Determination of the gluon contribution to the nucleon spin with COMPASS

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New double-spin asymmetry data from the COMPASS experiment at CERN are presented. The data are used to determine the polarized gluon distribution $\Delta G/G(x)$, via three different techniques. Next-to-leading order QCD fits to the nucleon polarized structure functions indicate that the first moment of $\Delta G/G(x)$ is small (either positive or negative) and compatible with zero. This observation is corroborated by three measurements of $\Delta G/G(x)$, based on the photon-gluon fusion process.

1. INTRODUCTION

During the years 2002-2004 the COMPASS collaboration at CERN has collected a large amount of data using a naturally polarized muon beam and a polarized ^{6}LiD target. Particular effort is dedicated to the determination of the gluon contribution ΔG/G to the nucleon spin. Three different techniques are employed. The first technique takes advantage of the largely improved accuracy of the deuteron spin structure function, particularly for the low values of the Bjorken variable x. The contribution of both quarks and gluons to the nucleon spin is then determined by a Next-to-Leading Order QCD analysis of the world data set on proton, deuteron and neutron (^{3}He) targets. The gluon contribution is more directly determined via the Photon-Gluon Fusion (PGF) process. In the second technique the PGF process is isolated by observing the decay of the charmed D^0 meson into a kaon and a pion (open charm). In the third technique the PGF process is selected by measuring two hadrons with high transverse momentum and opposite charges in coincidence (high-p_T pairs). The high-p_T pairs technique provide us with two independent measurements of ΔG/G, but with different theoretical uncertainties. Within their respective statistical and model errors, all three techniques indicate that ΔG/G is small and compatible with zero.

2. COMPASS SET-UP

The COMPASS set-up was designed for beam energies of 100 to 200 GeV and physics processes in which in addition to the scattered beam particle, one or more outgoing particles are detected. The set-up is built around two large dipole magnets that define two consecutive spectrometers, suitable for large and small scattering angles respectively. Several types of tracking detectors are used to cover the various phase space regions: silicon

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and scintillating fibers, Micromegas and GEM micromesh detectors, large proportional and drift chambers. Particle identification is performed using a RICH counter and both electromagnetic and hadron calorimeters. During the muon data taking a large polarized target, consisting of two oppositely polarized cells, 60 cm long each, surrounded by a large solenoid, was used. The two cells were filled with a ^{6}LiD target material, for which polarizations better than 50% are routinely achieved. Data with longitudinally polarized target were taken for about 75% of the total running time during the 2002-2004 period.

3. The gluon distribution via NLO QCD analysis

Inclusive deep-inelastic scattering cross section asymmetries were measured [1] for values of the Bjorken variable x ranging from 0.004 to 0.7 and for four-momenta Q^2 between 1 and 100 $(GeV/c)^2$. From the experimental asymmetries we determine the deuteron spin structure function $g_1^d(x)$. The data (Fig. 1) are in good agreement with previous results on $g_1^d(x)$ [2] and, in addition, significantly improve the available statistics in the lowest x region, between $x = 0.004$ and $x = 0.03$. In order to extend the data to even lower x values, we slightly released the Q^2 cut, from 1 $(GeV/c)^2$ to 0.7 $(GeV/c)^2$, adding two more bins to the data. These two points support the observation that at lower values of x the structure function $g_1^d(x)$ remains compatible with zero.

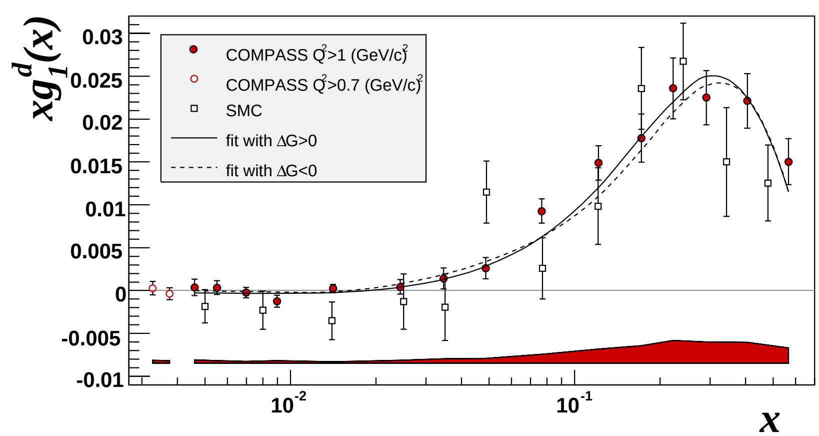

Figure 1. Measured COMPASS $xg_1^d(x)$ data, compared to previous results from SMC [2]. The error bars are statistical only. The systematic errors are indicated by the shaded area. The two lowest x points are obtained by lowering the Q^2 cut to 0.7 $(GeV/c)^2$. The solid and dashed lines represent the QCD fit to the world data with positive and negative gluon distributions respectively.

A Next-to-Leading Order (NLO) QCD analysis of the world proton, deuteron and ^{3}He data available (see Ref. [1] and references therein) was carried out, based on two different approaches, in the (x, Q^2) space [3] and in the space of moments [4] respectively. The fits use the QCD evolution equations that describe the Q^2 dependence of the nucleon polarized structure function in terms of singlet $\Delta\Sigma(x)$, non-singlet $\Delta q_3(x)$ and $\Delta q_8(x)$, and gluon $\Delta G(x)$ distributions. The fits are performed in the $\overline{MS}$ renormalization and factorization scheme at the reference Q_0^2 of 3 $(GeV/c)^2$. In total, 230 data points were used, out of which 43 are from COMPASS. The $Q^2 < 1(GeV/c)^2$ data points were not included in the fits.

Each of the two fits provide us with two different solutions, one with $\Delta G < 0$ and the other with $\Delta G > 0$. The two solutions for each of the two fits yield comparable singlet and non-singlet distributions and nearly identical χ^2 probabilities, an indication that the Q^2 evolution at NLO is properly described in both of them. The positive and negative solutions for the fit in the (x, Q^2) space are displayed in Fig. 1.

If we round up to the second digit, the total quark contribution to the nucleon spin as determined from both fits are: $\eta_\Sigma = 0.28 \pm 0.01$ and $\eta_\Sigma = 0.32 \pm 0.01$ for $\Delta G > 0$ and $\Delta G < 0$ respectively. Here η_Σ is the first moment of $\Delta\Sigma(x)$. The two results can be combined if adding their difference in the systematic: $\eta_\Sigma = 0.30 \pm 0.01(stat) \pm 0.02(evol)$.

From the QCD fits results in Fig. 2 and Fig. 3 we also determine the first moment of the strange quark contributions. The result: $\Delta s + \Delta\overline{s} = -0.10 \pm 0.01(stat) \pm 0.01(evol)$, indicates that the strange sea is negatively polarized.

Fig. 2 and Fig. 3 show the polarized quark ($u(x)$, $d(x)$ and $s(x)$) and gluon distributions ΔG for the two solutions. The first moments η_G for $\Delta G(x)$ are small for both solutions and nearly equal in absolute values, i.e. $\eta_G \approx 0.2 - 0.3$. The fit uncertainty does not rule out values of η_G compatible with zero.

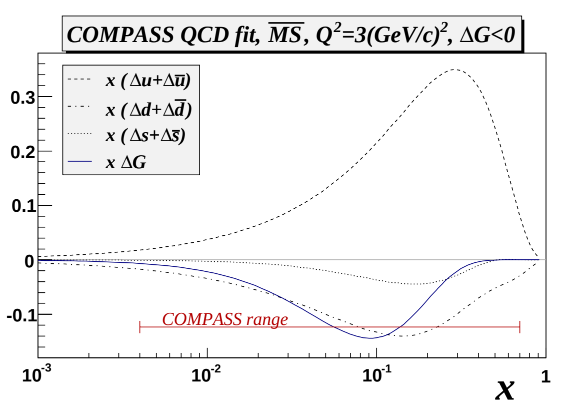

Figure 2. Parton distributions functions for the solution $\Delta G < 0$.

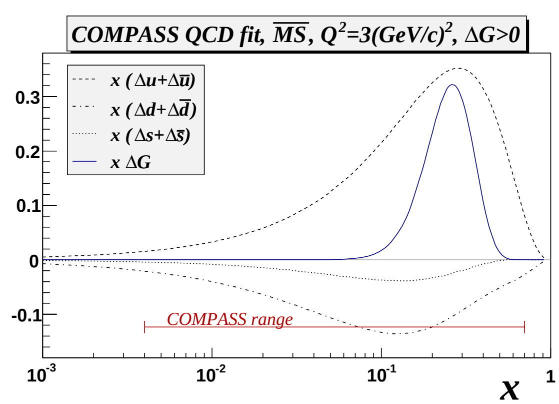

Figure 3. Parton distributions functions for the solution $\Delta G > 0$.

4. Gluon polarization from Photon-Gluon Fusion process

The gluon polarization can be directly measured via the spin asymmetry of the Photon-Gluon Fusion (PGF) process. In this process the fusion of the virtual photon and the gluon creates a quark-antiquark pair. The fragmenting quarks are then detected with two different, but complementary methods. In the open charm method one observes the decay of the D^0 and D^* mesons into $K + \pi$ and $K + \pi + \pi_s$ hadrons respectively. Since this method is based on the selection of charmed quarks, it has no contributions from other physics channels. However, the corresponding counting rate is low, and the associated combinatorial background high. In the second method the PGF events are identified by requiring that two opposite-charge high-transverse momentum hadrons (high-p_T pairs) are detected in coincidence. Since this method selects light quarks as well, its counting rate is high; however the competing processes involving e.g. resolved photon contributions, play a role and must be subtracted, introducing an additional model error in the results.

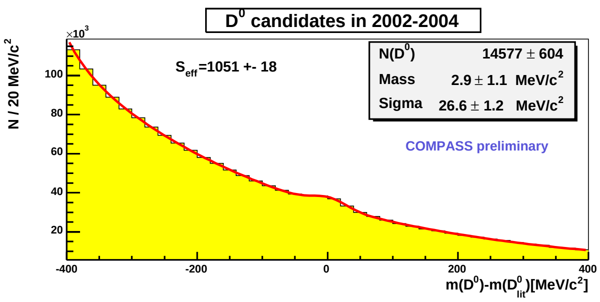

Figure 4. Invariant mass distribution in the D^0 mass range as computed from the $D^0 \rightarrow K\pi$ candidates.

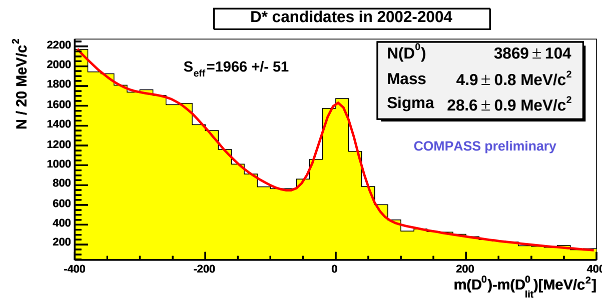

Figure 5. Invariant mass distribution in the D^* mass range as computed from the $D^* \rightarrow K\pi\pi_s$ candidates.

4.1. Open charm

The open charm channel selects a small but pure fraction of the PGF events, those originating from a charmed quark-antiquark pair. It is identified by the hadronic modes of the decays $D^0 \rightarrow K^-\pi^+$ and $\bar{D}^0 \rightarrow K^+\pi^-$. The background associated with the D^0 is particularly large; detection of the decays $D^{*+} \rightarrow D^0\pi_s^+$ and $D^{*-} \rightarrow \overline{D}^0\pi_s^-$ with π_s being a low-energy (soft) pion, significantly improve the signal over background ratio. This is illustrated in Fig. 4 and Fig. 5 where the effective signals $S_{eff} = S/(1 + S/B)$ for the two processes are displayed. The gluon polarization is calculated from the experimental asymmetry using the relation:

$$A_{exp} = P_B P_T f a_{LL} \frac{S}{S+B} \Delta G/G, \tag{1}$$

where P_B and P_T are the beam and target polarizations respectively, f is the dilution factor, and $S/(S + B)$ the signal over background ratio. The analyzing power a_{LL} is calculated using a Monte-Carlo simulation. The resulting value of the gluon polarization obtained at $x_g = 0.15$ is $\Delta G/G(x_g) = -0.57 \pm 0.41(stat)$ at a scale of $\langle \mu^2 \rangle = 13\ (GeV/c)^2$.

4.2. High-p_T pairs

Contrary to the open charm, the high-p_T channel benefits from a much larger statistics. Fig. 6 and Fig. 7 display the Q^2 and the $\sum p_T^2$ experimental distributions. However, large

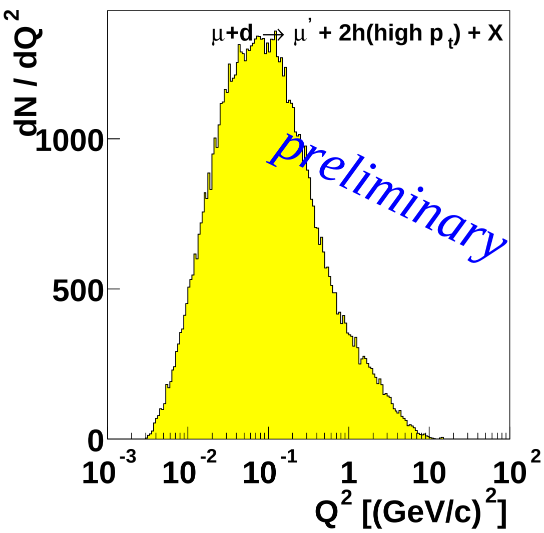

Figure 6. Measured distribution of Q^2 for high-p_T pairs. The data are separated into two sets, below and above Q^2=1 $(GeV/c)^2$.

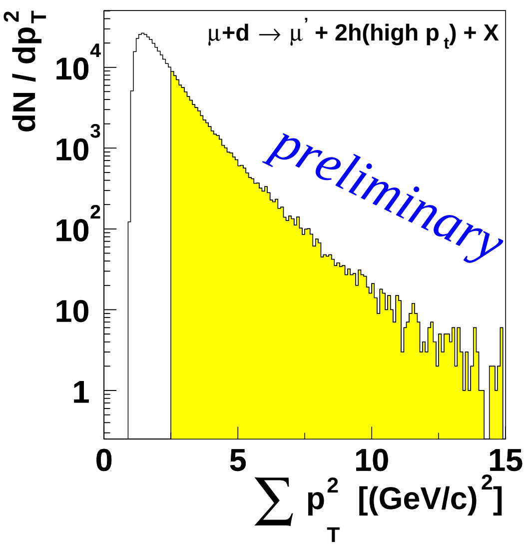

Figure 7. Measured distribution of $\sum p_T^2$ for high-p_T pairs. The cut applied at $\sum p_T^2 = 2.5 (GeV/c)^2$ is indicated.

part of these events comes from background physics processes that are experimentally unknown. The corresponding contributions must be estimated using a Monte-Carlo simulation, on the expense of an additional model dependence in the result. Two parallel analysis of the data are done. The first analysis takes into account the high-p_T quasi-real photoproduction events with $Q^2 < 1$ $(GeV/c)^2$ only. In the second analysis the events with $Q^2 > 1$ $(GeV/c)^2$ are considered. The two kinematic domains differ not only by the number of events in the sample, but also by the relative amount of the various background processes contributing to the experimental asymmetry. In the low Q^2 domain the dominant effect comes from the resolved photon contributions. We have simulated these processes using the PYTHIA Monte-Carlo generator and found that the PGF events represent 30% of the sample and about half of the total number is due to the resolved photon processes. The simulation procedure and the resulting model errors are described in Ref. [5]. When the data from 2004 are included, the result at $\langle x_g \rangle = 0.085$ and for $\langle \mu^2 \rangle = 0.085$ is: $\Delta G/G = 0.016 \pm 0.058(stat) \pm 0.055(syst)$. Here the systematic error includes both experimental and simulation systematics, the largest model error coming from the uncertainties on the Monte-Carlo parameters.

In contrast to the low Q^2 region, the background for the events with $Q^2 > 1$ $(GeV/c)^2$ is dominated by the leading and QCD-Compton processes. These were estimated [5] using the LEPTO Monte-Carlo generator. After all cuts have been applied we obtain: $\Delta G/G = 0.06 \pm 0.31(stat) \pm 0.06(syst)$ for the data taken in 2002 and 2003.

Fig. 8 shows the three COMPASS data points together with previous measurements from SMC [6] and HERMES [7]. The two QCD fit solutions for the $\Delta G/G(x)$ distribution,

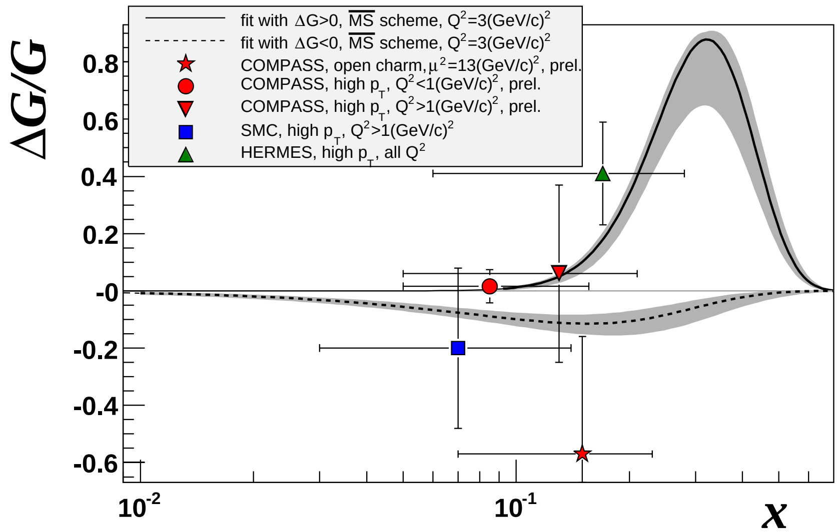

Figure 8. Polarized gluon distribution $\Delta G/G(x)$ in the nucleon. The two solutions resulting from the QCD fits based on the approach of Ref. [3] are displayed. The shaded bands represent the statistical errors. The data points measured by COMPASS (open charm, high-p_T with $Q^2 > 0$ and and high-p_T with $Q^2 < 0$ are shown, together with previous results [6,7]. The horizontal bars indicate the x-range of the measurements.

are also shown. The new COMPASS measurements are all compatible with both solutions, while the data point from HERMES seems to favor a positive $\Delta G/G(x)$ distribution.

5. Conclusion

During the period of 2002-2004 COMPASS has collected a large amount of new data that give access to polarized gluon distribution $\Delta G/G(x)$ in the nucleon. A QCD next-to-leading order fit to the COMPASS deuteron spin-dependent structure function, together with the older data on the nucleon, indicate that the gluon contribution to the nucleon spin is small and can be either positive or negative. The resulting positive and negative gluon distributions are both consistent with our three independent measurements of $\Delta G/G(x)$ which all point to values compatible with zero.

REFERENCES

1. COMPASS Collaboration, V. Alexakhin et al., CERN preprint hep-ex/0609038.
2. SMC Collaboration, B. Adeva et al., Phys. Rev. D58 (1998) 112001.
3. SMC Collaboration, B. Adeva et al., Phys. Rev. D58 (1998) 112002.
4. A.N. Sissakian, O.Yu. Shevchenko and O.N Ivanov, Phys. Rev. D70 (2004) 074032.
5. COMPASS Collaboration, E.S Ageev et al., Phys. Lett. B633 (2006) 25.
6. SMC Collaboration, B. Adeva et al., Phys. Rev. D70 (2004) 012002.
7. HERMES Collaboration, A. Airapetian et al., Phys. Rev. Lett. 84 (2000) 2584.