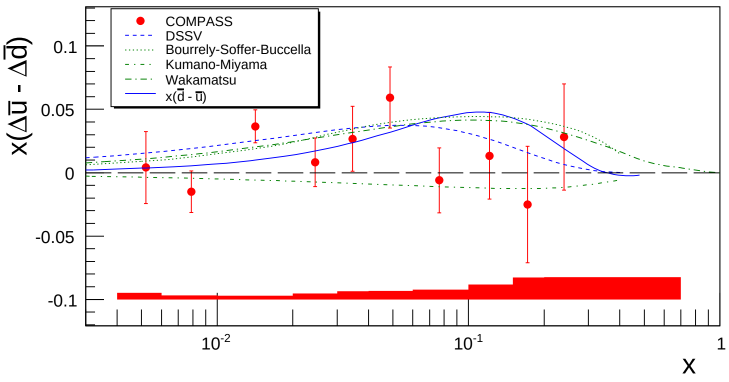

Figure 3. The flavour asymmetry of the helicity distribution of the sea $x\,(\Delta\overline{u} - \Delta\overline{d})$ at $Q_0^2 = 3$ $(\mathrm{GeV}/c)^2$. The band at the bottom of the plot shows the systematic error. The dashed curve is the result of the DSSV fit at NLO. The solid curve shows the MRST parameterisation for the unpolarised difference $x\,(\overline{d} - \overline{u})$ at NLO. The other curves are model predictions from Wakamatsu[12] (long dash-dotted line), Kumano and Miyama[18] (short dash-dotted line), and Bourrely, Soffer and Buccella[20] (dotted line).

Table 1. Full first moments of the quark helicity distributions at $Q_0^2 = 3$ $(\mathrm{GeV}/c)^2$. The unmeasured contributions at low and high x were estimated by extrapolating the data towards $x = 0$ and $x = 1$ and by using the DSSV parameterisation[17]

	Extrapolation	DSSV
Δu	$0.71 \pm 0.02 \pm 0.03$	$0.71 \pm 0.02 \pm 0.03$
Δd	$-0.34 \pm 0.04 \pm 0.03$	$-0.35 \pm 0.04 \pm 0.03$
$\Delta\overline{u}$	$0.02 \pm 0.02 \pm 0.01$	$0.03 \pm 0.02 \pm 0.01$
$\Delta\overline{d}$	$-0.05 \pm 0.03 \pm 0.02$	$-0.07 \pm 0.03 \pm 0.02$
$\Delta s(\Delta\overline{s})$	$-0.01 \pm 0.01 \pm 0.01$	$-0.05 \pm 0.01 \pm 0.01$
$\Delta\Sigma$	$0.32 \pm 0.03 \pm 0.03$	$0.22 \pm 0.03 \pm 0.03$

The sum of the quark and anti-quark contributions, $\Delta\Sigma = 0.32 \pm 0.03(\mathrm{stat.})$, obtained by extrapolating the data, is nearly identical to the value of a_0 derived in Ref.[16] from the first moment of $g_1^d(x)$ using the octet axial charge a_8 ($a_0 = 0.33 \pm 0.03(\mathrm{stat.})$ after correction for the ^{7}Li admixture in the target material). The sum of the valence quark contributions $\Delta u_v + \Delta d_v = \Delta u - \Delta\overline{u} + \Delta d - \Delta\overline{d} = 0.39 \pm 0.03(\mathrm{stat.})$ is also consistent with a previous determination based on the difference asymmetry of positive and negative hadrons in a subsample of the present deuteron data ($0.41 \pm 0.07(\mathrm{stat.})$ at $Q_0^2 = 10$ $(\mathrm{GeV}/c)^2$)[22].

4.2. Dependence on fragmentation functions

The relation between the semi-inclusive asymmetries and the quark helicity distributions (Eq.(1)) depends only on the ratios of fragmentation functions integrated over the selected range of z ($0.2 < z < 0.85$). Relevant for the kaon asymmetries are the unfavoured to favoured, R_{UF}, and strange to favoured, R_{SF}, ratios of fragmentation functions

$$R_{UF} = \frac{\int D_d^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}, \quad R_{SF} = \frac{\int D_{\overline{s}}^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}. \tag{2}$$

In the DSS parameterisation, the R_{UF} and R_{SF} ratios at $Q_0^2 = 3$ (GeV/c)^2 are equal to 0.13 and 6.6, respectively. In the earlier EMC parameterisation [11] R_{SF} is substantially smaller, $R_{SF} = 3.4$, whereas R_{UF} is larger, $R_{UF} = 0.35$. Since the pion fragmentation functions are better constrained by the data than the kaon ones, the effect of the corresponding ratios on the final result is expected to be much smaller. The dependence of the moments truncated to the range $0.004 < x < 0.3$ has been evaluated by varying R_{SF} from $R_{SF} = 2.0$ to $R_{SF} = 7.0$. In order to keep the K^+ multiplicity approximately constant, the value of R_{UF} was simultaneously varied linearly from 0.45 to 0.10. The resulting truncated first moments Δu, $\Delta\overline{u}$, Δd, $\Delta\overline{d}$, Δs, and $\Delta\overline{u} - \Delta\overline{d}$ are shown in Fig.4 as a function of R_{SF}. We observe that the values of Δu ($\Delta\overline{u}$) increase (decrease) by one standard deviation when the ratios evolve from the DSS to the EMC values. In contrast, both Δd and $\Delta\overline{d}$ remain nearly constant. The variation of Δs is much more pronounced: its value evolves from -0.01 to -0.04, although with a much larger error. The difference $\Delta\overline{u} - \Delta\overline{d}$ follows the same trend as $\Delta\overline{u}$. It slightly decreases with R_{SF}, down to one standard deviation from zero at $R_{SF} = 3.4$. The simultaneous changes of the two ratios, while leaving the K^+ rate practically unchanged, affect the K^- rate only for $x \geq 0.1$. Precise values of R_{UF} and R_{SF} may thus be difficult to extract from the data.

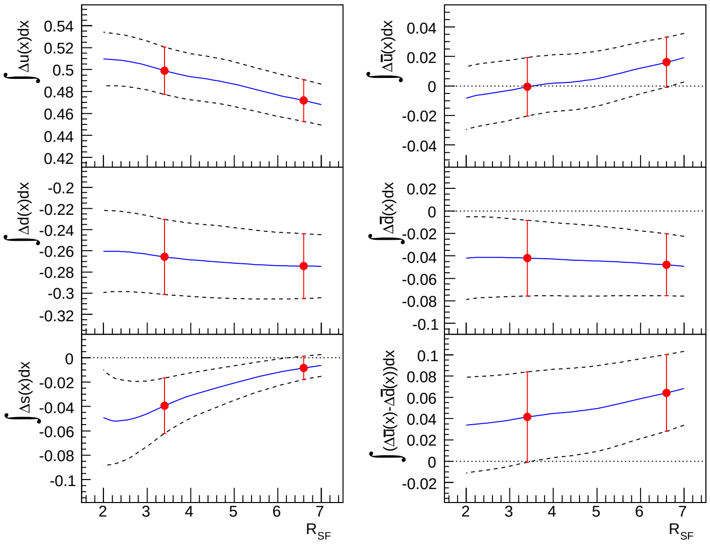

Figure 4. Variation of the quark helicity distributions Δu, $\Delta\overline{u}$, Δd, $\Delta\overline{d}$, Δs and $\Delta\overline{u} - \Delta\overline{d}$ integrated over the interval $0.004 < x < 0.3$ as a function of the ratio of $\overline{s}$ and u quark fragmentation functions into K$^+$, R_{SF} (Eq.(2)). The ratio R_{UF} is varied linearly from 0.13 at $R_{SF} = 6.6$ to 0.35 at $R_{SF} = 3.4$. The left and right points correspond to the EMC [11] and DSS [8] fragmentation functions into kaons, respectively.

4.3. Δs from DIS and SIDIS

The LO relation between the first moment of the isoscalar spin structure function, $\Gamma_1^N = \frac{1}{2}\int(g_1^p(x) + g_1^n(x))dx$, measured in DIS, and the axial charges a_0 and a_8

$$\Gamma_1^N = \frac{1}{9}(a_0 + \frac{1}{4}a_8) \tag{3}$$

provides an evaluation of the first moment of the strange quark helicity distribution

$$\Delta s + \Delta\overline{s} = 3\Gamma_1^N - \frac{5}{12}a_8. \tag{4}$$

The measured value of Γ_1^N (≈ 0.05 at $Q^2 = 3$ (GeV/c)^2) and the value of a_8 obtained from hyperon decays under the assumption of SU(3)$_f$ symmetry ($\approx 0.585\pm0.025$) imply that $\Delta s + \Delta\overline{s}$ must be negative (≈ -0.09).

On the other hand, the measurements of $\Delta s(x)$ based on semi-inclusive spin asymmetries do not show negative values in the range covered by the data ($x > 0.02$ for HERMES [6, 23], $x > 0.004$ for the present COMPASS data) and are thus at variance with the expected negative first moment. This apparent inconsistency can be explained by the limited range of the SIDIS measurements if one assumes a large enough negative contribution to Δs in the unmeasured region at low x. This is the case in the DSSV fit [17] where $\Delta s(x)$ becomes negative for $x < 0.03$. In the recent LSS10 fit [24] $\Delta s(x)$ changes sign at about the same value of x and has about the same first moment although its shape is quite different. This fit reproduces very well the COMPASS semi-inclusive asymmetries[25].

A change of the value of a_8 in Eq.(3) can also bring the DIS and SIDIS results on Δs in agreement. The quoted value of a_8 is obtained under the condition of $\mathrm{SU}(3)_f$ symmetry and may be reduced if this symmetry is violated. In the cloudy bag model calculation of Ref.[26], $a_8 \approx 0.42$ so that $\Delta s + \Delta\overline{s}$ increases to ≈ -0.02, in fair agreement with the SIDIS results. As shown above, the SIDIS result on Δs may also be affected by possible changes in the fragmentation functions. However a drastic change in the value of the ratio R_{SF} would be needed to bring the first moment measured in SIDIS in agreement with the DIS value (Fig.4).

As an alternative the full first moment of $\Delta s + \Delta\overline{s}$ can be extracted from a combined analysis of the νp, $\overline{\nu} p$ elastic cross sections and the parity-violating asymmetries in $\vec{e}p$ elastic scattering [27]. However a recent analysis has shown that the precision of the existing neutral-current neutrino data and their limited Q^2 range do not allow a reliable determination [28].

5. Conclusions and prospects

The COMPASS experiment has provided a new evaluation of the polarised PDFs at LO, based on the DIS and SIDIS $\mathrm{K}^{+,-}$ and $\pi^{+,-}$ asymmetries measured on ^{6}LiD and NH_3 targets. The antiquark distributions $\Delta\overline{q}$ are small and do not show any significant variation over the measured range of x ($0.004 < x < 0.3$). No significant difference is observed between $\Delta s(x)$ and $\Delta\overline{s}(x)$. The flavour asymmetry of the polarised sea, $\Delta\overline{u} - \Delta\overline{d}$, is slightly positive but not larger than $\overline{d} - \overline{u}$. The moments of Δu, $\Delta\overline{u}$ and Δs are found to vary with the choice of the fragmentation function into kaons. This dependence is critical for Δs which may become negative but with very large errors.

COMPASS will take more data on NH_3 in the year 2011 in order to equalize the precision of the hydrogen and deuterium samples. In particular the improved precision on $\Delta\overline{u} - \Delta\overline{d}$ may allow to discriminate between various models. Ongoing investigations on the fragmentation functions from the K^+ and K^- rates are expected to clarify the SIDIS evaluation of Δs.

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6. References

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