Highlights from the COMPASS Experiment

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Abstract. An update is given of the ongoing experimental investigation of the spin structure of the nucleon carried on by the COMPASS Collaboration at CERN. Both longitudinal and transverse spin phenomena are covered. In the first case, the hot topic is the direct measurement of the gluon polarisation. Evidence is presented for $\Delta G/G$ being small around $x_g \simeq 0.1$, and its first moment should not be larger than 0.2 - 0.3 in absolute value. About transverse spin effects, evidence is given for new phenomena, associated with transverse momentum dependent distribution and fragmentation functions.

Keywords: QCD, polarised DIS, spin dependent parton distributions

THE COMPASS SPECTROMETER

Since 2002 the COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy) experiment at CERN has carried on DIS measurements impinging a 160 GeV/c momentum μ^+ beam on solid polarized deuteron and proton targets to investigate the spin structure of the nucleon. In 2002, 2003, 2004 and 2006 a ^{6}LiD target has been used. In 2007 data have been collected on a NH_3 polarized proton target and we have exhausted the approved program with muon beam. In 2008 the COMPASS Collaboration has started measuring central production and diffractive processes, scattering a 160 GeV/c pion beam on a liquid H_2 target, to search for exotic hadronic states (glueballs and hybrids). In this report I will summarize the nucleon structure studies we have performed with the high-energy muon beam and the polarized deuteron target.

The COMPASS apparatus consists of a two stage magnetic spectrometer which detects the scattered muon and the produced hadrons. Charged particles are identified by a RICH (Ring Imaging CHerenkov) counter and by hadron calorimeters. The target material is contained in two 60 cm long cells which are polarized by dynamic nuclear polarization in opposite directions, so that data from both spin directions are recorded at the same time. Since 2006, a new target magnet has been used, increasing the acceptance from ± 70 mrad to ± 180 mrad. Also, the target material has been distributed in three cells, of 30, 60 and 30 cm length, and polarized as $+-+$ or $-+-$. The full description of the spectrometer can be found in [1]. In 2005 major upgrades have been carried on. A part from the already mentioned new magnet system for the polarized target, tracking and electromagnetic calorimeters have been improved, a new photon detector has been integrated in the central part of the RICH, and the entire read-out of the RICH has been

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redesigned and implemented.

The physics programme of COMPASS is very broad. When the target polarization is longitudinal, it spans from the measurement of the structure function $g_1(x)$, to the measurement of ΔG, the gluon polarization in a longitudinally polarized nucleon, to the flavour separated helicity distributions, to Λ-physics and to vector meson -physics. Alternatively, the target polarization can be rotated orthogonally to to the incoming muons, and transverse spin effects are investigated.

THE PHYSICS OBJECTIVES OF COMPASS

Understanding the spin structure of the nucleon has been a central topic for the last twenty years. In general terms one writes the spin equation for the proton (or neutron) as

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + < L_z > \qquad (1)$$

where $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ is the contribution of the quarks spins, ΔG is the contribution of the gluons, and $< L_z >$ is a possible contribution from the gluons and quarks angular momentum. The quantities Δq are defined as

$$\Delta q = \int_0^1 \left\{ \left(q(x)^{\downarrow\uparrow} + \bar{q}(x)^{\downarrow\uparrow} \right) - \left(q(x)^{\uparrow\uparrow} + \bar{q}(x)^{\uparrow\uparrow} \right) \right\} dx = \int_0^1 \Delta q(x)\, dx\,, \qquad (2)$$

namely they are the differences of the integrated quark densities of a given flavour q, for quark spin anti-parallel or parallel to the proton direction.

Using polarized lepton beams and polarized nucleon targets one structure function, $g_1(x)$, can be measured from the cross-section asymmetry of the inclusive scattering. In the quark parton model this structure function can be written as

$$g_1(x) = \frac{1}{2}\Sigma_q e_q^2 \Delta q(x)\,, \qquad (3)$$

where e_q is the quark electric charge, and x the Bjorken variable. From the first moment of $g_1(x)$, $\Gamma_1 = \int_0^1 g_1(x)dx$ and using the values of the baryon decay constants (F+D) and (3F-D) one can extract from measurements of $g_1(x)$ the flavour-singlet moment $\Delta\Sigma$. Actually, $g_1(x)$ and $\Delta q(x)$ are also functions of Q^2, the photon virtuality, and $G(x,Q^2)$ and $\Delta q(x,Q^2)$ mix up in the DGLAP evolution equations, so that the extraction of the first moments requires a QCD fit. These fits provide also crude determinations of ΔG, from the Q^2 dependence of the spin structure function g_1, but the precision of these determinations is strongly limited by the small Q^2 range covered by the present experiments.

Given the smallness of $\Delta\Sigma$, firstly established twenty years ago by the European Muon Collaboration [2], understanding the nucleon spin requires the investigation of the other terms in eq.(1). While measurements of $< L_z >$ are for the moment out of reach, direct measurements of ΔG have become a priority issue and constitute the major physics goal of COMPASS. In polarized semi-inclusive DIS, the polarization $\Delta G/G$ of gluons carrying a fraction x_g of the nucleon momentum can be obtained from the cross-section helicity asymmetry of the photon–gluon fusion (PGF), $\gamma^* g \rightarrow q\bar{q}$, and this is the method followed by COMPASS.

The knowledge of the helicity distributions $\Delta q(x)$ and $\Delta G(x)$ does not exhaust the spin structure of the nucleon. It has been realised that to fully specify the quark structure of the nucleon at the twist-two level, the transverse spin distributions $\Delta_T q(x)$ must be added to the momentum distributions $q(x)$ and the helicity distributions $\Delta q(x)$ [3]. The definition of $\Delta_T q(x)$ is analogous to that of $\Delta q(x)$ but it refers to transversely polarised quarks in a transversely polarised nucleon.

The transversity distributions $\Delta_T q$ are difficult to measure, since they are chirally odd and therefore absent in inclusive DIS. They may instead be extracted from measurements of the single-spin asymmetries in cross-sections for semi-inclusive DIS (SIDIS) of leptons on transversely polarized nucleons, in which a hadron is also detected in the final state. In these processes the measurable asymmetry, the "Collins asymmetry" A_{Coll}, is due to the combined effect of $\Delta_T q$ and another chirally-odd function, $\Delta_T^0 D_q^h$, which describes the spin-dependent part of the hadronization of a transversely polarized quark into a hadron with transverse momentum $\vec{p}_T^{\,h}$. At leading order A_{Coll} can be written as

$$A_{Coll} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}, \tag{4}$$

and it is expected to show up as a $\sin\Phi_C$ modulation of the $\vec{p}_T^{\,h}$ dependent quark fragmentation function. Φ_C is the difference of the azimuthal angles of the hadron and of the spin direction of the struck quark.

A different mechanism has also been suggested in the past as a possible cause of a spin asymmetry in the cross-section of SIDIS of leptons on transversely polarized nucleons. Allowing for an intrinsic $\vec{k}_T$ dependence of the quark distribution in a nucleon, a left-right asymmetry could be induced in such a distribution by the transverse nucleon polarization. Neglecting the hadron transverse momentum with respect to the fragmenting quark, this $\vec{k}_T$ dependence could cause the "Sivers asymmetry"

$$A_{Siv} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h} \tag{5}$$

in the distribution of the hadrons resulting from the quark fragmentation with respect to the nucleon polarization. This "Sivers asymmetry" could be revealed as a $\sin\Phi_S$ modulation in the number of produced hadrons, where Φ_S is the difference of the azimuthal angles of the hadron and of the nucleon spin. Measuring SIDIS on a transversely polarized target allows the Collins and the Sivers effects to be disentangled.

Investigation of the transverse spin phenomena in SIDIS is complementary to the investigation of longitudinal spin phenomena and is also a major physics goal of COMPASS.

MEASUREMENTS OF $\Delta G/G$

In this short report I will concentrate only on the different measurements of $\Delta G/G$, and will skip all the other results COMPASS has obtained in the longitudinal target polarisation mode.

To directly measure ΔG two procedures have been followed to tag the PGF process. The first one consists in selecting open-charm events, which provide the purest sample of PGF events, but at a low rate. Another possibility is to select events with two jets at high transverse momentum, p_{T}, with respect to the virtual photon direction or, in fixed-target experiments like COMPASS, two high-p_{T} hadrons. The latter procedure provides much larger statistics but leaves a significant fraction of background events in the selected sample. As a result, the cross-section helicity asymmetry $A_{\parallel}$ contains in addition to the contribution from PGF a contribution A_{bgd} from the background processes:

$$A_{\parallel} = R_{PGF} \cdot \hat{a}_{LL}^{PGF} \cdot \frac{\Delta G}{G} + A_{bgd}. \tag{6}$$

Here, R_{PGF} is the fraction of PGF events and $\hat{a}_{LL}^{PGF} \equiv d\Delta\sigma_{PGF}^{\mu g}/d\sigma_{PGF}^{\mu g}$ is the analyzing power of PGF, that is the helicity asymmetry of the hard lepton–gluon scattering cross-section. This quantity is calculated from the leading order expressions of the polarized and unpolarized partonic cross-sections. On the other hand, R_{PGF} and A_{bgd} must be estimated by a simulation, which introduces a model dependence in the evaluation of $\Delta G/G$.

In the first method it is important to maximize the number of open charm events. For this reason the trigger system extends to very low Q^2-values (down to 0.002 (GeV/c)^2). Open-charm events are identified by reconstructing D°, $\bar{D}^\circ$, D^{*+} and D^{*-} mesons from their decay products. Kaon-pion pairs are selected by asking $9 < p_K < 50$ GeV/c in order to be in the RICH K identification region.

The full 2002-2006 data set has been analysed. The events in the analyses are weighted by the analysing power a_{LL} and by the signal to background ratio $r = S/(S+B)$. The quantity a_{LL} is obtained from a Neural network (NN) trained on Monte Carlo events. The ratio r is parametrized in terms of the event kinematics. The weighting brings a significant improvement in statistical error due to the large variation of a_{LL} and r in phase space. Fig. 1 shows the weighted mass spectra for D° and D^* for the four years of data taking. The value for $\Delta G/G$ using the D° and D^* data is:

$$\frac{\Delta G}{G} = -0.49 \pm 0.27\ (stat.) \pm 0.11\ (syst.)$$

corresponding to mean values of $< x_g > \simeq 0.11$ for the gluon and of $< \mu^2 > \simeq 13$ (GeV/c)^2 for the QCD scale.

The second method uses events which contain at least two charged hadrons associated to the primary vertex, in addition to the incident and scattered muons. Several kinematical cuts are applied to the two hadrons with highest transverse momentum to enhance the fraction of PGF events in the sample. DIS events ($Q^2 > 1$ (GeV/c)^2) and low Q^2 events are considered separately, and different generators are used as reliable models for the interaction of the virtual photon with the nucleons, LEPTO and PYTHIA respectively.

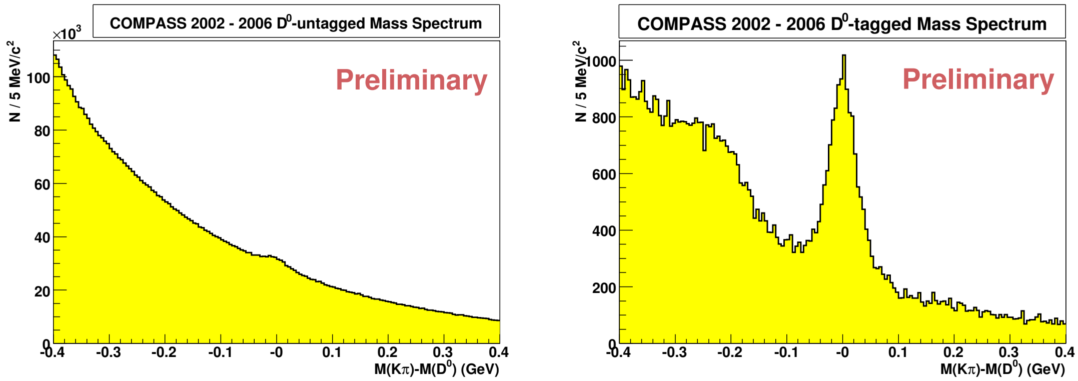

FIGURE 1. The weighted mass spectrum for D° (left) and D^{*} (right) for the 2002-2006 data.

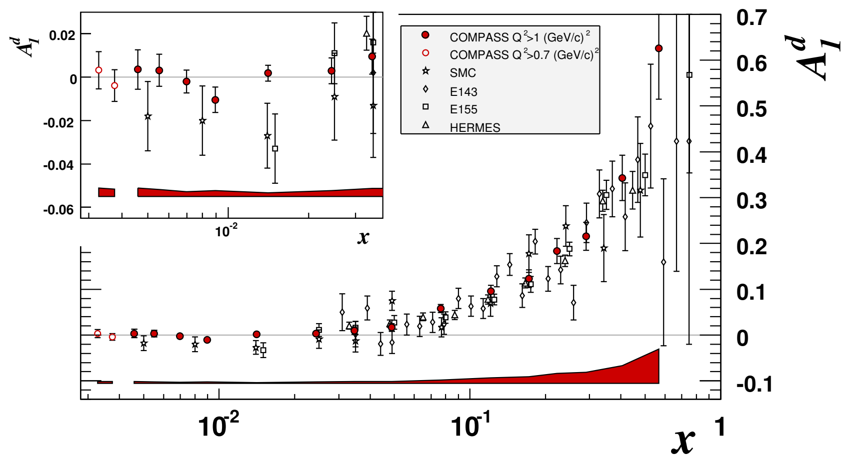

FIGURE 2. The asymmetry $A_1^d(x)$ as measured in COMPASS [5] and previous results from SMC [6], HERMES [7], SLAC E143 [8] and E155 [9] at $Q^2 > 1(GeV/c)^2$.

Various processes contribute to the Monte Carlo sample of high-p_{T} events. The direct processes are the PGF, the QCD Compton (QCDC, $\gamma^{*}q \rightarrow qg$), and the leading process ($\gamma^{*}q \rightarrow q$). For the small Q^2 sample, resolved photon processes are also important.

Results from the Q^2<1 (GeV/c)^2 data collected in the years 2002-2003 have already been published [4]. The 2004 data confirm the published result, and from the whole set of 2002-03-04 deuteron data a preliminary value for $\Delta G/G$ has been extracted at $< x_g >= 0.085$ and $< \mu^2 >= 3$ GeV^2:

$$\frac{\Delta G}{G} = 0.016 \pm 0.058\,(stat.) \pm 0.055\,(syst.)\,.$$

A similar analysis has been performed for the SIDIS events (Q^2 > 1 (GeV/c)^2). A preliminary analysis of the data collected in 2002, 2003 and 2004 has allowed the

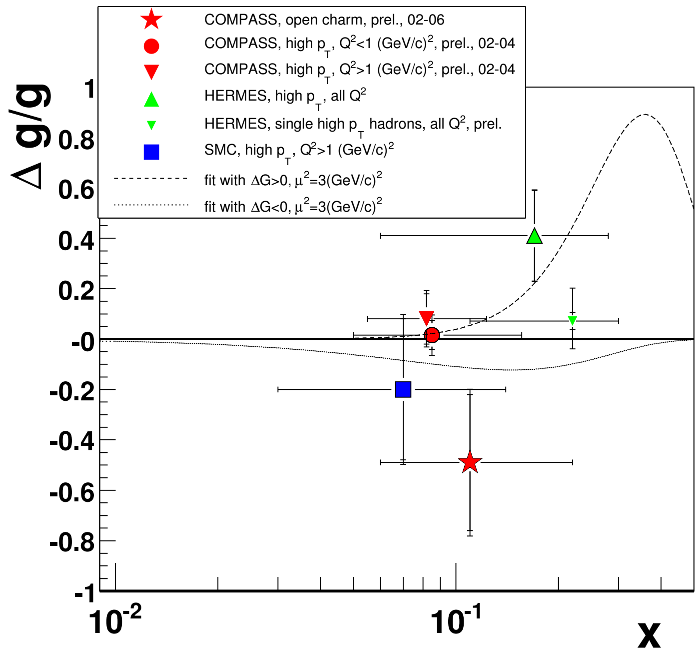

FIGURE 3. Distribution of the gluon polarisation $\Delta G(x)/G(x)$ at $Q^2 = 3(GeV/c)^2$ for the two fits with $\Delta G > 0$ and $\Delta G < 0$ performed by the COMPASS Collaboration [5]. The data points show the measured values from SMC [11], HERMES [10, 12] and COMPASS.

following determination of $\Delta G/G$

$$\frac{\Delta G}{G} = 0.08 \pm 0.10(stat.) \pm 0.05(syst.)\,.$$

at $< x_g >= 0.082$ for the gluon and of $< \mu^2 > \simeq 3$ (GeV/c)^2 for the QCD scale.

The COMPASS experiment has also measured with high precision the longitudinal virtual photon asymmetry A_1^d of the deuteron. Fig. 2 gives the COMPASS measurement, which refers to 2002-03-04 and has been recently published [5], compared with previous measurements. At small x (x <0.03) the COMPASS data exhibit errors which are considerably smaller than the previous SMC results. Most important, the negative trend of the low-x SMC data is not confirmed by the COMPASS data, which for x <0.03 are consistent with zero.

From A_1^d the structure function g_1^d of the deuteron is obtained. Using all the available g_1^d data, we have performed a QCD fit [5] and obtained the singlet moment a_0, which coincides with $\Delta\Sigma$ in the $\overline{MS}$ normalization scheme

$$a_0\left(Q^2 = 3\,(GeV/c)^2\right) = 0.30 \pm 0.01 \text{ (stat.)} \pm 0.02 \text{ (evol.)}.$$

The same fit provides estimates for $\Delta G(x)$ and for its first moment. Two different solutions are acceptable, one with $\Delta G(x) > 0$ and the other with $\Delta G(x) < 0$. Fig 3 shows the distributions of the gluon polarisation which result from the two fits. The

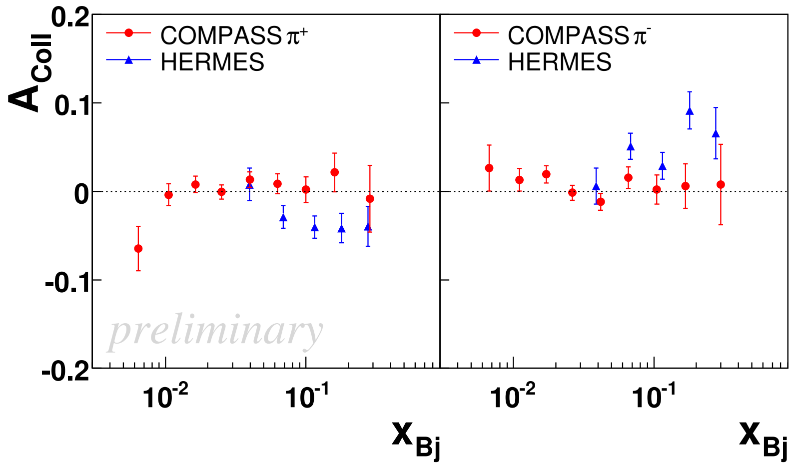

FIGURE 4. Preliminary results for Collins asymmetry against x from 2003 and 2004 data (COMPASS) and 2002-2004 data (HERMES).

two shapes are quite different, but both solutions equally well describe the present data. The conclusion from the fit is that the first moment of $\Delta G(x)$ is of the order of 0.2-0.3 in absolute value at $Q^2 = 3(GeV/c)^2$.

In Fig 3 also shown are the values obtained from the high-p_T hadron pairs and from the open-charm cross-section asymmetry. Also shown are the previous results (published) from the HERMES Collaboration [10] and from the SMC Collaboration [11], as well as the recent preliminary value released by the HERMES Collaboration [12]. The picture which emerges clearly favours small values of ΔG, at variance with past suggestions, which conjectured rather large values, of the order of 2-3 units of $h/2\pi$.

TRANSVERSE SPIN CASE

The COMPASS experiment has measured for the first time single hadron transverse spin asymmetries in DIS of high energy muons on deuterons, scattering the 160 GeV/c muon beam on the transversely polarised ^{6}LiD target. Also in this case, several asymmetries have been investigated, in particular for two hadron system, exclusive ρ, and Λ hyperons, but in this short report I will mention only the results for Collins and Sivers effects.

The resulting Collins and Sivers asymmetries for non-identified hadrons from the 2002, 2003, and 2004 data have already been published [13, 14]. The new results for the $\pi^{\pm}$ asymmetries are plotted against the kinematic variable x in Fig. 4 and in Fig. 5. The COMPASS data refer to the 2003 and 2004 run, and have been sent for publication [15]. For comparison, the HERMES [16] data on a transversely polarised proton target are also shown. The HERMES data refer to the runs 2002-2004 (new results which include the 2005 run are also available, and confirm the trend of the earlier data).

All the measured asymmetries on the deuteron target are small, if any, and compatible with zero. On the other hand, the proton data of HERMES definitively show a signal

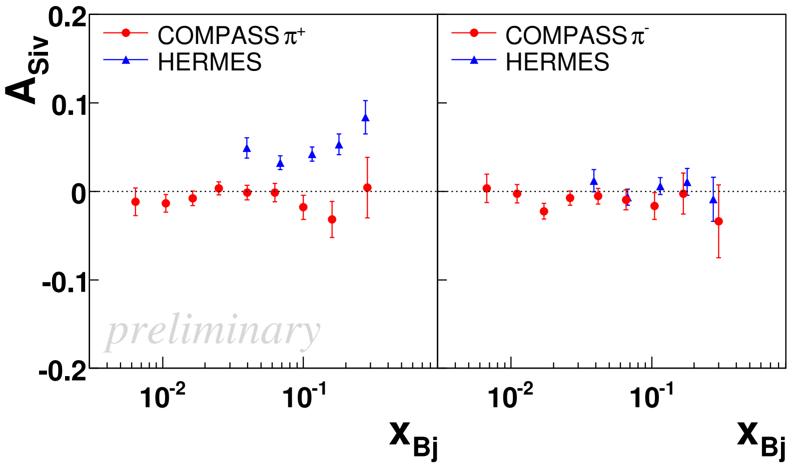

FIGURE 5. Preliminary results for Sivers asymmetry against x from 2003 and 2004 data (COMPASS) and 2002-2004 data (HERMES).

at 5% level for the Collins asymmetry on π^+ and π^-. Independent evidence that the Collins mechanism is a real measurable effect has come from the recent analysis of the BELLE Collaboration. The null result from COMPASS can be understood in terms of cancellation between u- and d-quarks, the deuteron being isoscalar, and the smallness of both the π^+ and π^- Collins asymmetries we have measured on the deuteron is a straightforward indication that $\Delta_T u_v \simeq -\Delta_T d_v$. A few analyses aiming at the extraction of the transversity distributions have already been performed, and all the observed phenomena can be described in a unified scheme.

The HERMES data on a proton target have also provided convincing evidence that the Sivers mechanism is at work. The approximately zero Sivers asymmetries for positive and negative hadrons observed in COMPASS require $\Delta_0^T d_v \simeq -\Delta_0^T u_v$, a relation which is also obtained in some models, and which anyhow has a simple physical interpretation if the Sivers distortion of the PDF of the nucleon is associated with the orbital angular momentum of the u and d quarks.

The analysis of the Collins and Sivers asymmetries measured by COMPASS in 2007 on a proton target will be available shortly, and will help in assessing the physical nature of these new phenomena.

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