Highlights of the COMPASS experiment

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Abstract. An overview of the muon part of the COMPASS results related to the spin structure of the nucleon is given.

Keywords: Polarised electroproduction, nucleon spin structure, QCD
PACS: 13.60Le, 13.88.+e

INTRODUCTION

Intensive studies of the nucleon spin structure have commenced after the European Muon Collaboration, 20 years ago, had published a surprising result that total quark spin constitutes a rather small fraction of the spin of the nucleon, [1]. This result has been later confirmed by several experiments using polarised electrons (muons), different polarised nucleon targets and incident energies from few to few hundred GeV. Possible other nucleon spin carriers, gluons and the parton angular momenta, should thus be investigated. The latter are presently inaccessible experimentally but the former may in principle be determined from the QCD evolution of the polarised inclusive DIS measurements. Contrary to the spin independent case and due to the limited range in the Q^2 values covered by the measurements, this method has a limited sensitivity to the gluon helicity distribution as a function of the gluon momentum fraction x, $\Delta g(x)$. Direct measurements of the gluon polarisation in the nucleon, through semi-inclusive reactions, where the final states select processes with gluons, have thus become an imperative.

The nucleon quark structure at the twist-two level and in the absence of (or after intergating over) the quark transverse momentum, k_T, is fully determined by a set of quark momentum ($q(x)$), helicity ($\Delta q(x)$), and transversity ($\Delta_T q(x)$) distributions. Helicity distribution is a difference of probabilities of quarks having spins parallel and antiparallel to the nucleon spin when the latter is oriented parallel to the virtual photon. Definition of the transversity is similar but refers to the transverse polarisation of the nucleon. Since boosts and rotations do not commute, helicity and transversity need not to be the same in the relativistic (high energy beam) case. Allowing for twists higher than two or for the non-zero k_T of quarks, results in additional distributions needed to describe the quark structure of the nucleon.

The COMPASS experiment at CERN pursues extended studies of the proton spin structure. They include: a direct mesurement of the gluon polarisation (the main goal of COMPASS), extraction of the flavour-separated quark helicity distributions, $\Delta q(x)$, quark transverse spin distributions, $\Delta_T q(x)$, production of the ρ, ϕ, J/ψ vector mesons and Λ hyperons. COMPASS also has an extensive hadron physics programme which has commenced in 2008 and which includes the studies of the Primakoff effect, search for the exotic states (glueballs), charmed hadrons, etc. Here only a part of the muon programme, dealing with the spin structure of the nucleon, will be presented.

THE EXPERIMENT

COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy) [2] is a fixed target experiment, situated at the M2 muon beam line of the CERN SPS. In 2002 it started to take data with a 160 GeV naturally polarised beam of positive muons, incident on a large, longitudinally or transversally polarised deuteron target of solid ^{6}LiD (in 2007 replaced by the solid ammonia, NH_3, as a proton target). The target container has two (three since 2006), oppositely polarised cells, for simultaneous recording of events with different spin orientations. A large, two-stage spectrometer determines the momenta of the scattered muon and of the final state hadrons. Charged particles are identified in the RICH counter and in the hadron calorimeters. In 2006 several elements of the spectrometer were upgraded. COMPASS acceptance extends to very small values of x, albeit at low values of Q^2.

LONGITUDINALLY POLARISED NUCLEON

Inclusive measurements

COMPASS has performed a precise measurement of the longitudinal virtual photon–nucleon asymmetry covering the low x region at both $Q^2 > 1$ (GeV/c)^2 ($0.004 < x < 0.7$, based on the 2002–2004 data) [3], Fig.1, and $Q^2 < 1$ (GeV/c)^2 (0.000 04$< x < 0.025$, based on the data collected in 2002–2003) [4]. These measurements permitted to extract the deuteron spin structure, $g_1^d(x,Q^2)$. The g_1^d values are consistent with zero for $x <$ 0.03, independently of the Q^2 interval. A new QCD fit of the world g_1^d data at NLO was performed and yielded two solutions with either $\Delta g(x) > 0$ or $\Delta g(x) < 0$, equally well describing the data. In both cases, the first moment of $\Delta g(x)$ is of the order 0.2 – 0.3 in absolute value at $Q^2 = 3(\text{GeV}/c)^2$ but the shapes of the distributions are very different. An accurate evaluation of the first moment of $g_1^d(x)$, and of the matrix element of the singlet axial current, a_0 was also obtained. In the $\overline{\text{MS}}$ renormalisation scheme the a_0 is the same as the quark spin contribution to the nucleon spin. At $Q^2 = 3$ (GeV/c)^2 it is equal to a_0 = 0.30 $\pm$ 0.01 (stat.) $\pm$ 0.02 (evol.). In the $Q^2 \to \infty$ limit, the first moment of the strange quark distribution $(\Delta s(x) + \Delta\bar{s}(x))$ = –0.08 $\pm$ 0.01 (stat.) $\pm$ 0.02 (syst.).

Semi–inclusive measurements

Quarks and antiquarks of the same flavour equally contribute to g_1 and thus the inclusive data do not allow to separate valence and sea contributions to the nucleon spin. Therefore additional, semi-inclusive spin asymmetries for positive and negative hadrons in the final state, h^+ and h^- were measured on the same data set as the inclusive results mentioned above [5].

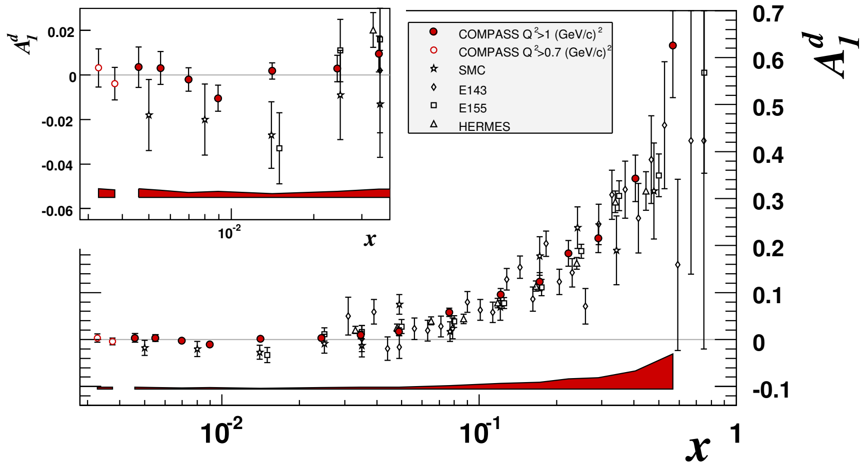

FIGURE 1. The asymmetry $A_1^d(x)$ as measured by COMPASS together with previous results from SMC, HERMES, SLAC E143 and E155, at $Q^2 > 1(\mathrm{GeV}/c)^2$. Only statistical errors are shown. The shaded band marks the size of the COMPASS systematic errors. Figure comes from [3].

In the LO QCD the difference asymmetry, $A^{h^+-h^-}$ measures the valence quark polarisation and provides an evaluation of the first moment of $\Delta u_v + \Delta d_v$ which was found to be equal to 0.41 ± 0.07 (stat.) $\pm\, 0.06$ (syst.) at $Q^2 = 10(\mathrm{GeV}/c)^2$. When combined with the first moment of g_1^d, this result favours a non-symmetric polarisation of light quarks, $\Delta\bar{u}(x) = -\Delta\bar{d}(x)$ at a confidence level of two standard deviations, in contrast to the often assumed symmetric scenario $\Delta\bar{u}(x) = \Delta\bar{d}(x) = \Delta\bar{s}(x) = \Delta s(x)$.

Recently the whole deuteron sample, collected in 2002 – 2006 has been used to extract the semi-inclusive asymmetries for the identified positive and negative pions and kaons, down to x = 0.004 [6]. Very desirable here is a precise evaluation of the $\Delta s(x) + \Delta\bar{s}(x)$ and of its first moment, now conditional on the fragmentation functions. The 2007 proton data, currently analysed, will further help in the accurate quark flavour helicity separation.

Measurement of $\Delta g/g$

The gluon polarisation in the nucleon is determined from the cross-section asymmetry for the virtual photon–gluon fusion (PGF), $\gamma^* g \to q\bar{q}$, see [7] for details. The PGF process was selected depending on the products of the $q\bar{q}$ pair fragmentation, either through production of hadron pairs with high transverse momenta, p_T (typically 1–2 GeV/c), with respect to the virtual photon direction or through the open-charm production, *i.e.* when $q \equiv c$ and the $c\bar{c}$ pair fragments into a pair of the D mesons. The former process results in a very high statistics but relies on Monte Carlo generators simulating the QCD processes; the latter provides the cleanest sample of interesting events albeit at a low rate.

The average gluon polarisation in a limited range of x, $\langle \Delta g/g \rangle_x$ (here $g(x)$ is the spin-averaged gluon distribution in the nucleon), has been determined from the open-charm production assuming that it is dominated by the PGF mechanism yielding a $c\bar{c}$ pair which fragments mainly into D mesons. This method has the advantage that in the lowest order of the α_s there are no other contributions to the cross section. Only one charmed meson is required in every event. It was selected through its decay in one of the two channels: $D^*(2010)^+ \rightarrow D^0\pi^+_{slow} \rightarrow K^-\pi^+\pi^+_{slow}$($D^*$ sample) and $D^0 \rightarrow K^-\pi^+$(D^0 sample) and their conjugates. To reduce the large combinatorial background only the RICH–identified $K\pi$ pairs were used. The resulting mass spectra for the D^0 and the D^* samples with one $K\pi$ pair in the mass range –400 MeV/$c^2 < M_{K\pi} - M_{D^0} <$ 400 MeV/c^2 are displayed in Fig. 2.

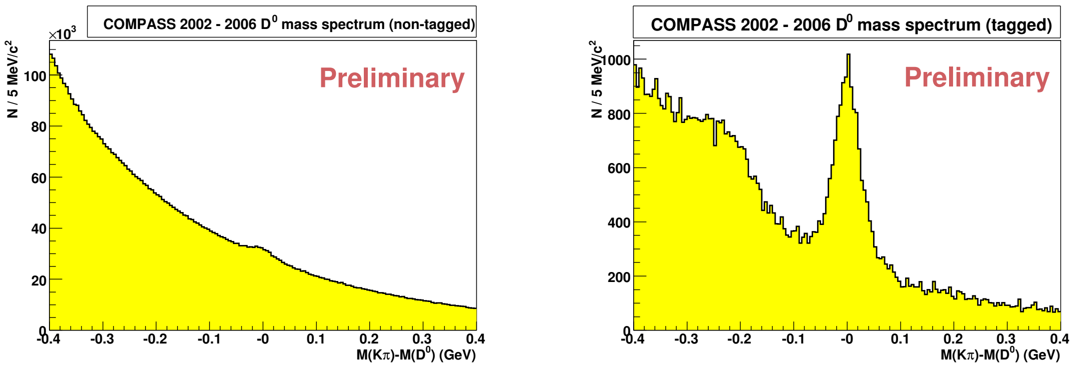

FIGURE 2. Invariant mass distributions of the Kπ pairs for the D^0 sample (left) and the D* sample (right).

In this analysis the perturbative scale μ^2 for the selected events is not given by Q^2 but by the $4(m_c^2 + p_T^2)$, m_c being the mass of the charm quark and p_T its transverse momentum with respect to the virtual photon. A leading QCD approach and the whole 2002–2006 data set give an average gluon polarisation of $\langle \Delta g/g \rangle_x$ = –0.49 $\pm$ 0.27 (stat.) $\pm$ (syst.) at a scale $\mu^2 \approx$ 13 (GEV/c)^2 and at an average gluon momentum fraction $\langle x \rangle \approx$ 0.11 [8].

The $\langle \Delta g/g \rangle_x$ has also been determined from the events which contain at least two high-p_T hadrons in addition to the incoming and outgoing muon. The cross-section helicity asymmetry for those events contains an asymmetry from the background processes in addition to the contribution from the PGF. This background asymmetry and the PGF contribution were estimated by a simulation which introduces a model dependence in the evaluation of $\langle \Delta g/g \rangle_x$. The $Q^2 > 1$(GeV/c)^2 and the $Q^2 < 1$(GeV/c)^2 events were considered separately since different generators (LEPTO and PYTHIA respectively) were used to model the interactions. In the latter case, the hard scale was set by the (high) p_T value of the final state hadrons, $\mu^2 \approx$ 3 (GeV/c^2) and apart of the direct processes also the resolved photon reactions were simulated.

COMPASS results on $\langle \Delta g/g \rangle_x$ are collected in Fig. 3 where also the measurements by SMC and HERMES are shown. The horizontal bars mark the range in x for each mesurement, the vertical ones give the statistical precision and the total errors (if available). All measurements are situated around $x \sim$0.1 and point towards a small gluon polarisation at that value of x. This, in principle, does not exclude a large value of the first moment of the gluon helicity distribution.

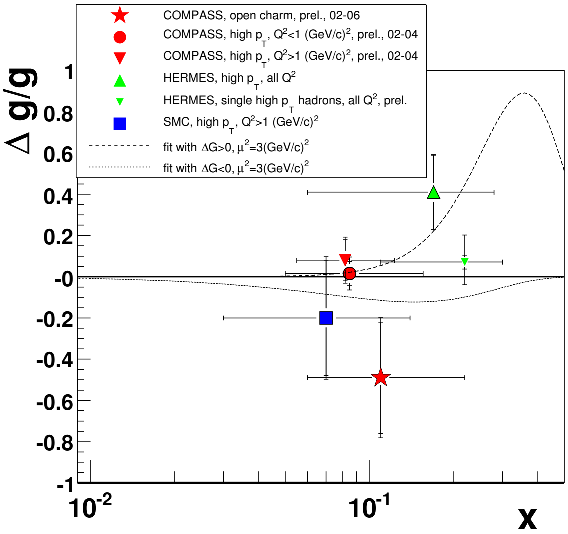

FIGURE 3. Compilation of the $\langle \Delta g/g \rangle_x$ measurements from the open charm and high p_T hadron pair production. The curves display two parametrisations from the COMPASS NLO QCD analysis, [3].

TRANSVERSALLY POLARISED NUCLEON

A full sample of the data taken with a transversally polarised deuteron target has been analysed. Several asymmetries (e.g. Λ polarisation, hadron pair production) were measured in this configuration, [10]. The respective distribution functions are sensitive to such quantities as spin dependent fragmentation functions, interference fragmentation function, etc. Particularly important are asymmetries due to the Collins and Sivers mechanisms, the former being due to the combined effect of $\Delta_T q$ and a chirally–odd spin–dependent fragmentation function and the latter to a correlation between the intrinsic transverse momentum of a quark and the transverse polarisation of the nucleon.

For the deuteron target and for all final state particles (charged pions, charged kaons, neutral kaons) both Collins and Sivers asymmetries are small, compatible with zero within the statistical errors. This result is in line with the previously published results for not identified charged hadrons, and with the expected cancellation between the u- and d-quark contributions but it is at variance with the signal of both Collins and Sivers effects seen by HERMES at lower energies and on the proton target[1]. First global analyses of the transverse parton distributions have already been performed and point towards small values of $\Delta_T q$ as compared to Δq.

Preliminary results obtained by COMPASS for the (part of the) data taken in 2007 with the transversely polarised proton target show a hint of a nonzero Collins asymmetry

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[1] Recently also the BELLE Collaboration observed a signal of the Collins effect.

at the x values larger than 0.1, Fig.4. The Sivers asymmetries stay compatible with zero. These facts await confirmation with a larger statistics, cf. [10].

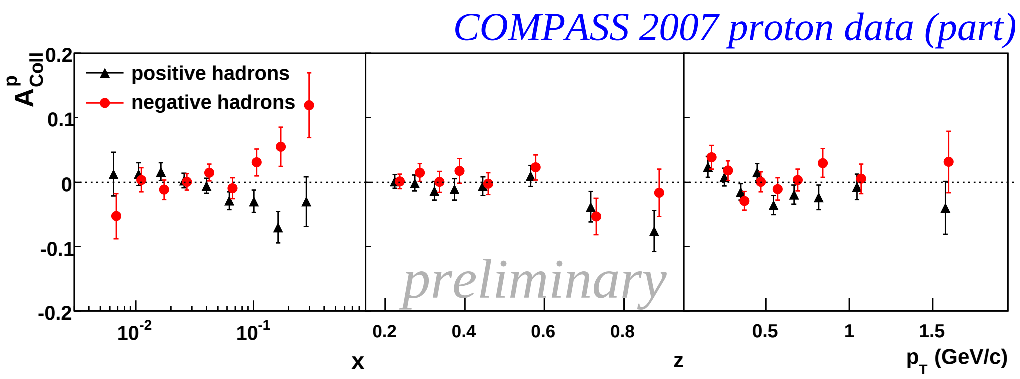

FIGURE 4. COMPASS preliminary results for the Collins asymmetry for the proton.

OUTLOOK

Polarised muon–proton and muon–deuteron scattering studied by COMPASS resulted in a wide spectrum of new results on the longitudinal and transverse spin phenomena. Average gluon polarisation around $x \sim 0.1$ is small and its first moment is limited to about 0.2–0.3 in absolute value by the scaling violation in the g_1^d. A large value of first moment of the gluon polarisation, i.e. a large gluon polarisation contribution to the nucleon spin, is thus unlikely. Flavour symmetric polarised sea seems disfavoured. Flavour separation of quark helicities, down to low values of x is in progress. Transversity effects appear weak but nonetheless may substantially influence global analyses of the transverse parton distributions, especially after the whole available data statistics is analysed.

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