Analysis of the deuteron spin structure by COMPASS

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New results on the longitudinal inclusive spin asymmetry A_1^d in the range $1 < Q^2 < 100$ (GeV/c)^2 and $0.004 < x < 0.7$ are presented. From these results we derive the spin-dependent structure function g_1^d which we include in a QCD analysis of the world data. The data were obtained by the COMPASS experiment at CERN using a 160 GeV polarized muon beam scattered off a large polarized ^{6}LiD target. The results are in agreement with those from previous experiments and improve considerably the statistical accuracy in the region $0.004 < x < 0.03$.

We present new results from the COMPASS experiment at CERN on the deuteron spin asymmetry A_1^d and the spin-dependent structure function g_1^d. The data were collected during the years 2002–2004. We refer the reader to [1] for the description of the 160 GeV muon beam, the ^{6}LiD polarised target and the COMPASS spectrometer. Ref. [1] also contains the description of cuts which relate to the method of asymmetry extraction and quality of the sample. The DIS events are selected by cuts on the virtuality of a photon, $Q^2 > 1\,(\text{GeV}/c)^2$, and its fractional energy, $0.1 < y < 0.9$. The resulting sample consists of $89{\times}10^6$ events.

The longitudinal virtual-photon deuteron asymmetry, A_1^d, is defined via the asymmetry of absorption cross sections of transversely polarised photon as

$$A_1^d = (\sigma_0^T - \sigma_2^T)/(2\sigma^T), \quad (1)$$

where σ_J^T is the γ^*-deuteron absorption cross-section for a total spin projection J and σ^T is the total transverse photoabsorption cross-section. The relation between the experimentally measured A^d and A_1^d is

$$A^d = D(A_1^d + \eta A_2^d), \quad (2)$$

where D and η depend on the event kinematics. The transverse asymmetry A_2^d has been measured at SLAC and found to be small [2]. In view of this, in our analysis, Eq. (2) has been reduced to $A_1^d \simeq A^d/D$.

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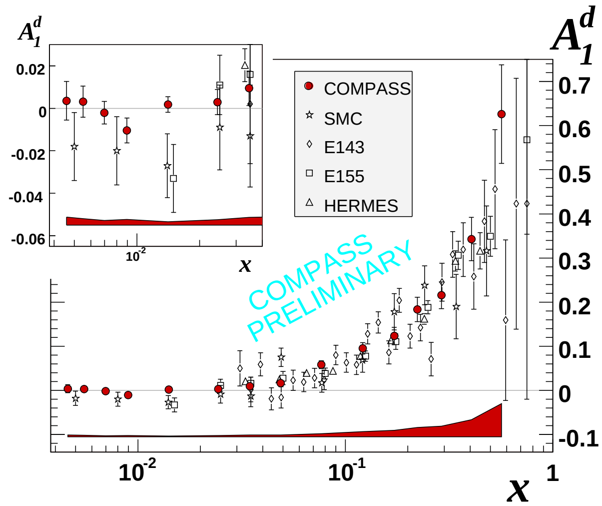

Figure 1. The asymmetry $A_1^d(x)$ as measured in COMPASS superposed to results of previous experiments. Only statistical errors are shown with the data points. The shaded areas show the size of the COMPASS systematic errors.

The values of A_1^d are shown as a function of x in Fig. 1 in comparison with previous results from experiments at CERN [4], DESY [5] and SLAC [6,7]. The values of A_1^d confirm, with increased statistical precision, the observation made in [1] that the asymmetry is consistent with zero for $x < 0.03$. Values of A_1^d originating from experiments at different energies tend to coincide due to the very small Q^2 dependence of A_1^d at fixed x.

The longitudinal spin structure function is obtained as

$$g_1^d = \frac{F_2^d}{2\ x\ (1+R)} A_1^d\,, \qquad (3)$$

where F_2^d is the spin-independent deuteron structure function. The values of g_1^d have been calculated with the F_2^d parametrisation of [4], which covers the range of our data, and the parametrisation of R [3].

We have performed a new NLO QCD fit of all g_1 data at $Q^2{>}1\,(\mathrm{GeV}/c)^2$ from deuteron target [4–7] including the COMPASS data, proton [4–6,10,11] and ^{3}He [12] targets. In total 230 data points are used. The fit is performed in the $\overline{\mathrm{MS}}$ renormalisation and factorisation scheme with input parametrisations of the quark singlet spin distribution $\Delta\Sigma(x)$, non-singlet distributions $\Delta q_3(x)$, $\Delta q_8(x)$ and the gluon spin distribution $\Delta G(x)$:

$$\Delta F_k \;=\; \eta_k \frac{x^{\alpha_k}\,(1-x)^{\beta_k}\,(1+\gamma_k x)}{\int_0^1 x^{\alpha_k}\,(1-x)^{\beta_k}\,(1+\gamma_k x)dx}\,. \qquad (4)$$

These distributions are given as an input at a reference $Q^2 = 3\,(\mathrm{GeV}/c)^2$ and evolved according to the DGLAP equations. The moments η_k for the non-singlet distributions Δq_3 and Δq_8 are fixed by the baryon decay constants (F+D) and (3F−D) respectively [13], assuming $\mathrm{SU}(3)_f$ flavour symmetry. The linear term γx is used only for the singlet distribution, in which case the exponent β_G is fixed because it is poorly constrained by the data. This leaves 10 parameters in the input distributions.

In order to keep the parameters in their physical range, the polarised strange sea and gluon distributions are required to satisfy the positivity condition $|\Delta s(x)| \leq s(x)$ and $|\Delta G(x)| \leq G(x)$ at all Q^2 values. The unpolarised distributions $s(x)$ and $G(x)$ used in this test are taken from the MRST parametrisation [14].

The fits have been performed with two different programs, the first one working in the (x,Q^2) space [15], the other one in the space of moments [16]. Both programs give consistent values of the fitted PDFs and similar χ^2-probabilities. Each program yields two solutions, one solution with $\Delta G > 0$, the other with $\Delta G < 0$ (Fig. 2). The fitted distributions of $g_1^d(x)$ slightly differ but are both compatible with the data.

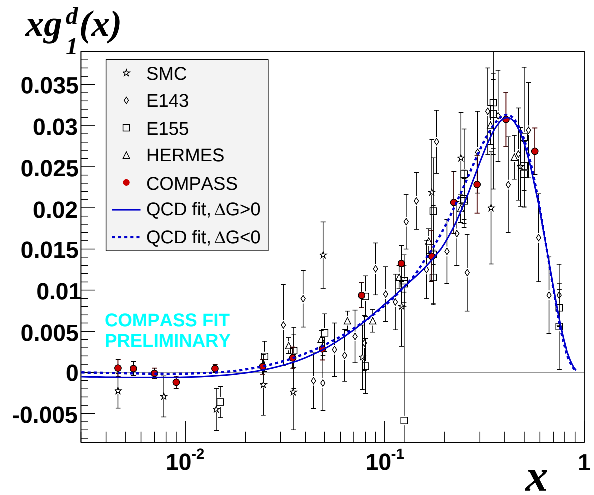

Figure 2. Measured values of $xg_1^d(x)$ evolved to $Q^2{=}3\,(\mathrm{GeV}/c)^2$. Only statistical errors are shown with the data points. The curves show the results of QCD fits with $\Delta G > 0$ and $\Delta G < 0$.

Further on we use $g_1^N{=}(g_1^p{+}g_1^n)/2$ instead of g_1^d:

$$g_1^N(x,Q^2) = g_1^d(x,Q^2)/(1-1.5\omega_D), \qquad (5)$$

where $\omega_D = 0.05 \pm 0.01$ is the correction for the D-wave state of the deuteron [8]. The integral of g_1^N in the measured region is obtained from the experimental values evolved to a fixed Q^2 and averaged over the two fits. Taking into account the contributions from the fits in the unmeasured regions at low and high x we obtain (Table 1):

$$\Gamma_1^N\Big|_{Q^2=3\,(\mathrm{GeV}/c)^2} = 0.050 \pm 0.003(stat.) \pm 0.002(evol.) \pm 0.005(syst.). \qquad (6)$$

The second error accounts for the difference in Q^2 evolution between the two fits. The systematic error is the dominant one and mainly corresponds to the 10% uncertainty resulting from the errors on the beam and target polarisations and on the

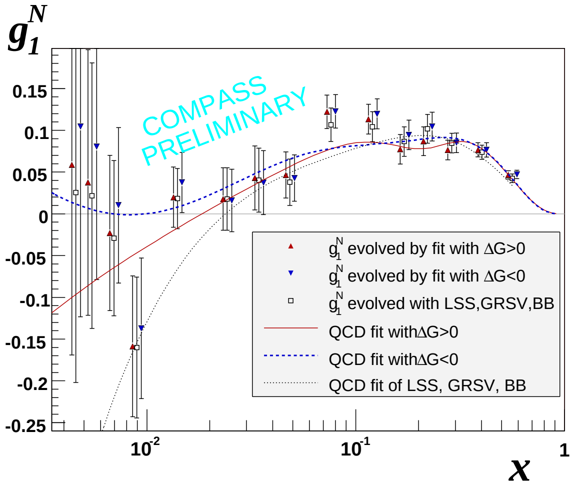

Figure 3. The COMPASS values of g_1^N evolved to $Q^2 = 3\,(\mathrm{GeV}/c)^2$. In addition to our fits the curve obtained with three published parameterizations (BB, GRSV and LSS05) [9] is shown. These parameterizations lead almost to the same values of $g_1^N(x, Q^2{=}3\,(\mathrm{GeV}/c)^2)$ and have been averaged. For clarity the data points evolved with different fits are shifted in x with respect to each other. Only statistical errors are shown.

dilution factor. In the COMPASS analysis the part of Γ_1^N obtained from the measured region represents 98% of the total value. This correction of only 2% differs essentially from a one of about 50% with respect to the measured value in case of the SMC analysis [4].

Γ_1^N is of special interest because it gives access to the matrix element of the singlet axial current a_0 which measures the quark spin contribution to the nucleon spin. At NLO, the relation between Γ_1^N and a_0 reduces to

$$\Gamma_1^N(Q^2) \overset{NLO}{=} \frac{1}{9}\left(1-\frac{\alpha_s(Q^2)}{\pi}\right)\left(a_0(Q^2)+\frac{1}{4}a_8\right). \quad (7)$$

Taking the value of Γ_1^N from Eq. (6) and the value of a_8 from hyperon β decay, assuming $SU(3)_f$ flavour symmetry [13], one obtains:

$$a_0\Big|_{Q^2=3(\mathrm{GeV}/c)^2} = 0.35 \pm 0.03(stat.) \pm 0.05(syst.). \quad (8)$$

Table 1
Contributions to $\Gamma_1^N \times 10^3$ at $Q^2{=}3\,(\mathrm{GeV}/c)^2$ from different kinematic regions and different fits. The numbers for the two first columns are obtained by using published parameterizations [9] BB and LSS05.

Range in x	Fits of BB[17]	Fits of LSS[18]	COMPASS fits $\Delta G{>}0$	COMPASS fits $\Delta G{<}0$
0.004 – 0.7	45.5	46.9	47.9	50.8
0.7 – 1	1.4	0.8	1.1	1.0
0 – 0.004	−4.0	−2.9	−0.9	0.4
Total	43.0	44.8	48.1	52.2

The quoted systematic error accounts for the error from the evolution and for the experimental systematic error, combined in quadrature.

Previous fits of g_1, not including the COMPASS data, found the positive $\Delta G(x)$ and the fitted fuction $g_1^d(x)$ becoming negative for $x \lesssim 0.025$ at $Q^2 = 3\,(\mathrm{GeV}/c)^2$, as shown by the dotted line in Fig. 3. The new COMPASS data do not show any evidence for a decrease of the structure function at the limit $x \to 0$. For our fit the data are still compatible with a positive ΔG, as shown by the full line in Fig. 3. However in this case an unexpected dip appears at $x \simeq 0.25$. The origin of this dip is related to the shape of the fitted $\Delta G(x)$, which is squeezed in a narrow interval around the maximum at $x \simeq 0.25$ (Fig. 4). Indeed, the $\Delta G(x)$ must be close to zero at low x, to avoid pushing g_1^d down to negative values, and is also strongly limited at higher x by the positivity constraint $|\Delta G(x)| < G(x)$. In contrast, the fit with negative ΔG reproduces very well the COMPASS low x data with a much smoother distribution of $\Delta G(x)$ (dashed line on Fig. 3) and without approaching the positivity limit.

Taking the average η_Σ over the two values coming from fits with positive and negative ΔG and defining the systematic error as the difference between the fits, we obtain for the singlet moment derived from the fits to all g_1 data:

$$\eta_\Sigma\Big|_{Q^2=3(\mathrm{GeV}/c)^2} = 0.30 \pm 0.01(stat.) \pm 0.02(evol.). \quad (9)$$

The singlet moment obtained with COMPASS data alone (Eq. (8)) is slightly above this value

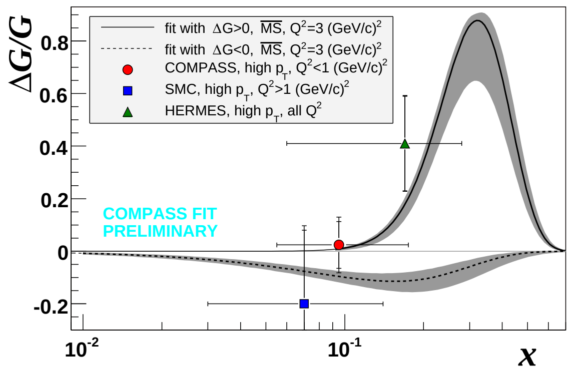

Figure 4. Distribution of the gluon polarisation $\Delta G(x)/G(x)$ at $Q^2 = 3\,(\mathrm{GeV}/c)^2$ for the fits with $\Delta G > 0$ and $\Delta G < 0$ obtained with the program of Ref. [15]. The error bands correspond to the statistical error on $\Delta G(x)$ at a given x. The three data points represent high p_T measurements [19].

and its statistical error is larger by a factor of 3. We remind that in $\overline{MS}$ scheme η_Σ is identical to the matrix element a_0.

Although the gluon distributions strongly differ in the two fits, the fitted values of their first moments are both small and about equal in absolute value $|\eta_G| \approx 0.2-0.3$. In Fig. 4 the existing direct measurements of $\Delta G/G$ [19] are shown with the distributions of $\Delta G(x)/G(x)$ derived from our fits with $G(x)$ taken from Ref. [14]. One can see that with current precisions no preference for any of the curves can be given so far.

In summary, we have measured the deuteron spin asymmetry A_1^d and its longitudinal spin-dependent structure function g_1^d at $Q^2 > 1\,(\mathrm{GeV}/c)^2$ over the range $0.004 < x < 0.7$. It have been found that g_1^d values are consistent with zero for $x < 0.03$. We have also performed the fit of world g_1 data at NLO which yields two solutions with $\Delta G(x) > 0$ and $\Delta G(x) < 0$. From the first moment Γ_1^N at $Q^2 = 3\,(\mathrm{GeV}/c)^2$ we have derived the singlet axial charge with COMPASS data alone: $a_0 = 0.35 \pm 0.03(stat.) \pm 0.05(syst.)$. This value is well compatible with results of QCD fits for the quark polarization: $\eta_\Sigma = 0.30 \pm 0.01(stat.) \pm 0.02(evol.)$. In both cases, the first moment of $\Delta G(x)$ is of the order of $0.2-0.3$ in absolute value at $Q^2 = 3\,(\mathrm{GeV}/c)^2$ but the shapes of the distributions are very different.

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