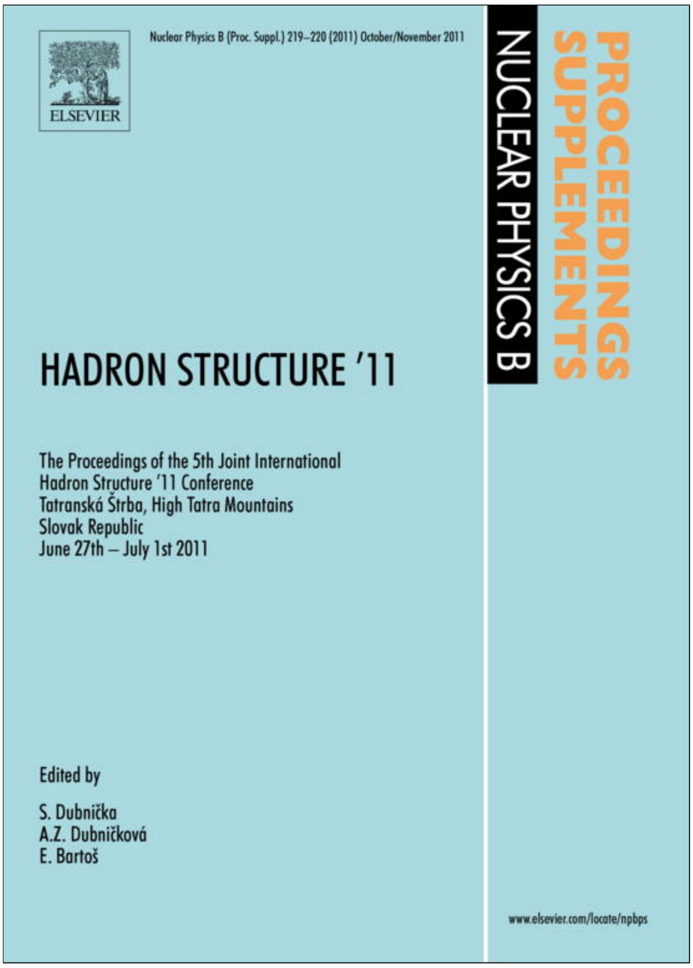
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COMPASS results on the nucleon spin structure

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Abstract

A review of the COMPASS results on the longitudinal and transverse spin structure of nucleon is presented. The gluon contribution to the spin of nucleon, measured by several methods, is found to be small. The solid evidence for Sivers and Collins asymmetries is observed.

Keywords: deep inelastic scattering, structure functions, polarized quark distributions, gluon polarization, parton distribution functions

1. Introduction

COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy [1]) is the new fixed target facility at CERN. It is constructed by the large International Collaboration of 30 Institutions from 12 Countries to perform high energy experiments in the muon and hadron beams available in the M2 beam line. COMPASS has started to take data in 2002.

The COMPASS muon program includes experiments on the nucleon spin structure studies. Deep inelastic scattering (DIS) of muons off polarized nucleons is one of the best "microscopes" for these studies. The first DIS measurements off polarized deuterons were optimized for determination of the unknown gluon polarization $\Delta G/G$ in polarized nucleons, as well as for determination of the unknown transversity spin structure function $h_1(x)$ and transverse-momentum-dependent (TMD) parton distribution functions (PDF). The last task required DIS measurements off polarized protons as well.

The main information on the spin structure of the nucleon is obtained from inclusive and semi-inclusive (SIDIS) spin asymmetries. They are calculated from measured DIS cross section asymmetries of leptons off longitudinally or transversally polarized protons and deuterons. The longitudinal (transverse) asymmetry is determined as a difference of cross sections for the target polarized along and opposite (up and down) to the beam divided by its sum. For calculations of inclusive asymmetries one needs to know characteristics of the incident and scattered lepton only. SIDIS asymmetries require additionally characteristics of the identified hadrons h (i.e., $h = \pi^+, \pi^-, K^+$ or K^-) produced in the same event.

From the inclusive longitudinal spin asymmetries one can obtain, particularly, the spin-dependent structure functions (SF) of proton and deuteron, $g_1^p(x, Q^2)$ and $g_1^d(x, Q^2)$, as functions of the Bjorken variable x and four-momentum transfer Q^2, characterizing in the Quark-Parton model the difference of quark distributions in nucleon with parallel and antiparallel orientations of the quark and nucleon spin. With these SFs one can perform sensitive tests of the QCD and fundamental Bjorken sum rule. From the QCD fits of the g_1 one can get the first indication on the value of the gluon polarization in the polarized nucleon. Semi-inclusive and inclusive spin asymmetries provide possibilities to calculate quark helicity distributions $\Delta q(x)$ for each quark and antiquark flavor and to test the flavor asymmetries of polarized quarks. Semi-inclusive asymmetries originated from the processes of photon-gluon fusion (PGF) provide the direct methods of the gluon polarization measurements.

In the so called collinear approximation, additionally

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to the SF f_1 and g_1 characterizing the structure of unpolarized and longitudinally polarized nucleons, there must be SF h_1 of the transversally polarized nucleon. But, if one assumes that quarks have intrinsic transverse momentum, more TMD PDFs are needed to describe the nucleon structure. The results on the longitudinal and transverse spin structure studies by COMPASS [1–15] are shortly summarized in this report.

2. The longitudinal spin structure of nucleons

2.1. Inclusive longitudinal spin asymmetries

The COMPASS values of the longitudinal spin asymmetries for deuteron $A_1^d(x, Q^2)$ [2, 5] and proton $A_1^p(x, Q^2)$ [12] are shown in Fig. 1 together with values from previous experiments. All data points are with statistical errors. Bands at the top of each plot represent systematic errors. In this figure points correspond to the different value of Q^2, which varies from 6 to 200 GeV^2. In spite of this fact, all points align approximately along the single curve confirming known observation that Q^2 dependence of $A_1(x)$ is weak in DIS region which is usually referred to as the region of $Q^2 > 1\,\mathrm{GeV}^2$. COMPASS data cover the widest DIS region in x from 0.004 to 0.7, with improved precision, especially at $x < 0.03$. At $Q^2 < 1\,\mathrm{GeV}^2$ COMPASS has measured $A_1^d(x)$ up to $x = 0.00004$. In the region of $x < 0.03$ these asymmetries are consistent with zero [7].

2.2. Spin-dependent structure functions

The spin-dependent structure functions of deuteron $g_1^d(x)$, and proton $g_1^p(x)$, are presented in Fig. 2. They are calculated from corresponding inclusive spin asymmetries, **spin-independent** structure functions, $\mathbf{F_2^d}$ and $\mathbf{F_2^p}$, and ratios of longitudinal to transverse photoabsorbtion cross sections R. The last three functions are taken from other experiments. A new feature in SFs is observed for deuterons: in the region of $x < 0.02$ the structure function $g_1^d(x)$ is consistent with zero and do not confirm the negative tendency seen from SMC data.

2.3. The QCD tests of the nucleon spin dependent structure functions and preliminary estimation of the gluon polarization

An impact of the COMPASS data is visualized after the QCD fits performed with the world data including COMPASS g_1^d [2, 5]. Two different programs have been used. One of them [16] uses the DGLAP evolution equations for SFs; the other one uses the evolutions of the SF moments [17]. As is known, in NLO QCD the SF g_1 is represented by a sum of several quark distributions entering in it with Wilson coefficients. These distributions are: the quark spin singlet distribution $\Delta\Sigma(x)$, non-singlet distributions $\Delta q_3(x)$ and $\Delta q_8(x)$, and gluon spin distribution $\Delta G(x)$. These distributions have been parameterized using the SMC parameterization [17] at the reference $Q^2 = Q_0^2$ and evolved to the Q^2 of the data points. The programs converged to the identical solutions, one for $\Delta G > 0$ and one for $\Delta G < 0$. Each of them fits the data with the same χ^2 probability (see Fig. 2). The solutions for the gluon polarization are very different (see Fig. 3) but their first moments both small and about equal in absolute value, $|\Delta G| = 0.2 - 0.3$. That was the first indication of the small contribution of the gluon spin to the spin of nucleon. The first moments of singlet quark distribution $\Delta\Sigma$, characterizing the total quark contribution to the nucleon spin, and the first moment of strange quark ΔS, determined from the COMPASS alone, are equal to

$$\Delta\Sigma = 0.33 \pm 0.03\ (\text{stat.}) \pm 0.05\ (\text{syst.}),$$
$$\Delta S = (\Delta\Sigma - \Delta q_8)/3 =$$
$$= -0.08 \pm 0.01\ (\text{stat.}) \pm 0.02\ (\text{syst.}).$$

2.4. Test of the Bjorken sum rule

The non-singlet SF $g_1^{NS}(x, Q^2) = g_1^p(x, Q^2) - g_1^n(x, Q^2)$ is decupled from the singlet quark and gluon distributions and can be expressed via the non-singlet quark distribution Δq_3 only. As a consequence, the QCD fit of it requires a small number of parameters. The COMPASS results for $g_1^{NS}(x)$ and the NLO QCD fit of them are presented in Fig. 4 (left) [12]. The values of the SF are obtained from the COMPASS data for protons and deuterons. The programs described above are used for the fits.

The Bjorken sum rule predicts the relationship between the first moment of $g_1^{NS}(x)$ and the absolute value of axial to vector couplings of the weak interaction $|g_A/g_V|$, multiplied with the Wilson coefficient known from QCD. The COMPASS data and the Bjorken predictions are shown in Fig. 4 (right). Quantatively: the data extrapolated to $x = 0$ give 0.180 ± 0.009 while the prediction gives 0.188 confirming the Bjorken sum rule validity with the statistical errors. The COMPASS value $|g_A/g_V| = 1.28 \pm 0.07\ (\text{stat.}) \pm 0.10\ (\text{syst.})$ is in agreement with PDG value derived from the neutron decay.

2.5. Semi-inclusive longitudinal spin asymmetries

Semi-inclusive asymmetries measured by Compass off protons [15] and deuterons [11] are shown in Fig. 5

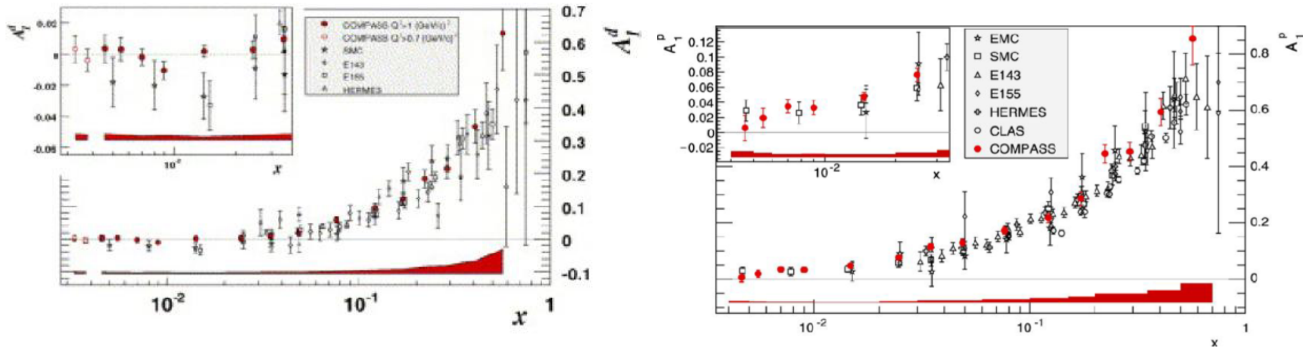

Figure 1: DIS asymmetries $A_1^d(x, Q^2)$ (left) and $A_1^p(x, Q^2)$ (right) from COMPASS and previous experiments.

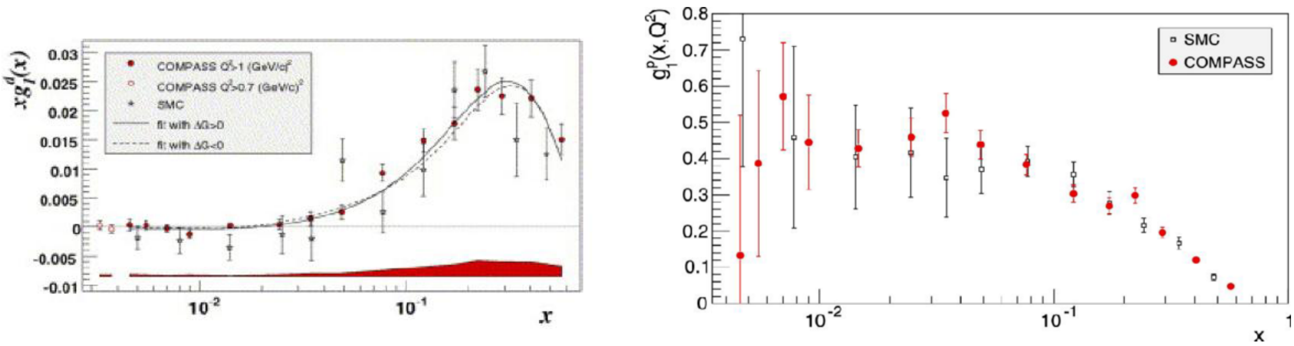

Figure 2: Values of $xg_1^d(x)$ (left) and $g_1^p(x)$ (right). Curves show the results of the QCD fits described below.

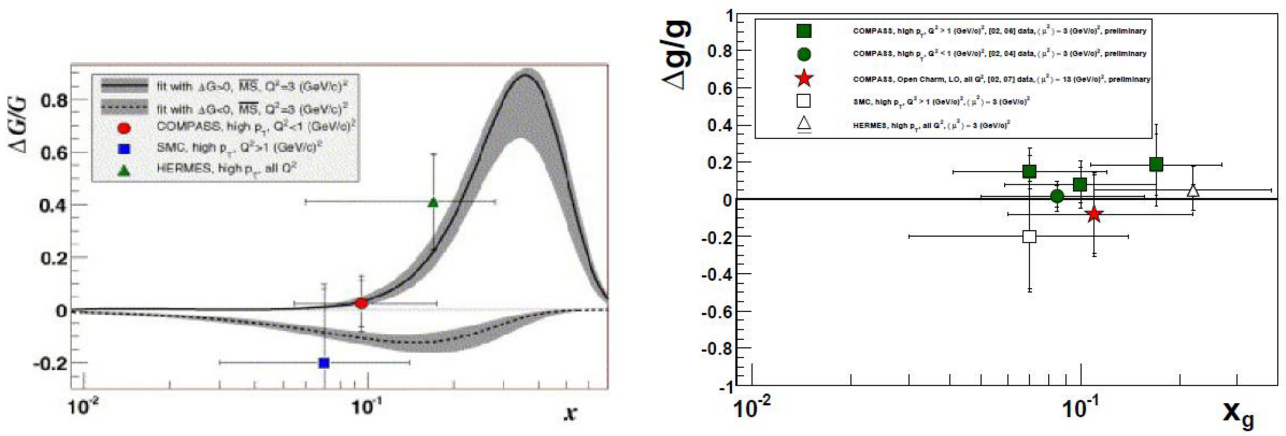

Figure 3: The gluon polarization as a function of x. Points represent results of the first direct measurement of COMPASS [4] in comparison with previous data of SMC and HERMES (left) and present COMPASS data [18] (right) (see below).

together with the inclusive asymmetries [12], HERMES data [19] and DSSV fit [20].

The kaon asymmetries for protons are measured by COMPASS for the first time. Measurements of pion asymmetries at low x are extended by an order of magnitude in the log scale. Agreement between the COMPASS and HERMES pion asymmetries in overlapping x regions is rather good in spite of the different kinematic conditions of two experiments. This indicates on the weak Q^2 dependence of semi-inclusive asymmetries.

Quark helicity distributions

At the LO in QCD, the semi-inclusive spin asymmetry for each hadrons is written as a sum of products of quark an antiquark helicities and their fragmentation

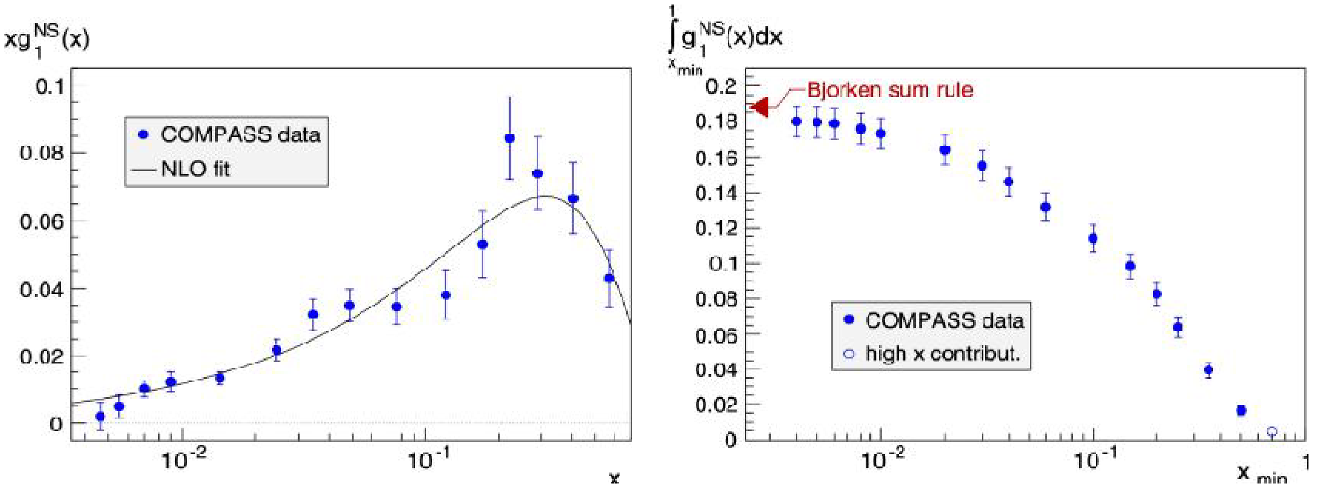

Figure 4: Left: the non-singlet SF $g_1^{NS}(x)$ as a function of x and results of it fit in NLO QCD. Right: the first moment of $g_1^{NS}(x)$ as a function of minimal x value.

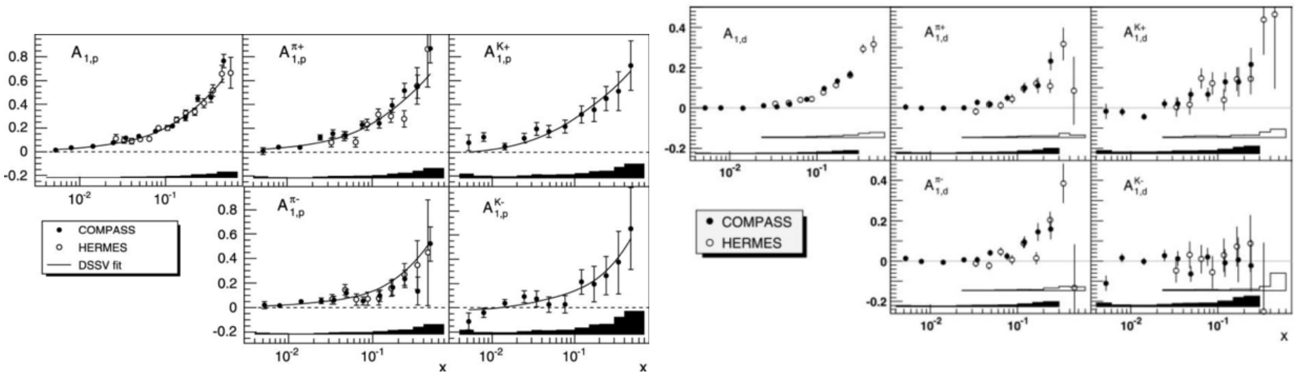

Figure 5: The proton (left) and deuteron (right) inclusive and semi-inclusive asymmetries. The curves show predictions of the DSSV fit.

functions divided by corresponding sum for unpolarized partons. The fragmentation functions and unpolarized distributions are taken from other experiments. In this case, for ten asymmetries shown in Fig. 5, one can have ten equations with six unknown parameters characterizing the x distributions of quarks at the reference Q^2.The least-square fit to the data, performed in each x bin in the region $x < 0.3$, produced for strange quark and antiqurk results [15] shown in Fig. 6 (left). It is seen that there is no significant difference between them and all distributions consistent with zero. This observation is in apparent contradiction with the negative first moment of strange quark helicity calculated from the measured structure function g_1^d. The results shown in Fig. 6 (left) are obtained before from the deuterium data only [11].

To reduce number of unknown parameters to five and improve statistical precision, the fit was repeated assuming that the strange and antistrange quark helicities are equal. Results are displayed in Fig. 6 (right) together with the DSSV predictions in NLO. Their comparison with experimental data, obtained in LO, is qualitative.

The distribution of differences of the light sea antiquark helicities (flavor asymmetry), shown in Fig. 7 together with model predictions, is compatible with zero. So, the data exclude models predicting negative values of this difference. The DSSV fit at NLO (dashed curve) and unpolarized antiquark asymmetry (solid curve) are shown for comparison.

As it was found in [15], helicity distributions for u and s quarks depend strongly on fragmentation functions (FF) which are poorly measured. But the COMPASS measurements of the valence quark helicities using the deuterium data only [5, 8] do not require a knowledge of the FF if the concept of difference asymmetries is applied. The valence quark helicities obtained in these measurements are displayed in Fig. 8 (left) together with the DNS [21] fit of data without COMPASS. Their first moment shown in Fig. 8 (right) disfavor an

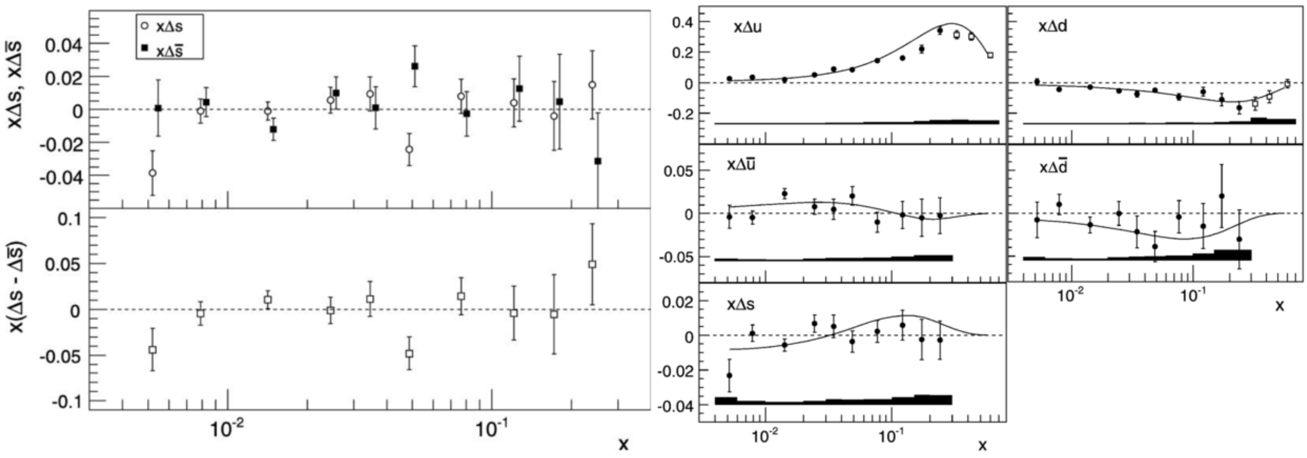

Figure 6: Left: helicity distributions of strange quark and antiquark (top) and their difference (bottom). Right: quark helicity distributions as a function of x. The curves are DSSV [20] predictions at NLO.

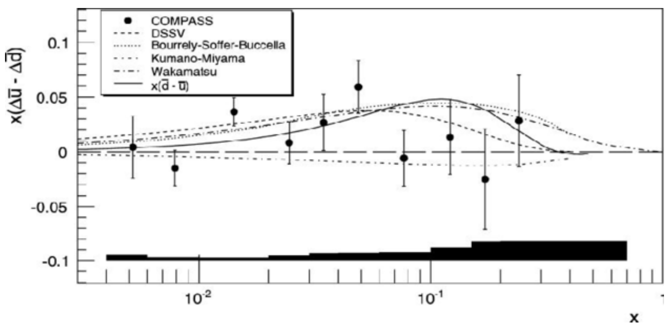

Figure 7: The flavor asymmetry of the light sea quark. The curves show various model predictions discussed in [15].

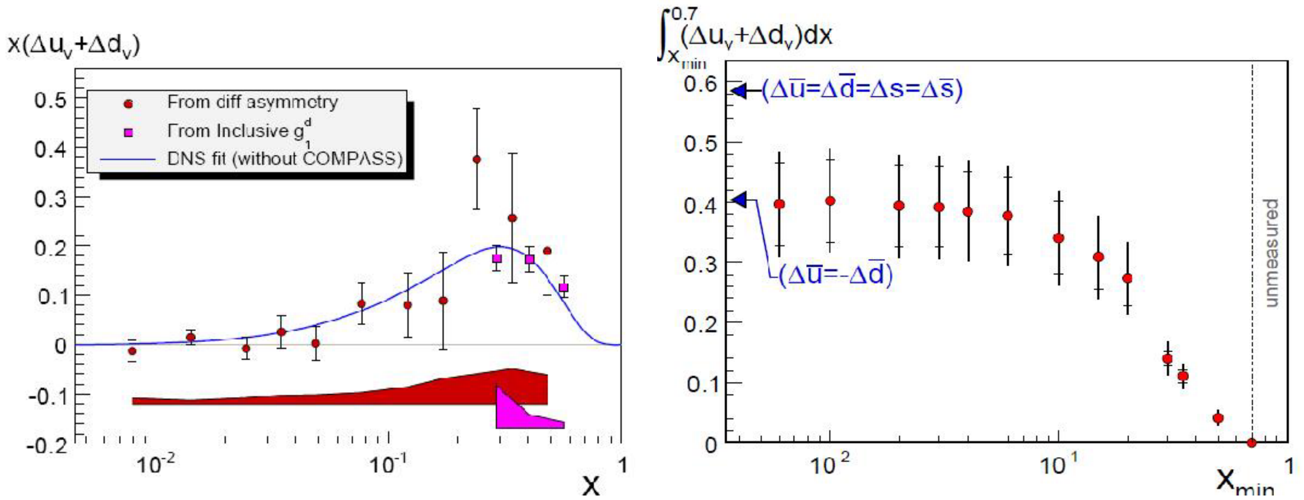

Figure 8: Left: the valence quarks helicity distribution as a function of x. Right: the first moment of the valence quark helicity distribution as function of the minimal x value.

assumption on a flavor symmetric polarized sea. It suggests that anti-u and anti-d quark helicities have opposite signs.

2.5.1. *Direct measurements of the gluon polarization*

The first direct measurement of the gluon polarization in nucleons has been published by COMPASS [4] very

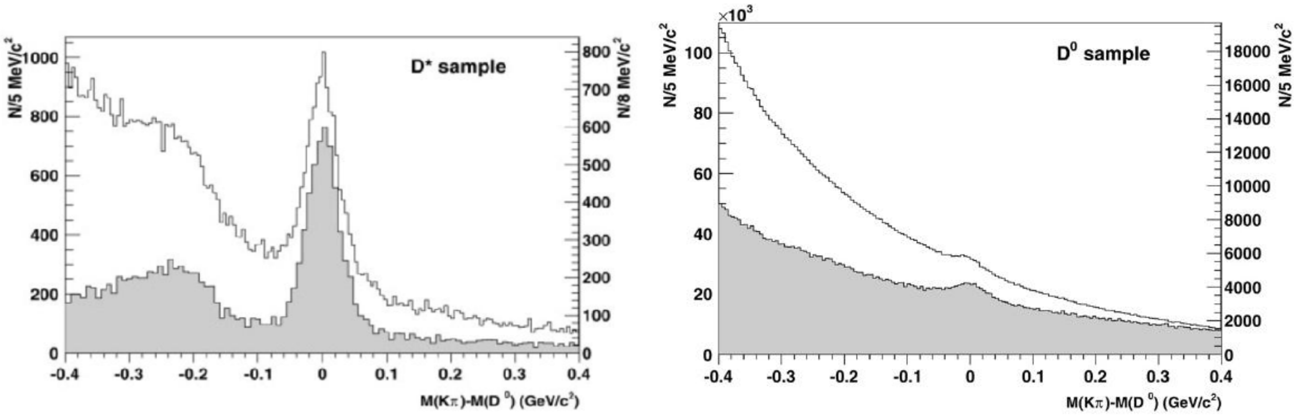

Figure 9: Invariant mass distributions of D^* and D^0 decay products. The non-shaded histograms are for the total samples, while the shaded ones show events from bins with the highest probabilities of the signal to background ratio.

soon after preliminary estimations of this value from the QCD analysis of g_1 data described above. For this measurement the helicity asymmetries in quasi-real photoproduction of events, $Q^2 < 1$ GeV^2, with a pair of large transverse momentum hadrons were used. The sample of these events, additionally to ones originated from the PGF, contains a physical background. This background comes from the QCD Compton and leading (virtual photon – quark) processes not sensitive to the gluon polarization. They are estimated and subtracted using the Monte Carlo simulations. The small gluon polarization determined from this sample is shown in Fig. 3 (left) confirming the results of QCD fits. Similar analysis is performed with the sample of the DIS events, $Q^2 > 1$ GeV^2, which also gave a small value of the gluon polarization.

The preliminary data on the gluon polarization in nucleons based on direct production of charmed mesons via the PGF processes are published in [10]. This process is almost free of the physics background. The D^0 were reconstructed through their decays into K- and π-mesons and selected using the invariant mass of identified decay products. They are further divided in D^* and D^0 samples which are analyzed separately using a rather complicated procedure of signal and background parameterizations in LO QCD. The invariant mass spectra of the samples are shown in Fig. 9. The gluon polarizations determined from this analysis are found to be consistent with each other and small.

The COMPASS data on the gluon polarization in polarized nucleons are still preliminary. Analysis of all samples is in progress. The latest released results, shown at various international conferences (see [18]) are presented in Fig. 3 (right), all confirming that gluons are unpolarized.

3. Transverse spin structure on nucleons

As it was mentioned in Sec. 1, the description of the nucleon structure at the twist-two level involves a number of new PDFs, still to be measured. Most of them are chiral odd and can be measured in the SIDIS reactions only in combination with other chiral odd functions. COMPASS has studied the SIDIS reactions in which hadrons are produced with a certain value of the transverse momentum p_T. The p_T leads to dependence of asymmetries on an azimuthal angle ϕ of the hadrons. This angle is defined as the angle between the lepton scattering plane and the hadrons production plane.

The azimuthal asymmetries in hadrons production from transversally polarized nucleons, particularly Collins and Sivers asymmetries [3, 6, 9, 13], are well presented at this Conference by Ch. Adolph [22]. The global analysis [23] of these and other world data resulted in the first determination of the Sivers and transversity PDFs.

The preliminary COMPASS data on the azimuthal asymmetries from longitudinally polarized deuterons, which are sensitive to new PDFs are shown in Fig. 10. A number of asymmetry modulations in production of h^+ and h^- have been studied. As it was found, the amplitudes of the $\sin(2\phi)$-, $\sin(3\phi)$- and $\cos(\phi)$-modulations are consistent with zero within experimental errors. The amplitude of the $\sin(\phi)$-modulation is consistent with that seen in the HERMES data [24]. Remind that this modulation in longitudinal azimuthal asymmetries is expected to be present due to combined effect of transversity PDF h_1, Sivers and some other PDFs. Analysis of longitudinal azimuthal asymmetries from deuterium and hydrogen is in progress.

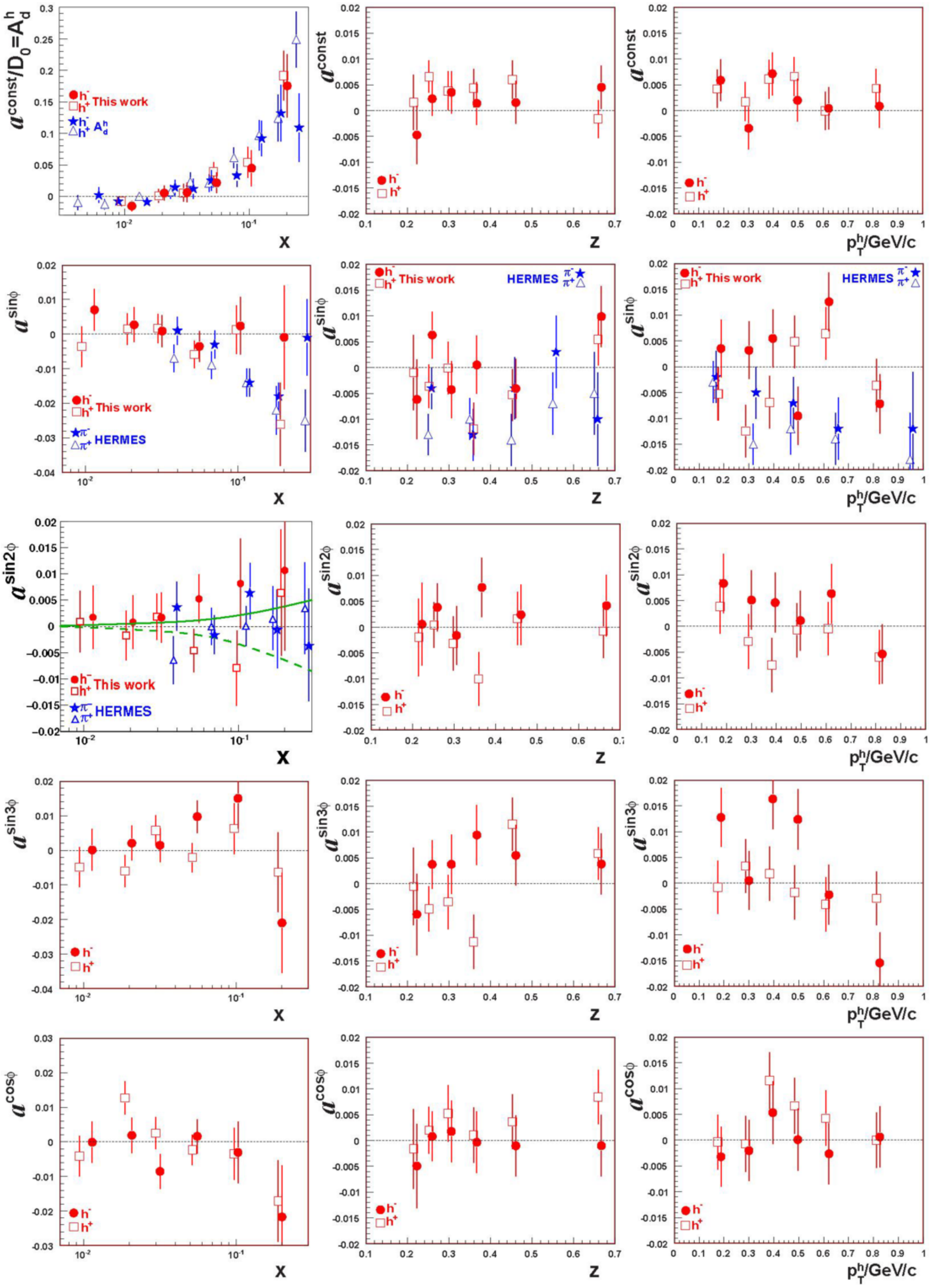

Figure 10: Dependence of the azimuthal asymmetry modulation amplitudes on kinematic variables.

4. Summary

Compass has produced a lot of new results on the nucleon longitudinal and transverse spin structure, some of them are surprising. "Spin crise" is not over: quarks and gluons do not account for the spin of nucleons. The last possibility to overcome the crises belongs to future observations of large contributions from orbital momentum of nucleon constituents.

The spin structure of nucleons became more and more complicated. The solid evidence for Collins and Sivers asymmetries is observed. Other new PDF and PFF are under studies.

More results are expected from continuation of the COMPASS data analysis, from realizations of COMPASS-2, JLAB and RHIC polarized programs.

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