POLARIZATION OF VALENCE, NON-STRANGE AND STRANGE QUARKS IN THE NUCLEON DETERMINED BY COMPASS

On behalf of the COMPASS Collaboration

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Abstract

The results of quarks helicity distributions are presented which were determined by COMPASS experiment at CERN. Different approaches have been accomplished in order to access various sets of quarks distributions. The analysis of spin structure function g_1 gives information about contribution to the spin of the nucleon from sum of quarks. From method of difference asymmetry for hadrons with opposite charges one can learn about polarized valence quark distributions. Finally, a recent analysis of full flavour separation was presented in Quark Parton Model (QPM) and LO QCD approximation. All analyses have been done in perturbative regime $Q^2 > 1$ $(\mathrm{GeV/c})^2$.

1 Introduction

Angular momentum conservation requires that the spin of the nucleon can be represented by the sum rule:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G, \tag{1}$$

where $\Delta\Sigma$ is a contribution from the sum of different flavours of quark helicity distributions, ΔG the contribution from helicities of gluons, and $L_{q,G}$ stands for quarks and gluons angular orbital momenta. The first experimental measurement of spin structure of the nucleon started at CERN with EMC collaboration [1]. At that time it was widely believed that Ellis-Jaffe sum rule [2] holds and thus quarks carry roughly 60% of the nucleon helicity. Unexpectedly the interpretation of the EMC results indicated very small $\Delta\Sigma$ [1, 3] and that is how the so-called "spin crisis" began. The EMC results have been later confirmed by many other experiments [4, 5, 6, 8, 9] and brought a conclusion that quarks carry only about 30% of the nucleon spin.

2 Experimental setup

The COMPASS is a fixed target experiment at CERN. The one the of the purposed is to study the spin structure of the nucleon. Until 2009 two separate programs have been realized: with muon and hadron beam respectively. The Muon beam program was divided into several sub-projects where the target was polarized either longitudinally or perpendicularly to the beam direction and the target material contained either polarized

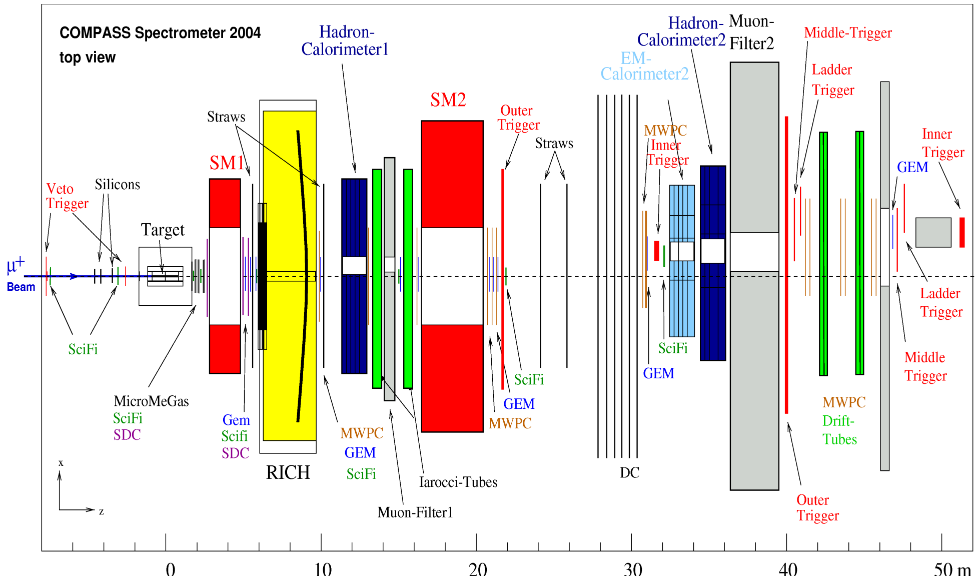

Figure 1: The COMPASS spectrometer.

deuterons (^{6}LiD) or protons (NH_3). The results presented in this paper are based on the data collected in the years 2002-2007 with muons scattered on longitudinally polarized deuteron and proton targets.

The COMPASS muon beam is produced in several steps. Protons of energy 400 GeV coming in the cycles from the Super Proton Synchrotron collide with solid beryllium target and producing among others charged pions and kaons. The momentum selected pions and kaons decay in 500 m long tunnel. One of the main decay products are naturally polarized muons. The average polarization is 76% at the energy of 160 GeV.

In the years 2002-2004 target was composed of two oppositely polarized 60 cm long cells, separated by a 10 cm gap. In 2006 and 2007 three target cells were used instead in order to minimize systematic errors. Cells are located inside a superconducting solenoid which provides a homogenious 2.5 T magnetic field and are exposed to the same beam flux. Target is polarized using dynamic nuclear polarization technique up to 50% in case of ^{6}LiD and 90% in case of NH_3.

The COMPASS spectrometer (Fig. 1) is made of two parts which detect tracks in different kinematical region. Each part contains its own bending magnet, hadron and electromagnetic calorimeter, and a set of tracking detectors of various types. Additionally first spectrometer is equipped with a large RICH detector, which provides hadron identification. RICH is designed to separate pions kaons and protons in wide range of momenta, from 2.5 GeV, up to 50 GeV. Detailed description of COMPASS spectrometer can be found in [10].

3 The spin-dependent structure function g_1^N

. The longitudinal spin-dependent structure function of the nucleon is given by:

$$g_1 \approx \frac{F_2}{2x(1+R)} A_1, \qquad (2)$$

where F_2 and R are spin-independent structure functions and A_1 is the cross section longitudinal spin asymmetry, which in quark parton model is related to the quark helicity distributions Δq in the following way:

$$A_1(x) = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} \approx \frac{\sum e_q^2 \Delta q(x)}{\sum e_q^2 q(x)}. \quad (3)$$

In above equation arrows correspond to relative helicity orientation of scattering muon and nucleon in the target.

In order to stay in DIS domain the analysis has been performed for events with $Q^2 > 1$ (GeV/c)^2 and $0.1 < y < 0.9$. This region allows COMPASS to collect 135 million events on deuteron target and 93 million events on proton target. The final results on g_1^d and g_1^p as a function of x Bjorken are presented in Fig. 2. For comparison the values of the several other experiments have been shown at the same plot. COMPASS deuteron data, evolved to $Q^2 = 3$ (GeV/c)^2, has been used to extract $\Delta\Sigma$ from the first moment of g_1^N [11, 12]:

$$\Gamma_1^N = 0.05 \pm 0.003(stat.) \pm 0.003(evol.) \pm 0.005(syst.). \quad (4)$$

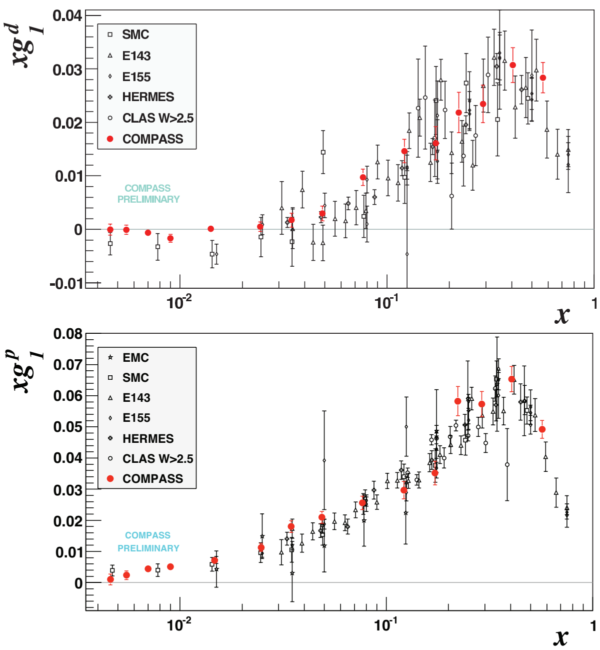

Figure 2: Spin dependent structure function xg_1^d (top) and xg_1^p (bottom) as a function of x at measured Q^2. The error bars indicate statistical errors. Agreement with other experiments is well visible.

Correction to the first moment from the unmesured region of $x < 0.004$ and $x > 0.7$ is about 2%. This value can be translated to the flavour-singlet axial current matrix element a_0:

$$\Gamma_1^N(Q^2) = \frac{1}{9}\left(1 - \frac{\alpha_s(Q^2)}{\pi} + \mathcal{O}(\alpha_s^2)\left(a_0(Q^2) + \frac{1}{4}a_8\right)\right), \quad (5)$$

which is directly related to the fraction of nucleon spin carried by quarks. The value of $a_8 = 0.585 \pm 0.025$ has been taken from hyperon β decays [13], assuming SU(3)$_f$ flavour symmetry. Finally

$$\Delta\Sigma = \hat{a}_{0(Q^2\rightarrow\infty)} = 0.33 \pm 0.03(stat.) \pm 0.05(syst.) \quad (6)$$

and the strange quark polarization

$$(\Delta s + \Delta\bar{s}) = \frac{1}{3}(\hat{a}_0 - a_8) = -0.08 \pm 0.01(stat) \pm 0.02(syst). \quad (7)$$

4 Valence quark distribution

For the semi-inclusive reaction $\mu N \rightarrow \mu' h X$ asymmetry in LO QCD can be written in the form

$$A_1^h = \frac{\sum e_q^2 \Delta q(x) D_q^h(z)}{\sum e_q^2 q(x) D_q^h(z)}. \quad (8)$$

Comparing this formula to inclusive case (Eq. 3) one can see that additionally fragmentation functions D_q^h are required. Due to this fact semi-inclusive asymmetries evaluated for different hadron types give a possibility to determine polarization separately for different quark flavours. Such analysis will be presented in the next section. Now let us consider the so-called difference-charge asymmetry defined as follows [14, 15]

$$A^{h^+-h^-} = \frac{(\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h-}_{\uparrow\downarrow}) - (\sigma^{h+}_{\uparrow\uparrow} - \sigma^{h-}_{\uparrow\uparrow})}{(\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h-}_{\uparrow\downarrow}) + (\sigma^{h+}_{\uparrow\uparrow} - \sigma^{h-}_{\uparrow\uparrow})}. \quad (9)$$

In the leading order QCD approximation the fragmentation functions cancel out in the $A^{(h^+-h^-)}$, giving direct access to valence quark polarization. Moreover for the deuteron target hadron identification is not needed, since

$$A^{h^+-h^-} = A^{\pi^+-\pi^-} = A^{K^+-K^-} = \frac{\Delta u_v(x) + \Delta d_v(x)}{u_v(x) + d_v(x)}. \quad (10)$$

Difference asymmetry can be obtained from single hadron asymmetries as $A^{h^+-h^-} = \frac{A^{h^+} - rA^{h^-}}{1-r}$, where $r = \sigma^{h^-}/\sigma^{h^+}$. This ratio of the cross-sections has been determined with the help of Monte Carlo simulation. Figure 3 shows difference asymmetry as a function of x Bjorken. In addition to standard selections as in the inclusive case the cut on the fraction of photon energy carried by hadron $0.2 < z < 0.85$ was implemented. Valence quark polarization was evaluated with formula (10) after correction for R and deuteron D-state contribution:

$$\Delta u_v + \Delta d_v = \frac{u_v + d_v}{(1+R)(1-1.5\omega_D)} A^{h^+-h^-}$$

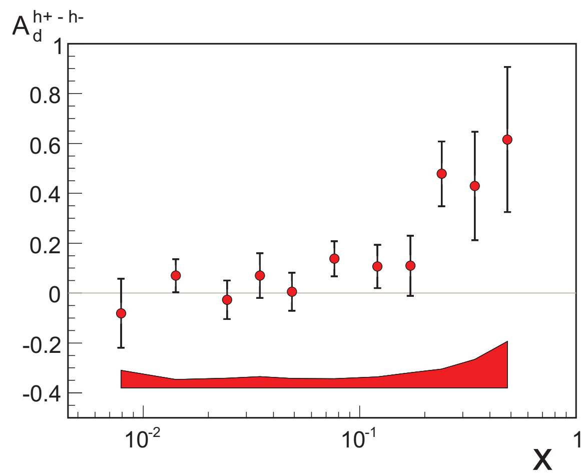

Figure 3: Difference-charge asymmetry of unidentified hadrons $A^{h^+-h^-}$. The error bars are statistical ones and the band at the bottom represents systematical uncertainties.

As an unpolarized valence distribution MRST 2004 at LO has been used [16]. It is worth to notice that contribution from sea can be neglected in last three bins ($x > 0.3$). This gives opportunity to use alternative approach in this region:

$$\Delta u_v + \Delta d_v = \frac{36}{5} \frac{g_1^d(x, Q^2)}{(1-1.5\omega_D)} - \left[2(\Delta\bar{u} + \Delta\bar{d}) + \frac{2}{5}(\Delta s + \Delta\bar{s})\right]. \quad (11)$$

One can judge from Fig. 4 (left) that this method is much more precise. The integral over x range is equal $0.40 \pm 0.07(stat.) \pm 0.05(syst.)$ what supports models with asymmetric sea polarization $\Delta\bar{u} = -\Delta\bar{d}$.

5 Flavour separation of helicity distributions

Recently COMPASS published results of helicity densities of valence, non-strange sea and strange quarks obtained in LO QCD approximation from deuteron data [17]. Just

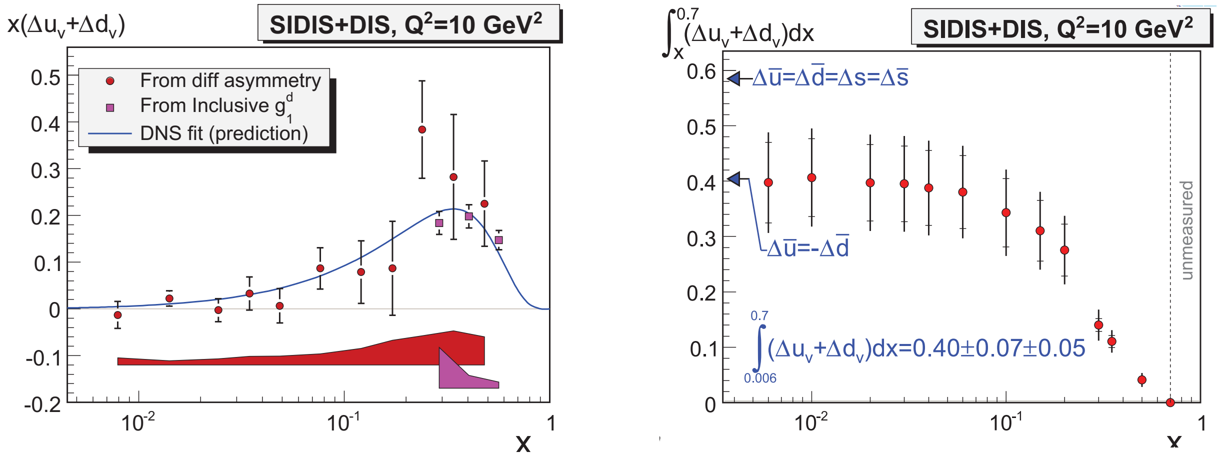

Figure 4: Left: Polarized valence quark distribution obtained from difference asymmetry. The line shows DNS fit in which presented data wasn't used. The additional points at high x come from g_1^d. Right: Integral of $\Delta u_v + \Delta d_v$ as a function of low x limit of integration.

now analysis of data collected in 2007 on proton target has been finished, what allowed to separate helicity distributions for different quark flavours. In order to do that asymmetries from identified hadrons has been measured. The identification was provided by RICH detector. In total COMPASS has collected 43 (8) million of events with identified charged pions (kaons) on deuteron target and 25 (6.5) million of events with identified charged pions (kaons) on proton target. The same kinematical cuts were used for proton and deuteron target, mainly $Q^2 > 1$ GeV^2 to select DIS events. Hadrons were required to have momenta in the range $10 < p < 50$ GeV/c where RICH identification is most accurate.

Figure 5 presents asymmetries as a function of x together with HERMES results [18]. One can observe a good agreement between two experiments. It is also worth to notice that proton asymmetries are significantly larger than deuteron ones. In LO QCD approximation we can use Eq. 8 to access quark helicities. Writing explicitly

$$
\begin{aligned}
A_{1,d} &= \frac{5(\mathbf{\Delta u}+\mathbf{\Delta d}) \;+\; 5(\mathbf{\Delta \bar{u}}+\mathbf{\Delta \bar{d}}) \;+\; 4\mathbf{\Delta s}}{5(u+d)+5(\bar{u}+\bar{d})+2(s+\bar{s})} \\
A_{1,d}^{h} &= \frac{(4D_u^h+D_d^h)(\mathbf{\Delta u}+\mathbf{\Delta d}) \;+\; (4D_{\bar{u}}^h+D_{\bar{d}}^h)(\mathbf{\Delta \bar{u}}+\mathbf{\Delta \bar{d}}) \;+\; 2(D_s^h+D_{\bar{s}}^h)\mathbf{\Delta s}}{(4D_u^h+D_d^h)(u+d)+(4D_{\bar{u}}^h+D_{\bar{d}}^h)(\bar{u}+\bar{d})+2(D_s^h s+D_{\bar{s}}^h\bar{s})} \\
A_{1,p} &= \frac{4(\mathbf{\Delta u}+\mathbf{\Delta \bar{u}}) \;+\; (\mathbf{\Delta d}+\mathbf{\Delta \bar{d}}) \;+2\mathbf{\Delta s}}{4(u+\bar{u})+(d+\bar{d})+(s+\bar{s})} \\
A_{1,p}^{h} &= \frac{4(D_u^h\mathbf{\Delta u}+D_{\bar{u}}^h\mathbf{\Delta \bar{u}}) \;+\; (D_d^h\mathbf{\Delta d}+D_{\bar{d}}^h\mathbf{\Delta \bar{d}}) \;+\; (D_s^h+D_{\bar{s}}^h)\mathbf{\Delta s}}{4(D_u^h u+D_{\bar{u}}^h\bar{u})+(D_d^h d+D_{\bar{d}}^h\bar{d})+(D_s^h s+D_{\bar{s}}^h\bar{s})}
\end{aligned}
\tag{12}
$$

one can see that quark distributions are multiplied by different weights for various types of asymmetries. These weights are made from the combinations of fragmentation functions D_q^h.

We assumed that polarized strange sea is symmetric ($\Delta s = \Delta\bar{s}$), so in total we have only 5 parameters ($\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta s$). Thus with 10 different equations of asymmetries ($A_{1,d}, A_{1,d}^{\pi^+}, A_{1,d}^{\pi^-}, A_{1,d}^{K^+}, A_{1,d}^{K^-}, A_{1,p}, A_{1,p}^{\pi^+}, A_{1,p}^{\pi^-}, A_{1,p}^{K^+}, A_{1,p}^{K^-}$) it is possible to determine a quark helicities using standard least-square method. The final results as a function of x have

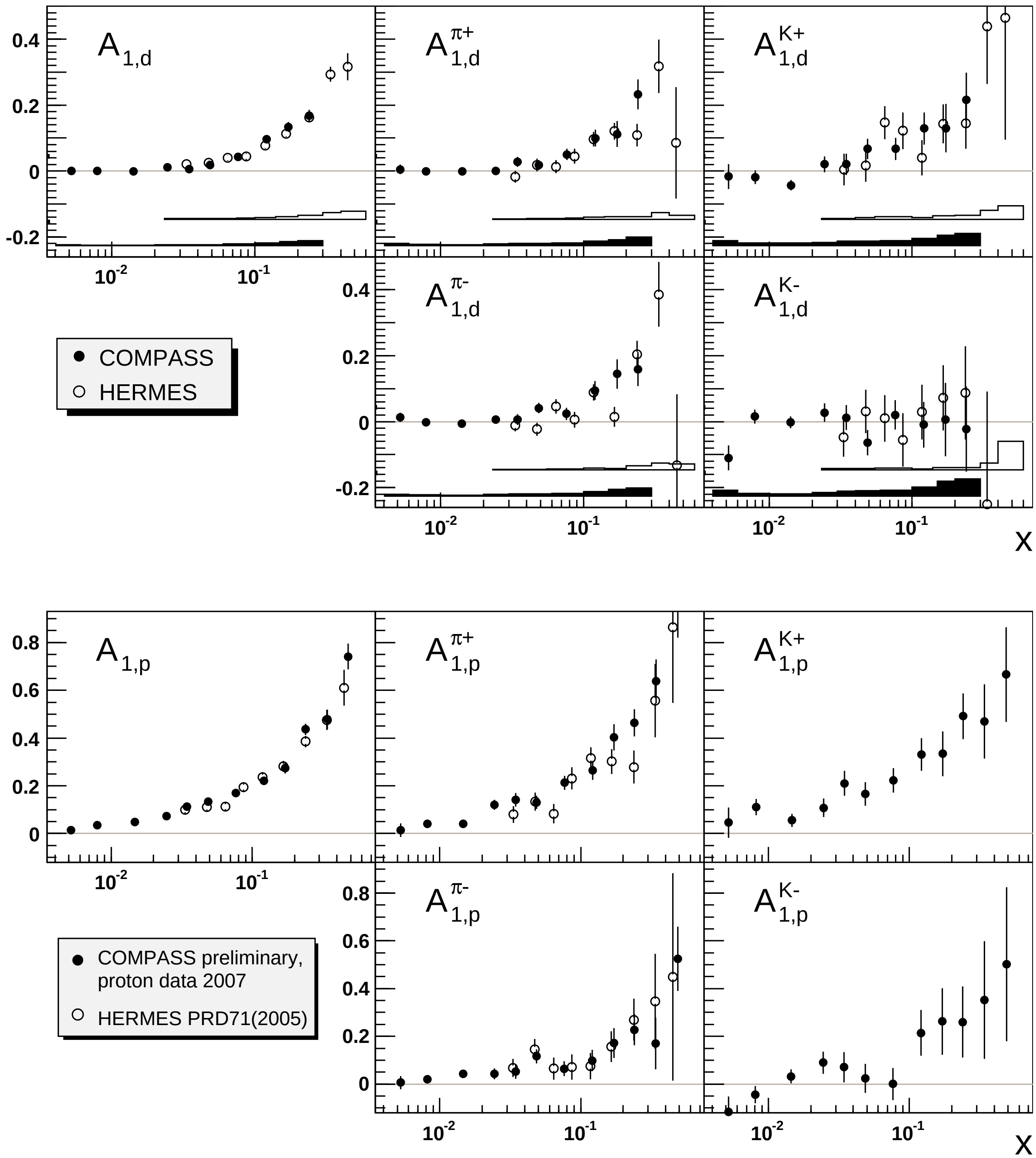

Figure 5: Comparison of COMPASS inclusive and hadron asymmetries of deuteron (top) and proton (bottom) data with HERMES results [18].

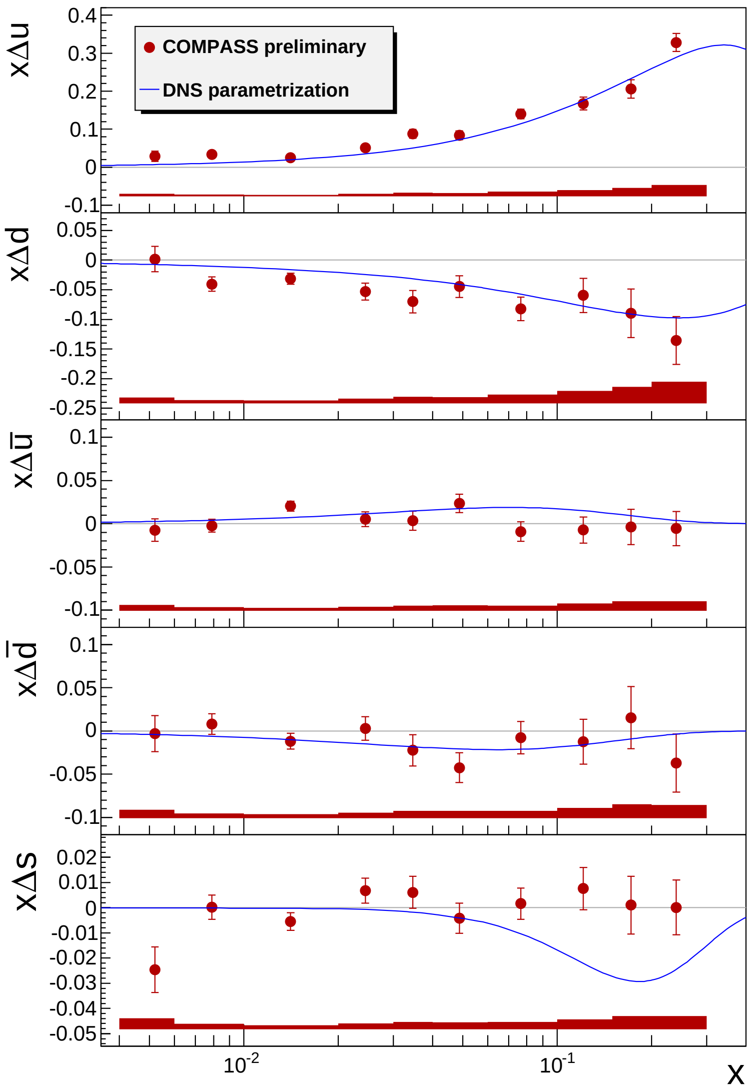

Figure 6: The quark helicity distributions evaluated at $Q^2 = 3$ (GeV/c)^2 as a function of x. For strange quarks $\Delta s = \Delta \bar{s}$ was assumed. Bands at the bottom of each plot represent systematic errors. Solid line is a LO DNS parametrization.

been shown in Fig. 6. Parametrization of quark helicity distributions estimated in LO by DNS [19] is also shown. It fits very well to the COMPASS data for light quarks but while the disagreement for strange quarks is well visible. As an unpolarized parton distributions MRST04 LO QCD set [16] was used. For fragmentation functions DSS parametrization at LO QCD was chosen [20], which is the most recent published one. The first moments truncated to measured x-range are:

$$\begin{aligned} \Delta u &= 0.45 \pm 0.02(stat.) \pm 0.03(syst.) \\ \Delta d &= -0.25 \pm 0.03(stat.) \pm 0.02(syst.) \\ \Delta \bar{u} &= 0.01 \pm 0.02(stat.) \pm 0.004(syst.) \\ \Delta \bar{d} &= -0.04 \pm 0.03(stat.) \pm 0.01(syst.) \\ \Delta s &= \Delta \bar{s} = -0.01 \pm 0.01(stat.) \pm 0.02(syst.). \end{aligned} \quad (13)$$

6 Conclusions

The review of COMPASS results on helicity quark distributions has been shown. COMPASS analyzed all available longitudinal data for the years 2002-2007. 2002-2006 data were collected on deuteron target while in 2007 the proton target was used. The g_1 structure function has been measured and provided information about $\Delta\Sigma$ and polarization of strange quarks. Valence helicity distribution have been precisely examined using the so-called difference asymmetry. Flavour separation was possible using full set of semi-inclusive data. The last result strongly depends on the chosen parametrization of the fragmentation functions.

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