Recent results from COMPASS muon scattering measurements

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Abstract. A sample of recent results in muon scattering measurements from the COMPASS experiment at CERN will be reviewed. These include high energy processes with longitudinally polarised proton and deuteron targets. High energy polarised measurements provide important constraints for studying the nucleon spin structure and thus permit to test the applicability of the theoretical framework of factorisation theorems and perturbative QCD. Specifically, latest results on longitudinal quark polarisation, quark helicity densities and gluon polarisation will be reviewed.

Keywords: Hadron Structure, Perturbative QCD, Spin Physics
PACS: 14.20.Dh - Proton and Neutron

INTRODUCTION

Since hadrons are composite particles, their spin structure emerges from the dynamics governing the interaction among their constituents. Therefore, studying the nucleon spin provides a testbed for QCD or any other theory of the strong interaction. Furthermore, QCD is applied at high energies within its perturbative regime by means of factorisation theorems. Thus, checking the validity of this whole framework is a test for quantum field theories in general.

Nucleon spin studies are carried on by the COMPASS collaboration at CERN through high energy polarised inelastic lepton scattering. This contribution concentrates on measurements of double spin asymmetries, performed by scattering a longitudinally polarised muon beam, i.e. the direction of the polarisation is parallel to the beam momentum, on longitudinally polarised proton (NH_3) and deuteron (^{6}LiD) targets. Details on the experimental setup can be found in [1].

These measurements give the possibility to study different contributions to the longitudinal component of the nucleon spin S_N. As an ansatz, one can write the simple decomposition for this quantity

$$S_N = \frac{1}{2}\Delta\Sigma + \Delta G + L_z \,, \tag{1}$$

where the three terms on the left-hand side represent the longitudinal polarisation of quarks $\Delta\Sigma$ and gluons ΔG and the longitudinal component of the orbital angular momentum L_z. The formal definition of each of these quantities is not unique but rather depends on how angular momentum operators are defined and on the renormalisation scheme. Nevertheless, Eq. (1) provides, under reasonable assumptions, a starting point for measurements. Although much activity, also within the COMPASS Collaboration, is being undertaken for determining L_z, this subject will not be treated in this contribution which concentrates only on the first two terms of Eq. (1).

At high momentum transfer $Q^2 > 1\,(\mathrm{GeV}/c)^2$ the lepton-nucleon inelastic scattering cross section factorises into a hard part which is calculable in perturbative QCD and a soft part which depends on parton distribution functions (PDFs) and permits to relate the nucleon structure functions to quark and gluon PDFs. The polarised PDFs in turn measure the longitudinal parton polarisation and thus the contribution of parton spins to the nucleon spin.

QUARK POLARISATION

The longitudinal polarisation of quarks can be accessed in polarised deeply inelastic scattering (DIS). At leading order in QED, the hadronic part of the polarisation-dependent inclusive lepton-nucleon inelastic scattering cross section can be generally parametrised in terms of two structure functions g_1 and g_2 which depend on the momentum transfer Q^2 and on the Bjorken scaling variable x.

The structure function g_1 can be accessed through the measurement of the double-polarisation asymmetry $A = (\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow})/(\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow})$, where the arrows indicate parallel or antiparallel beam and target polarisations.

Provided the hard scale $Q^2 > 1\,(\mathrm{GeV}/c)^2$, factorisation is applied and $g_1(x,Q^2)$ can be written in terms of the helicity densities $\Delta q(x,Q^2)$ and $\Delta\bar{q}(x,Q^2)$ of quarks and antiquarks ($q = \mathrm{u,d,s}$ at moderate energy scales, where heavy flavour contributions are negligible). These give the degree of polarisation of (anti)quarks along the nucleon spin.

Measurement of $\Delta\Sigma$

More formally, the first moment $\Gamma_1 = \int dx\, g_1(x,Q^2)$ can be related within this framework to the axial charges of the baryons, because the Δq's are proportional to matrix elements of axial vector current operators. Assuming SU(3) flavour symmetry the isoscalar combination of this moment reads

$$\Gamma_1^N \equiv \frac{1}{2}\left(\Gamma_1^{\mathrm{p}} + \Gamma_1^{\mathrm{n}}\right) = \frac{1}{9} C_1^{\mathrm{S}}(Q^2)\, a_0 + \frac{1}{36} C_1^{\mathrm{NS}}(Q^2)\, a_8 \tag{2}$$

where Γ_1^{p} and Γ_1^{n} refer to proton and neutron, respectively, $C_1^{\mathrm{S,NS}}$ are renormalisation factors, calculable in perturbative QCD, $a_8 = 0.585 \pm 0.025$ is measured in hyperon β-decay and $a_0 = \Delta\Sigma$ in the $\overline{\mathrm{MS}}$ renormalisation scheme. From deuteron measurements, g_1^{N} and its first moment can be extracted and then $\Delta\Sigma$ is determined from Eq. (2) [2].

Combining all available world data of g_1^{d}, the obtained value is

$$\Delta\Sigma(Q^2 = 3(\mathrm{GeV}/c)^2) = 0.30 \pm 0.01_{\mathrm{stat}} \pm 0.02_{\mathrm{syst}}\ , \tag{3}$$

where the systematic uncertainty takes into account the evolution of all data points to a common Q^2.

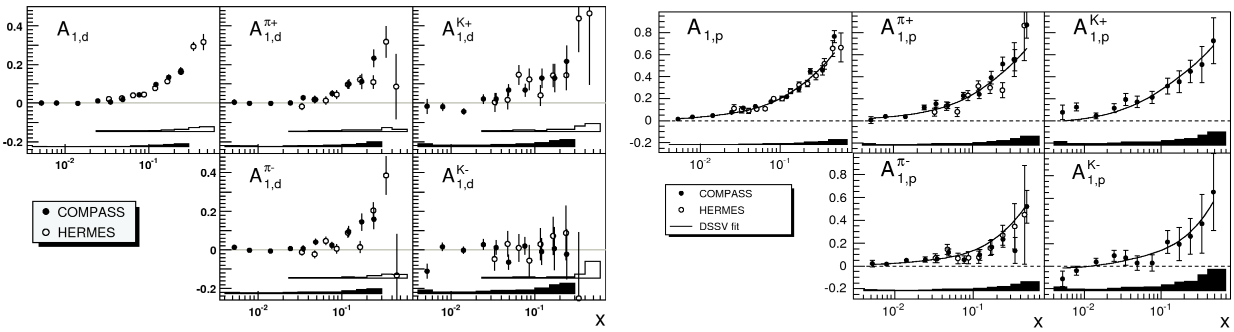


FIGURE 1. SIDIS asymmetries as a function of x from measurements on deuteron (left) and proton (right) targets. $A_{1,\mathrm{d/p}}$ are the corresponding inclusive DIS asymmetries. The HERMES points are from Ref. [5]. The curves on the right are given by the DSSV fit [3].

Flavour separation of quark helicity densities

In order to further investigate the contribution of the quark polarisation to the nucleon spin, one can try to separate the contribution of the different flavours. To this end, one can make use of semi-inclusive DIS (SIDIS) measurements. In this case one or more of the hadrons produced in the inelastic reaction is detected and identified. Knowing the species of the emitted hadrons offers the possibility to tag the flavour of the quark which takes part in the hard scattering, since the different flavours hadronise with different probabilities into different hadron species. Kinematical cuts have to be applied to the detected hadrons, in order to assure that current fragmentation dominates.

At leading order in the strong coupling constant, the double-polarised cross section for the production of a hadron h depends on the unpolarised $q(x)$ and polarised $\Delta q(x)$ PDFs and on the so called fragmentation functions (FF) (D_q^h) in the following way:

$$A_1^h(x,z) = \frac{\sigma_h^{\uparrow\uparrow} - \sigma_h^{\uparrow\downarrow}}{\sigma_h^{\uparrow\uparrow} + \sigma_h^{\uparrow\downarrow}} = \frac{\sum_q e_q^2 \left(\Delta q(x) D_q^h(z) + \Delta\bar{q}(x) D_{\bar{q}}^h(z)\right)}{\sum_q e_q^2 \left(q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z)\right)} . \tag{4}$$

The COMPASS results of the SIDIS asymmetries from both deuteron and proton target measurements for pions and kaons are shown together with the inclusive DIS asymmetries in Fig. 1. The latter provide an additional linear combination of the Δq's. Using all asymmetries together, 10 linear combinations for each x bin are available. Under the assumption $\Delta \mathrm{s} = \Delta\bar{\mathrm{s}}$, 5 unknowns have to be determined. The COMPASS results of Ref. [4] are shown in Fig. 2. In that analysis, the values of the unpolarised PDFs and FFs were taken from the parametrisation of ref. [6] and [7], respectively. One interesting result is the strange quark polarisation. A direct integration of $\Delta \mathrm{S} = \int dx [\Delta \mathrm{s}(x) + \Delta\bar{\mathrm{s}}(x)]$ over the x range covered by measurements is compatible with zero, whereas extracting $\Delta \mathrm{S}$ from inclusive measurements gives a significantly negative result [2]. One possible explanation comes from the poor knowledge of the kaon FFs, entering in Eq. (4). Measurement of FFs from SIDIS data are ongoing at COMPASS, in order to clarify this point.

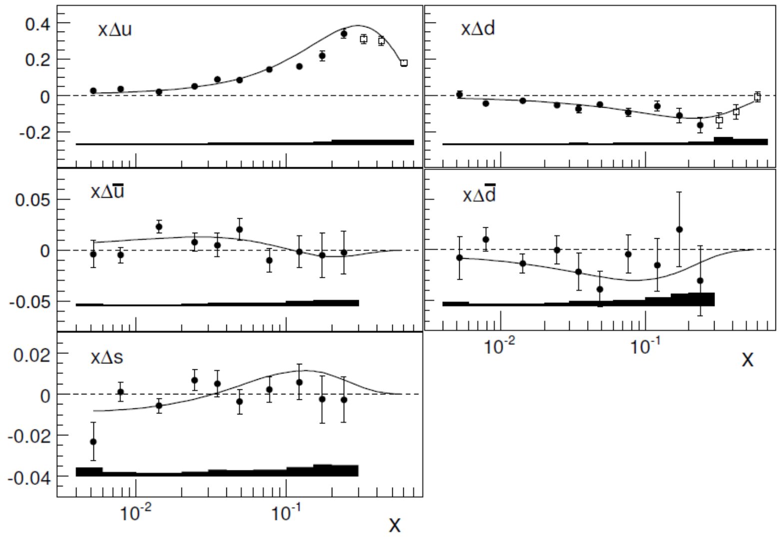
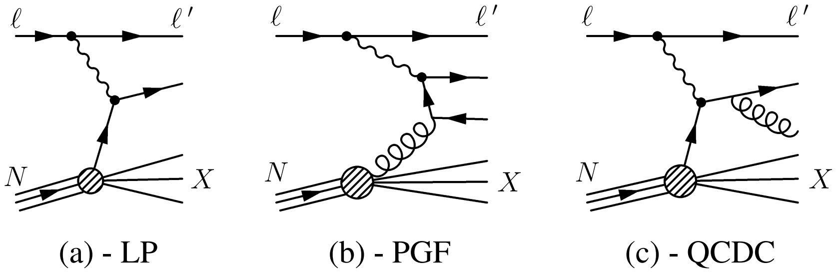


FIGURE 2. Δq distributions from SIDIS and DIS COMPASS data. The curves show the results of the DSSV fit [3].



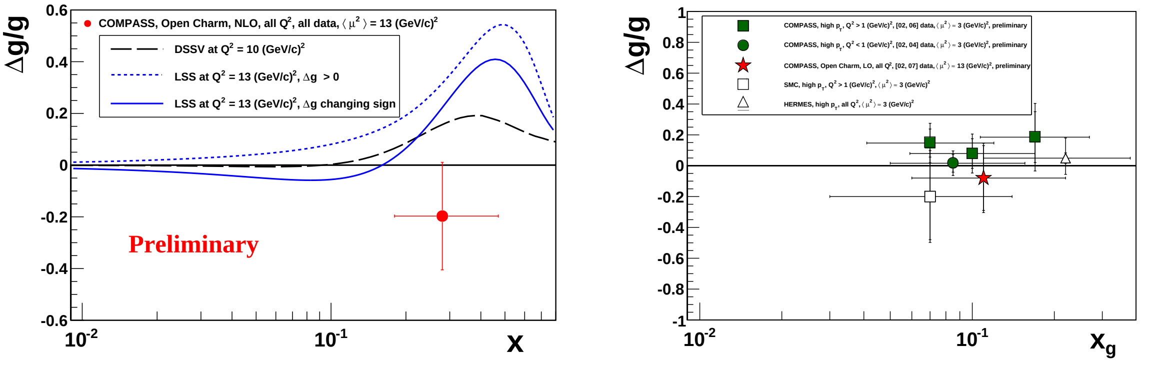
(a) - LP (b) - PGF (c) - QCDC

FIGURE 3. Low α_s order hard processes for hadron production. (a) Leading process, (b) photon-gluon fusion, (c) QCD Compton.

GLUON POLARISATION

In order to measure the contribution of gluons to the nucleon spin, sensitivity to gluon PDFs is needed. "Direct" access can be achieved through hard processes with gluons in the initial state. "Indirect" determinations are obtained studying the scale evolution of the polarised quark PDFs.

In lepton scattering the leading order hard process involving a gluon in the initial state is the so called photon-gluon fusion (PGF) (Fig. 3 (b)). The cleanest way of tagging the PGF process is via the open charm reaction, that is the production of charmed mesons (D^0, D^*). At the scales under consideration, i.e. a few GeV, the c-quark PDF is negligible with respect to the light quark ones, thus the creation of a $c\bar{c}$-pair can happen only at the level of a hard process. In addition, factorisation holds without needing a high Q^2, since the c-quark mass provides a sufficiently large energy scale. The neutral D-mesons are reconstructed by detecting their decay products, one charged pion and one charged kaon, having an invariant mass close to the resonance pole. The gluon polarised PDF ΔG can



(a)

(b)

FIGURE 4. $\Delta G/G$ results vs. x_g. (a) Preliminary COMPASS NLO from open charm. The curves show the global fits [3, 8]. (b) COMPASS results from high p_T and LO open charm [11] together with the SMC [9] and HERMES [10] points.

be accessed through the measurement of the double polarisation asymmetry A^{D} in the quasi-real photoproduction of the $\mathrm{D}^{0,*}$-mesons:

$$\frac{\Delta G}{G} = \frac{1}{P_{\mathrm{T}}\, P_{\mathrm{B}}\, f\, a_{\mathrm{LL}}\, \frac{S}{S+B}}\, A^{\mathrm{D}}\,, \tag{5}$$

where G is the unpolarised gluon PDF and the factors in the denominator of the left-hand side are target polarisation, beam polarisation, target dilution factor, analysing power of the hard process (i.e. the asymmetry of the hard scattering cross section) and the signal-to-total ratio, respectively. This last factor accounts for the combinatorial background in the K-π invariant mass spectrum, used for determining the number of produced D-mesons. Systematics coming from model dependence is weak in this measurement and the statistical uncertainty is the most important limitation. Figure 4-(a) shows the preliminary COMPASS result of a NLO analysis, whereas the LO result [11] is shown in Fig. 4-(b) (star-shaped point). The mean value of x_g, the nucleon momentum fraction carried by the initial state gluon, is larger for the NLO analysis compared to LO, because at NLO gluon bremsstrahlung is taken into account. Both results do not deviate significantly from zero.

Another way of accessing the PGF hard process and thus the polarised gluon PDF is by measuring the double polarisation asymmetry in the production of high transverse momentum (p_T) hadrons, where p_T is the hadron momentum component perpendicular to the momentum transfer from the muon to the target. In this case the hard scale for factorisation is given by p_T itself and all three hard processes in Fig. 3 contribute to about the same magnitude. Note that although LP is of a lower order in the coupling constant with respect to the other diagrams, its contribution to the high p_T hadron production is suppressed, because the intrinsic transverse momenta of partons are small. In order to extract the contribution to the asymmetry coming from PGF, Monte Carlo has to be relied upon heavily, introducing strong model dependence and thus large systematic uncertainties. Other model dependence comes at low Q^2 from the strong contribution of resolved virtual photons, i.e. the effects due to their fluctuations into hadronic states. The COMPASS data set has been split into a low and a high Q^2 ($\lessgtr 1$ $(\mathrm{GeV}/c)^2$) sample and $\Delta G/G$ was extracted from both independently [11]. The results are displayed in Fig. 4-(b) together with the LO open charm result and the SMC [9] and HERMES [10] measurements. All of these measurements are compatible with zero.

CONCLUSIONS

The value for the contribution of the longitudinal quark polarisation to the spin of the nucleon, quoted in Eq. (3), is larger than what was measured by the EMC experiment [12] which gave rise to the so-called “spin crisis” but still does not match the expected value of 0.6, if the quark polarisation had to saturate the nucleon spin. Large contributions were supposed to come from the gluon polarisation but direct measurements suggest rather small values, although the x_g range covered by the measurement is limited and there could be still room for contributions to the first moment $\Delta G = \int_0^1 dx_g \Delta G(x_g)$. What certainly emerges from the COMPASS results on ΔG is that an analysis at NLO is crucial for the determination of the gluon polarisation.

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