

# Measurement of the longitudinal spin structure of the proton by COMPASS

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## Abstract

The inclusive  $A_{1,p}$  and hadron double-spin asymmetries  $A_p^{\pi^+}$ ,  $A_p^{\pi^-}$ ,  $A_p^{K^+}$ ,  $A_p^{K^-}$  measured at COMPASS (CERN SPS) in deep-inelastic scattering of a polarized muon beam off a polarized  $\text{NH}_3$  solid target are presented. The results have been obtained with the full statistics collected in 2007 for the longitudinal polarization of the target. Proton asymmetries have been combined with published deuteron ones. An evaluation of the non-singlet spin-dependent structure function  $g_1^{NS}(x, Q^2)$  and its first moment, which confirms the validity of the Bjorken sum-rule, is presented. A LO evaluation of polarized quark densities is also presented. The use of the proton data allows to perform a full flavor separation analysis and to extract individual PDFs of  $u$ ,  $d$ ,  $\bar{u}$ ,  $\bar{d}$  and  $s$  quarks. All sea quark densities are found to be compatible with zero in the full range of measurements.

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## 1. Introduction

New results of the COMPASS experiment at CERN on the proton spin asymmetry  $A_{1,p}$  and the structure function  $g_1^p$  are presented. The data were collected during the year 2007. We refer the reader to [1] for the description of the 160 GeV muon beam, the  $\text{NH}_3$  polarized target and the COMPASS spectrometer. The DIS events are selected by cuts on the virtuality of the photon,  $Q^2 > 1 (\text{GeV}/c)^2$ , and its fractional energy,  $0.1 < y < 0.9$ . The values of the spin-dependent structure function  $g_1^p(x, Q^2)$  have been combined with the published  $g_1^d(x, Q^2)$  ones [2] in order to evaluate the non-singlet structure function  $g_1^{NS}(x, Q^2)$ .

We also present an evaluation of the helicity quark distributions  $\Delta u$ ,  $\Delta d$ ,  $\Delta \bar{u}$ ,  $\Delta \bar{d}$  and  $\Delta s (= \Delta \bar{s})$  which were obtained in a combined analysis of inclusive and identified hadron asymmetries. Both deuteron [3] and proton data have been used. In addition to the kinematic cuts mentioned above for hadron tracks coming from the primary vertex, the cut  $z > 0.2$  is applied to select the current fragmentation region. To avoid ambiguity between the secondary  $\mu$  and the scattered  $\mu$  we demand  $z < 0.85$ . Hadrons are identified as pions or kaons by the RICH detector which limits their momenta to the range  $10 < p < 50 \text{ GeV}/c$ .

The total statistics of samples obtained with the proton target for the inclusive,  $\pi^+$  ( $\pi^-$ ) and  $K^+$  ( $K^-$ ) events

after all cuts is 92.5, 13.3 (11.8) and 3.9 (2.6) million events, respectively.

## 2. Structure function $g_1^p$ and NLO QCD fit of $g_1^{NS}$

The longitudinal virtual-photon proton asymmetry  $A_{1,p}$  is defined via the asymmetry of absorption cross sections of transverse photons as

$$A_{1,p} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}, \quad (1)$$

where the subscripts refer to the total spin projection of the  $\gamma^*$ -proton system. The measured values of  $A_{1,p}$  are shown as a function of  $x$  in Fig. 1 in comparison with results from HERMES [4].

The longitudinal spin structure function is obtained from  $A_{1,p}$  as

$$g_1^p = \frac{F_2^p}{2x(1+R)} A_{1,p}^p, \quad (2)$$

where  $F_2^p$  and  $R$  are spin-independent structure functions.  $g_1^p$  as a function of  $x$  and  $Q^2$  is shown in Fig. 2 where it is superposed to results of previous DIS experiments.

The availability of  $g_1^d$  and  $g_1^p$  data with good and comparable precision at low  $x$  provides ideal conditions for a new evaluation of the non-singlet structure function

$$g_1^{NS}(x) = g_1^p(x) - g_1^n(x) = 2 \left[ g_1^p(x) - \frac{g_1^d(x)}{1 - 3/2\omega_D} \right], \quad (3)$$

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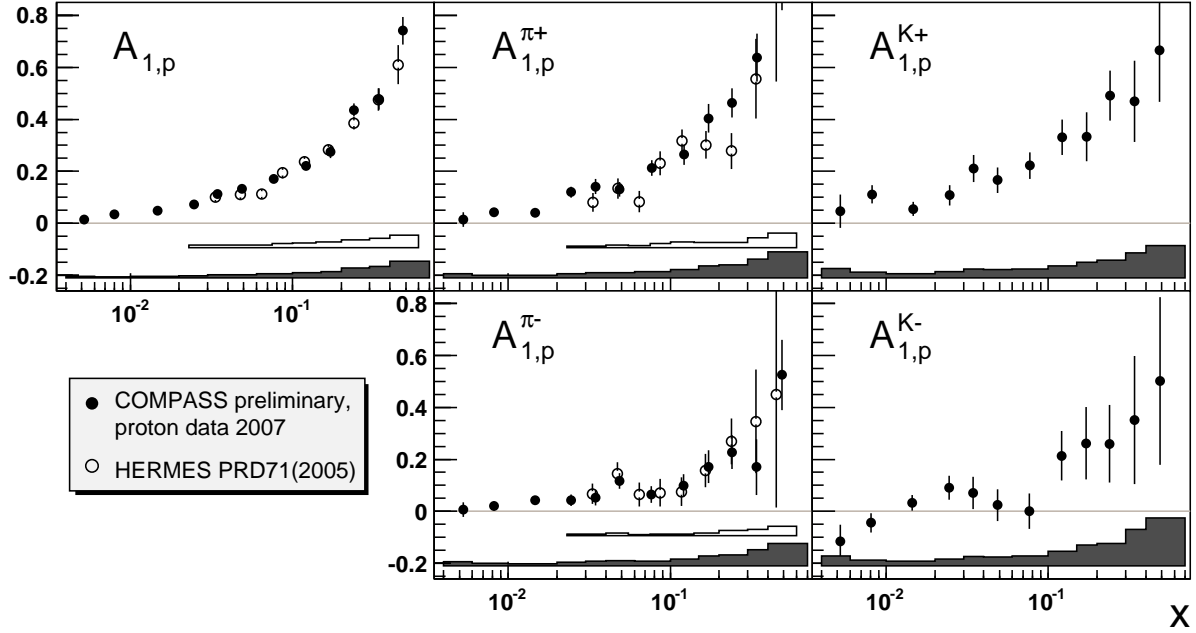


Figure 1: The double-spin asymmetries of COMPASS compared to results of HERMES [4]. Bands at bottom of each graph represent systematic uncertainties. Solid markers and bands correspond to COMPASS data. Open markers and bands are taken from HERMES.

where  $\omega_D$  is the probability of the D state in the deuteron ( $\omega_D = 0.05 \pm 0.01$ ). An evaluation of the first moment of  $g_1^{NS}(x)$  provides a new test of the Bjorken sum rule. This sum rule was first derived using current algebra is considered as a fundamental result of QCD.

The  $Q^2$  dependence of  $g_1^{NS}$  is decoupled from the evolution of  $\Delta\Sigma$  and  $\Delta G$ . Consequently a fit of the  $Q^2$  evolution of  $g_1^{NS}$  requires only a small number of parameters to describe the shape of  $\Delta q_3(x)$  at some reference  $Q^2$  and its integral, which is proportional to the ratio  $g_A/g_V$  of the axial and vector coupling constants. The comparison of the fitted value of this ratio with the one derived from neutron  $\beta$  decay ( $|g_A/g_V| = 1.2695 \pm 0.0029$  [6]) provides a test of the Bjorken sum rule, free of systematic errors arising from uncertainties on  $\Delta G$ .

In the present analysis,  $Q^2 = 3 \text{ (GeV/c)}^2$  has been taken as reference  $Q^2$  and the following parametrization has been used for the isovector distribution  $\Delta q_3$ :

$$\Delta q_3(x) = \frac{g_A}{g_V} \frac{x^\alpha(1-x)^\beta}{\int_0^1 x^\alpha(1-x)^\beta dx} \quad (4)$$

The result of the fit is shown in Fig. 3.

The dominant systematic error is due to the uncertainty of 5% on the beam polarisation, which translates directly into a 5% error on  $g_A/g_V$  (i.e.  $\pm 0.065$ ). The other contributions due to  $P_T$  and  $f$  are  $\pm 0.041$  for  $A_{1,d}$  and  $\pm 0.056$  for  $A_{1,p}$ . In total this leads to a systematic

error of  $\pm 0.10$ . The errors related to the fit or to the evolution of the data to a common  $Q^2$  are found to be negligible. In particular, it was checked that the same value is obtained for  $g_A/g_V$  when the reference  $Q^2$  is 1.0, 3.0 or 10.0  $(\text{GeV/c})^2$  although the shape of  $g_1^{NS}(x)$  becomes quite different.

Finally the following value have been obtained

$$|g_A/g_V| = 1.30 \pm 0.07(\text{stat}) \pm 0.10(\text{syst}). \quad (5)$$

It is in a perfect agreement with the one derived from neutron  $\beta$  decay.

### 3. LO QCD analysis for polarized quark densities

As in our previous LO analysis [3], we assumed that hadrons in the current fragmentation region are produced by independent quark fragmentation, so that their spin asymmetries can be written in terms of parton distribution functions (PDFs)  $q(x, Q^2)$ ,  $\Delta q(x, Q^2)$  and fragmentation functions (FFs)  $D_q^h(z, Q^2)$ :

$$A^h(x, Q^2) = \frac{\sum_q e_q^2 \Delta q(x, Q^2) \int D_q^h(z, Q^2) dz}{\sum_q e_q^2 q(x, Q^2) \int D_q^h(z, Q^2) dz}. \quad (6)$$

In the present analysis we use the unpolarized PDFs from MRST [7] and the recent DSS parametrization of FFs at LO which was obtained from a combined analysis of inclusive pion and kaon production data from

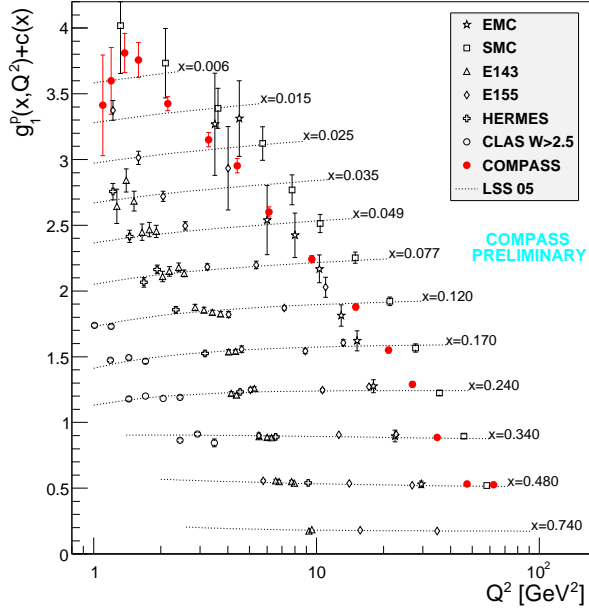


Figure 2:  $g_1^p$  as a function of  $x$  and  $Q^2$ . To align points along curves corresponding to a fixed  $x$ , the LSS 05 parametrization [5] has been used. Only statistical errors are shown. For the purpose of plotting, a constant  $c(x) = 0.28(11.6 - i_x)$  is added to each  $g_1$  values, where  $i_x$  is the number of the  $x$  bin ranging from  $i_x = 0$  ( $x = 0.006$ ) to  $i_x = 11$  ( $x = 0.74$ ).

$e^+e^-$  annihilation, semi-inclusive DIS data from HERMES and proton-proton collider data [8]. The sensitivity of the obtained polarized PDFs on the choice of FFs have been studied in [3] where an alternative set of FFs from the EMC experiment [9] have been used.

The 10 measured asymmetries (see Eq. 6) form a linear system of equations with 5 unknowns  $\Delta u$ ,  $\Delta d$ ,  $\Delta \bar{u}$ ,  $\Delta \bar{d}$  and  $\Delta s$ . The system is solved by a least-square fit independently in each  $x$ -bin. Only statistical errors were used in the fit and correlations between asymmetries were taken into account. A symmetry of the polarized strange sea is assumed  $\Delta s \equiv \Delta \bar{s}$ . In principle  $\Delta s$  and  $\Delta \bar{s}$  could both be extracted from the charged kaon asymmetries  $A_{p,d}^{K^+}$  and  $A_{p,d}^{K^-}$  but in view of the precision of the data, they are assumed to be equal. All asymmetries are also assumed to be independent of  $Q^2$ . In this way the resulting PDFs are obtained at a common  $Q^2$  fixed to  $3(\text{GeV}/c)^2$ .

The quark helicity distributions, obtained with the DSS fragmentation functions, are shown as a function of  $x$  with their statistical and systematic errors in Fig. 4. The curves obtained with the LO DNS [10] parametrization of polarized PDFs are also shown.

The  $\Delta u$ ,  $\Delta d$ ,  $\Delta \bar{u}$ ,  $\Delta \bar{d}$  curves from the DNS parametrization fit well our points. However one can

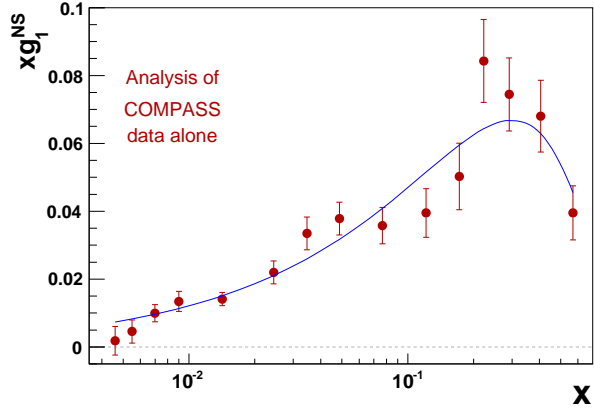


Figure 3: Values of  $g_1^{NS}(x)$  at  $Q^2 = 3(\text{GeV}/c)^2$ . The curve was obtained in the QCD NLO fit of the COMPASS data.

see a discrepancy in the  $\Delta s$  graph. The shape of the  $x\Delta s$  curve of DNS is quite typical for QCD fits of  $g_1(x, Q^2)$  data, with a minimum in the medium  $x$  region ( $x \approx 0.2$ ). The SIDIS measurements of COMPASS (it is also true for HERMES) do not support this behavior, at least not with the DSS fragmentation functions. More details on the distribution  $\Delta s(x)$  are given in Ref. [3]. The present analysis including the 2007 proton data confirms the results obtained with the deuteron data and reduces significantly the statistical errors.

In the most recent global fit of polarized PDFs, DSSV [11], a more flexible parametrization for the strange quark distribution was adopted. This fit includes HERMES data and therefore provides a positive strange polarization at large  $x$  and a negative one at small  $x$ . A full comparison to our points obtained at LO is not possible because the parametrization is provided at NLO only.

The sizable flavor asymmetry between the unpolarized up and down sea quark distributions ( $\bar{u}(x) - \bar{d}(x) < 0$ ) is a well established experimental fact since more than ten years (see for instance [12] and references therein). It has inspired a large theoretical activity and lead to various nonperturbative models which also naturally predict a flavor asymmetry for the helicity densities of the light sea ( $\Delta \bar{u} - \Delta \bar{d} \neq 0$ ). Most of the models, like Pauli-blocking models, instanton model, chiral quark soliton model, statistical models (see review [13] and references therein), predict a positive value of  $\Delta \bar{u} - \Delta \bar{d}$ . The meson cloud models are the only ones which predict a  $\Delta \bar{u} - \Delta \bar{d}$  small in absolute value but with a negative sign. Only experimental measurements can provide a test of these predictions.

The  $x$  distribution of  $\Delta \bar{u} - \Delta \bar{d}$  calculated with the PDFs obtained in the LO fit described above is shown in Fig. 5. For comparison the HERMES points are pre-

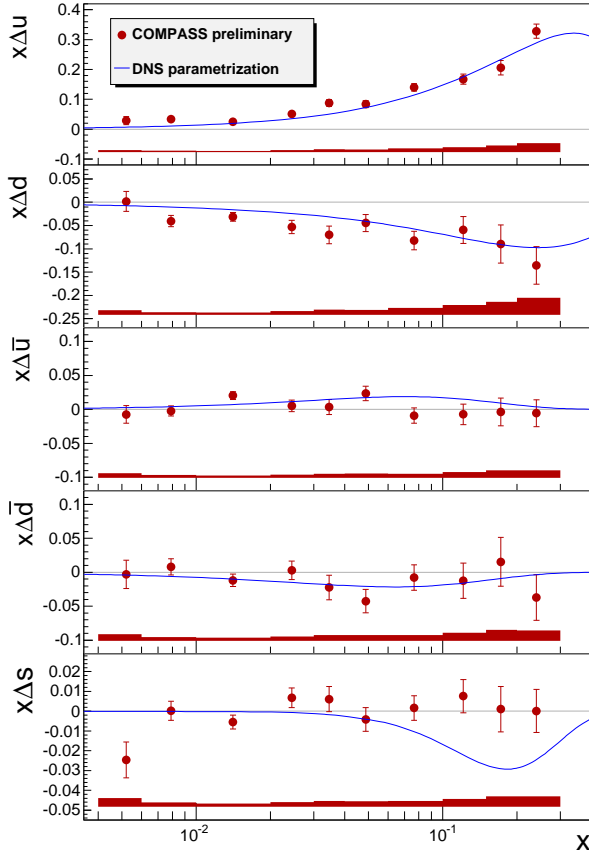


Figure 4: The quark helicity distributions evaluated at common value  $Q^2 = 3(\text{GeV}/c)^2$  as a function of  $x$ . Bands at bottom of each graph represent systematic uncertainties. Solid markers and bands correspond to COMPASS data. For comparison the LO DNS parametrization [10] is shown.

sented on the same plot. A little excess of  $\Delta\bar{u}$  with respect to  $\Delta\bar{d}$  is seen. The first moment of the distribution in the range of the measurements is

$$\int_{0.004}^{0.3} (\Delta\bar{u} - \Delta\bar{d}) dx = 0.052 \pm 0.035(\text{stat}) \pm 0.013(\text{syst}). \quad (7)$$

One should note that the systematics error does not include the uncertainty from the FF parametrization since it was not provided by DSS authors. A one-sigma effect in a narrower  $x$  range is also claimed by HERMES:  $\int_{0.023}^{0.3} (\Delta\bar{u} - \Delta\bar{d}) dx = 0.048 \pm 0.057(\text{stat}) \pm 0.028(\text{syst})$ . The prediction of the DNS parametrization is shown in Fig. 5. One can notice a remarkable agreement of COMPASS measurements with the DNS curve which is driven by the measurements of HERMES, the only other experiment which measured asymmetries of identified hadrons on a proton target.

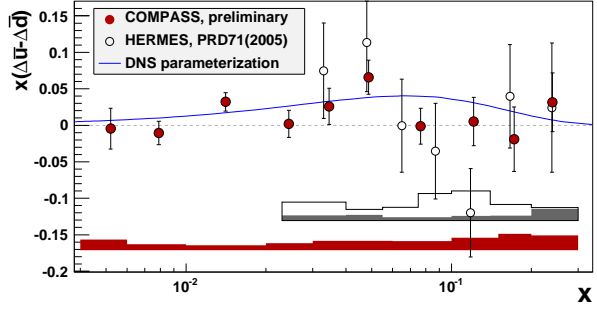


Figure 5: The flavor asymmetry in the helicity densities of the light sea,  $\Delta\bar{u} - \Delta\bar{d}$  evaluated at  $Q^2 = 3(\text{GeV}/c)^2$ . The data are compared with predictions of the DNS parametrization.

#### 4. Summary

A first COMPASS measurement of inclusive and identified hadron spin asymmetries on a proton target has been presented. These asymmetries were included to a combined analysis together with the previously published deuteron ones. An evaluation of the non-singlet spin-dependent structure function  $g_1^{NS}(x, Q^2)$  was presented. The first moment of this function confirms the validity of the Bjorken sum-rule with better than one  $\sigma$  precision.

A LO evaluation of polarized quark densities was also presented. The use of the proton in addition to deuteron data allowed to extract a full set of polarized PDFs  $\Delta u$ ,  $\Delta d$ ,  $\Delta\bar{u}$ ,  $\Delta\bar{d}$  and  $\Delta s (= \Delta\bar{s})$ . All sea quark densities are found to be compatible with zero in the full range of measurements. However the discrepancy in a shape of  $\Delta s(x)$  with the one obtained in a typical global QCD fit was discovered. A small excess of  $\Delta\bar{u}$  with respect to  $\Delta\bar{d}$  was observed.

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