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New COMPASS results on A_1^p and g_1^p and QCD fit

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Abstract

During its 2011 data taking campaign, the COMPASS experiment at CERN has collected data of 200 GeV polarised muons scattering off a target with polarised protons. These data allow the extension of the phase-space coverage of the COMPASS data obtained in 2007 with a beam of 160 GeV polarised muons, namely to access lower values of x for any given value of Q^2.

The data in the DIS region were used to extract the longitudinal double spin asymmetry A_1^p and the spin dependent structure function g_1^p. Thereafter, our world data NLO QCD fits of polarised parton distributions were updated. It was also possible to improve our test on the Bjorken sum rule.

The asymmetries A_1^p and the structure function g_1^p were likewise extracted from the two beam energy data sets for $Q^2 < 1$ (GeV/c)^2, thus complementing our extraction of similar quantities in the non-perturbative region for the deuteron.

Keywords: COMPASS, deep inelastic scattering, spin, A_1, g_1, structure function, polarised parton distribution functions, QCD analysis, Bjorken sum rule, low x, low Q^2

1. Introduction

The COMPASS experiment at CERN [1] aims to measure the different contributions to the nucleon spin: those attributed to the quarks helicity, gluons helicity and orbital angular momenta of quarks and gluons. One of the ways to do this, discussed here, is to study the spin dependent structure functions of the proton and of the deuteron, g_1^p and g_1^d, respectively. COMPASS is a fixed target experiment that uses the unique naturally polarised high energy and high intensity muon beam of CERN's M2 beam line. The beam impinges on a solid state polarised target, either of ^{6}LiD or NH_3, thus accessing, receptively, the inelastic scattering of polarised muons on polarised deuterons or protons. From 2002 to 2006, data was taken with a target of ^{6}LiD, thus allowing the extraction of A_1^d and g_1^d [2, 3].

The target is divided into two or three cells (in 2002-2004, or 2006-2011, respectively), with consecutive cells having opposite polarisation, to allow the simultaneous recording of the two possible longitudinal polarisations, with similar acceptance for both.

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2. Data sample and method

In 2007, data was taken with a longitudinally polarised ammonia target and a beam of 160 GeV, from which g_1^p was extracted [4, 5]. In 2011, more data was taken with an ammonia target, but this time with a beam of 200 GeV, thus accessing lower values of x and, for any fixed x, higher values of Q^2. Only events where the fraction of beam particle energy carried by the virtual photon, $y = \nu/E$ is between 0.1 and 0.9 are selected for further analysis. The lower limit allows to reject events in the region where there is a higher sensitivity to false asymmetries, whereas the upper limit discards events where the radiative corrections would be large. The contamination of events of elastic scattering of beam muons on electrons from the target material was also removed.

For the subsample with $Q^2 < 1$ (GeV/c)^2, at least one hadron track had to be found in each event. This condition allows to correctly separate events with interaction vertices different target cells.

The double longitudinal spin asymmetry A_1^p is obtained from the number of events having the spin projection of the target particles in the parallel or antiparallel directions with respect to the spin projection of the beam particle:

$\frac{1}{fDP_bP_t}\frac{N^{\stackrel{\rightarrow}{\Leftarrow}}-N^{\stackrel{\rightarrow}{\Rightarrow}}}{N^{\stackrel{\rightarrow}{\Leftarrow}}+N^{\stackrel{\rightarrow}{\Rightarrow}}} = A_1^p + \eta A_2^p$, where f is the dilution factor that accounts for the fraction of polarisable particles in the target material, P_b and P_t are the beam and particle polarisations, and D is the depolarisation factor. The kinematic quantity η is small in the COMPASS case, and thus the term ηA_2^p is neglected. The asymmetries are corrected for an unpolarised radiative term, obtained from the program TERAD [6], that is included in the dilution factor, and a polarised term obtained from the program POLRAD [7]. The presence of a small quantity of polarised ^{14}N in the target material is also corrected for.

The spin dependent structure function g_1^p is obtained from the asymmetry A_1^p using $g_1^p = \frac{F_2^p}{2x(1+R)} A_1^p$, where F_2^p is one of the spin independent structure function of the proton and R is the ratio of the cross-sections of absorption of longitudinal to transverse virtual photons.

3. The $Q^2 > 1$ (GeV/c)^2 subsample

The results of $A_1^p(Q^2)$ in bins of x are shown in Fig. 1. Note that with the larger beam energy, it was possible to have one additional bin in x. The results obtained with the two beam energies are compatible within errors. Furthermore, in each x bin, the asymmetries are well fit by constants.

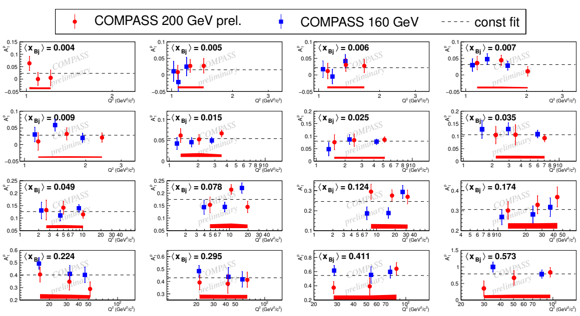

Figure 1: Preliminary COMPASS results of $A_1^p(Q^2)$ in bins of x.

The dependence of g_1^p with Q^2 is shown in Fig. 2, in bins of x. The curves with the new COMPASS NLO fit on world data are superimposed to the data points and describe the data well in all the kinematic domain covered.

World data on g_1^p and g_1^n obtained with proton, deuteron and neutron targets were used to perform a NLO fit on spin dependent distribution functions. Out of the total 674 data points used, 139 are from COMPASS. We can decompose $g_1^{p(n)}$ as

$$g_1^{p(n)} = \frac{1}{9}\left[C_S \otimes \mathbf{\Delta q_S} + C_{NS} \otimes \left(\pm\frac{3}{4}\mathbf{\Delta q_3} + \frac{1}{4}\mathbf{\Delta q_8}\right) + C_g \otimes \mathbf{\Delta g}\right],$$

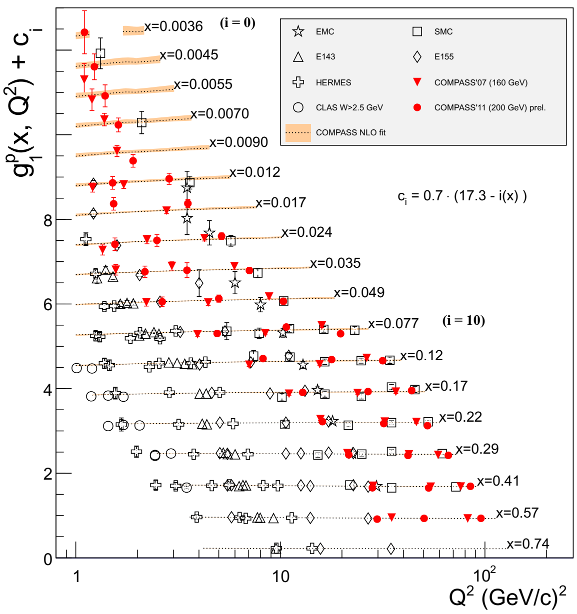

Figure 2: Preliminary COMPASS results and previous results from other experiments of $g_1^p(Q^2)$ in bins of x. The curves represent the results of the new COMPASS NLO fit on world data described in the text.

where $\Delta q_S = \Delta u + \Delta d + \Delta s$ is the spin singlet parton distribution, $\Delta q_3 = \Delta u - \Delta d$ is the triplet non-singlet spin distribution, $\Delta q_8 = \Delta u + \Delta d - 2\Delta s$ is the octet non-singlet spin distribution, and C_S, C_{NS} and C_g are the Wilson coefficients associated to each distribution.

The assumed functional forms at a given reference scale Q_0^2 are:

$$\begin{aligned}
\Delta q_S(x, Q_0^2) &= \eta_S x^{\alpha_S}(1-x)^{\beta_S}(1+\gamma_S+\rho_S\sqrt{x})/N_S \\
\Delta q_g(x, Q_0^2) &= \eta_g x^{\alpha_g}(1-x)^{\beta_g}(1+\gamma_g+\rho_g\sqrt{x})/N_g \\
\Delta q_3(x, Q_0^2) &= \eta_3 x^{\alpha_3}(1-x)^{\beta_3}/N_3 \\
\Delta q_8(x, Q_0^2) &= \eta_8 x^{\alpha_8}(1-x)^{\beta_8}/N_8
\end{aligned}$$

To fix the non-singlet distribution first moments, SU(3)$_f$ is assumed: $\int_0^1(\Delta u - \Delta d)\,dx = F + D = g_a/g_v$ and $\int_0^1(\Delta u + \Delta d - 2\Delta s)\,dx = 3F - D$. Furthermore, for $x > 0.1$, the positivity constraint is used: $|\Delta g(x)| < |g(x)|$ and $|\Delta(s(x) + \bar{s}(x))| < |s(x + \bar{s}(x))|$.

The polarised parton distribution functions resulting from the fit are shown in Fig. 3. The quark polarisation in the nucleon obtained from the fit is $0.26 < \Delta\Sigma < 0.34$ at a reference scale $Q_0^2 = 3$ (GeV/c)^2, in the $\overline{\mathrm{MS}}$ scheme. The gluon polarisation in the nucleon is not well constrained by the data. In Fig. 4 we see that the fit describes our data on $g_1^p(x)$ well, although there are still large uncertainties at low values of x.

The new fit uses more data than our previously published fit [5], and a more complete study on the statisti-

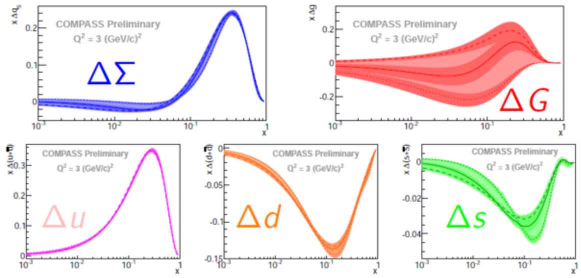

Figure 3: Results of the updated QCD fit of the polarised PDFs using world data. The bands on darker colours correspond to the statistical bands of the three sets of solutions, corresponding to $\Delta G > 0$, $\Delta G < 0$ or ΔG with a node.

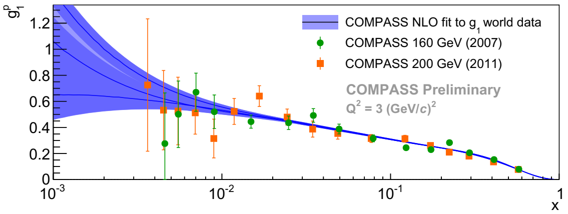

Figure 4: Results of the updated QCD fit of the spin dependent distribution $g_1^p(x)$ function using world data.

cal and systematic errors was done. Three sets of solutions have similarly good χ^2: (1) $\gamma_S = \rho_S = \gamma_g = \rho_g = 0$, (2) $\gamma_S \neq 0$ and $\rho_S = \gamma_g = \rho_g = 0$, and (3) $\gamma_S \neq 0$, $\gamma_g \neq 0$ and $\rho_S = \rho_g = 0$. They yield, respectively, for ΔG: (1) a negative value, (2) a positive value and (3) a value compatible with zero. The dependence of the fit with the reference scale is quite large, as shown in Fig. 5.

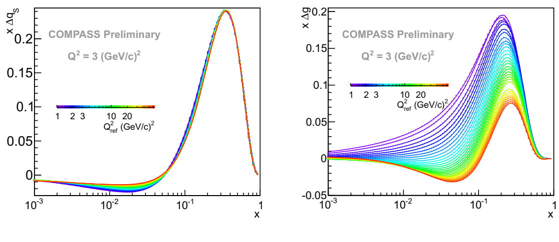

Figure 5: Dependence of fit with the reference scale Q_0^2, for the set of solutions where ΔG is positive at the reference scale $Q_0^2 = 1\ (\mathrm{GeV}/c)^2$.

The new data set also allowed us to update our check on the Bjorken sum rule:

$$\Gamma_1^{NS}(Q^2) = \int_0^1 g_1^{NS}(x, Q^2)\, dx =$$
$$= \int_0^1 \left[g_1(x, Q^2) - g_1^n(x, Q^2)\right] dx = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2).$$

Here g_A/g_V is the ratio of the axial-vector to vector weak coupling constants, which is measured with good precision in the neutron beta decay: $\left|\frac{g_A}{g_V}\right| = 1.2701 \pm 0.0020$. Moreover, C_1^{NS} is the non-singlet coefficient function, which has been calculated up to the third order in $\alpha_S(Q^2)$ in perturbative QCD:

$$C_1^{NS} = \underbrace{1}_{LO} - \underbrace{\left(\frac{\alpha_S}{\pi}\right)}_{NLO} - \underbrace{p_1\left(\frac{\alpha_S}{\pi}\right)^2}_{NNLO} - \underbrace{p_2\left(\frac{\alpha_S}{\pi}\right)^3}_{NNNLO} - \ldots$$

The Bjorken sum rule is a fundamental QCD prediction. It connects observables of the proton, $g_1^p(x, Q^2)$ and of the neutron, $g_1^n(x, Q^2)$, and is therefore a test of $SU(2)_f$. It is decorrelated from ΔG, which is not well known. In addition, it is possible to extract g_1^{NS} from COMPASS data alone, using data taken with deuteron and proton targets, hence reducing systematic effects, by use of

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

with $\omega_D = 0.05 \pm 0.01$. The results obtained, respectively, for the first moment of the non-singlet g_1 and for the ratio of axial to vector coupling constants are:

$$\Gamma_1^{NS}(Q_0^2 = 3\ (\mathrm{GeV}/c)^2) = 0.181 \pm 0.008(\mathrm{stat}) \pm 0.014(\mathrm{syst});$$

$$\left|\frac{g_A}{g_V}\right| = 1.220 \pm 0.053(\mathrm{stat}) \pm 0.095(\mathrm{syst}) \text{ using } C_1^{NS}\big|_{NLO};$$

$$\left|\frac{g_A}{g_V}\right| = 1.256 \pm 0.054(\mathrm{stat}) \pm 0.098(\mathrm{syst}) \text{ using } C_1^{NS}\big|_{NNLO}.$$

The Bjorken sum rule is thus validated within 4%.

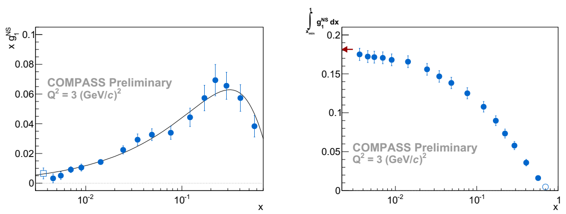

Figure 6: Left: spin dependent distribution function obtained from a QCD fit and used for the test of the Bjorken sum rule. Superimposed are the data points. Right: $\int_{x_{\min}}^1 g_1^{NS}\, dx$ as a function of $x_{\min}$. The open circle corresponds to the contribution taken from the non-singlet fit for the unmeasured range $0.7 < x \leq 1$. The arrow indicates the value of the integral in the full range from 0 to 1.

4. The $Q^2 < 1\ (\mathrm{GeV}/c)^2$ subsample

The study of the low x region is important because this is the region associated to high parton densities, which occur in extreme conditions in the history of the universe. Unfortunately, in fixed target experiments, the kinematic variables x and Q^2 are highly correlated, and accessing low x implies accessing low Q^2, *i.e.* the non-perturbative region of the phase-space, where DGLAP equations are not expected to be valid. However, some theoretical models allow a smooth extrapolation to the low Q^2 and high Q^2 regions [8–10], and should be confronted with experimental results.

COMPASS is now presenting for the first time its preliminary results of A_1^p and g_1^p for $Q^2 < 1$ (GeV/c)^2, both as functions of the Bjorken scaling variable x and of the virtual photon energy ν. These results complement our published results on an isoscalar target (^{6}LiD), of A_1^d and g_1^d [3], thus allowing the extraction of the singlet and non-singlet components of g_1, g_1^S and g_1^{NS}.

The values of $F_2^p(\langle x\rangle, \langle Q^2\rangle)$ were taken from the SMC fit to data or, for low x and Q^2, from a model [11], whereas the values for R were taken from an extension to low Q^2 of a SLAC parameterisation, as described in [3].

The results of the spin asymmetries and g_1^p as functions of x and ν for the sample with $Q^2 < 1$ (GeV/c)^2 are shown in Fig. 7. The first plot in Fig. 7 shows a comparison with previous experimental results. The improvement in precision by COMPASS is well noticeable at the very low x region.

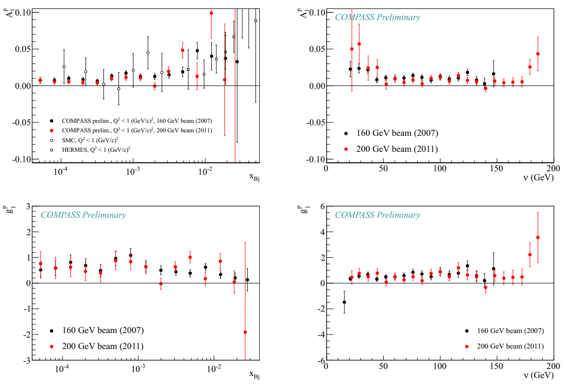

Figure 7: Preliminary COMPASS results for $A_1^p(x)$, $A_1^p(\nu)$, $g_1^p(x)$ and $g_1^p(\nu)$, in the non-perturbative region ($Q^2 < 1$ GeV$^2/c^2$) and, for $A_1^p(x)$, comparison with previous results from other experiments [12–14].

The results obtained with the two different beam energies are compatible within errors. One can see significant asymmetries over three orders of magnitude of x. This is the first time that spin effects are observed at such low values of x. Furthermore, no significant dependence with ν was found.

Numerous tests were performed in search for sources of false asymmetries; theses studies indicate that the systematic errors are smaller than the statistical ones.

The model from [8] includes a prediction for $A_1^p(x)$ for different values of a parameter that accounts for the relative contributions to g_1^p of a VDM term and a partonic term. Our new preliminary results favour values of that parameter (C) between 0 and 4, *i.e.* the two terms having the same sign and similar magnitude.

5. Conclusions

The COMPASS data taken in 2007 and in 2011 with a longitudinally polarised NH_3 target allowed us to extract the double spin longitudinal asymmetries A_1^p and the spin dependent structure function g_1^p, both in the perturbative ($Q^2 > 1$ (GeV/c)^2) and in the non-perturbative ($Q^2 < 1$ (GeV/c)^2) regions. With the data with $Q^2 > 1$ (GeV/c)^2) from 2011, taken with a higher beam energy, it is possible to update the NLO QCD fits using world data and the test of the Bjorken sum rule. With the data with $Q^2 < 1$ (GeV/c)^2), confrontation with predictions from theoretical models is also possible.

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