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Spin physics at COMPASS

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Summary. — COMPASS is a fixed-target experiment at the CERN SPS. The COMPASS physics program is dedicated to the study of the nucleon spin structure and of hadron spectroscopy. The nucleon spin structure is investigated by means of Deep Inelastic Scattering reactions, using a 160 GeV muon beam, impinging on a solid-state target. The recent results on the gluon contribution to the nucleon spin, on the helicity distributions for different quark flavors and on the transverse spin effects are presented.

PACS 13.60.-r – Photon and charged-lepton interactions with hadrons.
PACS 13.88.+e – Polarization in interactions and scattering.
PACS 13.60.Hb – Total and inclusive cross sections (including deep-inelastic processes).
PACS 13.87.Fh – Fragmentation into hadrons.

1. – The COMPASS experiment

COMPASS [1] is a fixed-target experiment at the CERN M2 beam line. The main aim of COMPASS is the study of the hadronic structure, using two different sources of information: nucleon spin structure and hadron spectroscopy. The nucleon spin structure is studied by means of Deep Inelastic Scattering (DIS) reactions, using a high energy muon beam; hadron spectroscopy measurements are performed using pion and proton beams. From the beginning of physics data taking in year 2002 until now, two years have been dedicated to hadron spectroscopy measurements, six years to spin physics. In order to cope with all the requirements for the different measurements, the COMPASS apparatus is highly flexible, and is capable to stand high luminosity, to cover wide kinematic acceptance and to provide particle identification.

For the spin physics program, a positive muon beam of momentum 160 GeV/c, with natural polarization of the order of 80% is used. The target is a solid-state target, polarized via Dynamic Nuclear Polarization. Two types of target materials have been used up to now. To access the deuteron spin structure, ^{6}LiD has been used, with a fraction of polarizable material of the order of 35% and polarization values around 50%. NH_3 has been used to study the proton spin structure; the fraction of polarizable material is lower

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in this case, 15%, but the polarization can reach higher level, around 80%. The target is segmented in cells, polarized in opposite ways in order to take data with different spin configurations with the same experimental conditions and thus lower the systematic effects in the measurements. Upstream of the target, fast detectors with very high resolution are used in order to measure the direction of the incoming beam track. Downstream the target, the scattered muon and the particles produced in the semi-inclusive reactions (SIDIS) are detected by two spectrometers, built around two analyzing magnets. The large acceptance of the first spectrometer allows to detect particles with angles up to 180 mrad, while the second spectrometer is used for the detection of high-momentum tracks at small angles. Several types of trackers are used in order to match the rates at different radial distances from the beam line. Particle identification (PID) is provided by muon filters, electron and hadronic calorimeters and a RICH detector in the first spectrometer.

2. – Spin physics

Spin physics research investigates how the spin of the nucleon is distributed among its constituents. This field of physics has received much attention after the surprising result of the EMC experiment in the late 80s [2], that the quarks account for only a small part of the nucleon spin. Much development in the theory and phenomenology of this field was done in order to explain the new finding. In particular it became clear that also the gluon contribution and the quark and gluon orbital angular momentum could have an important role; the nucleon spin decomposition taking into account all these contributions reads

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g, \tag{1}$$

where $\Delta\Sigma$ and ΔG are the helicities of quarks and gluons, and L_q and L_g are the quark and gluon orbital angular momenta. While measurements of the orbital angular momenta are for the moment out of reach, $\Delta\Sigma$ is known with good accuracy, and first information on ΔG have become available in recent years.

2˙1. *Measurements of* $\Delta\Sigma$ *and* Δq. – Using polarized beam and target, it is possible to measure the double spin asymmetries in inclusive DIS reactions, obtained comparing the event yields with parallel and antiparallel beam and target spins. From the measured asymmetries, the spin structure function $g_1(x, Q^2)$ can be extracted. Thanks to the high energy beam, COMPASS is the only experiment at the moment that can provide a measurement of g_1 in a wide x range, from 0.003 to 0.7. In particular the handle at the low-x region with high statistics allows to evaluate the first moment of the spin structure function with a low systematic error. The measurement of $g_1(x, Q^2)$ in different kinematic ranges is important since perturbative QCD analyses allow to extract $\Delta\Sigma$ and ΔG from the Q^2 dependence. The COMPASS results have an important role in this context since they are at higher Q^2 values than the other existing DIS data. Despite the different Q^2, the g_1 values measured by COMPASS on deuterium [3] and proton targets [4] are in agreement with the existing results from other experiments, implying a small Q^2 dependence at fixed x of g_1.

The wide x range accessed by COMPASS allows the evaluation of the first moment of g_1 and the extraction of $\Delta\Sigma$ from COMPASS data only. From the analysis of the deuterium data [3], the quark contribution to the nucleon spin has been found $\Delta\Sigma = 0.33 \pm 0.03(\text{stat})$. This value is in good agreement with all the measurements from

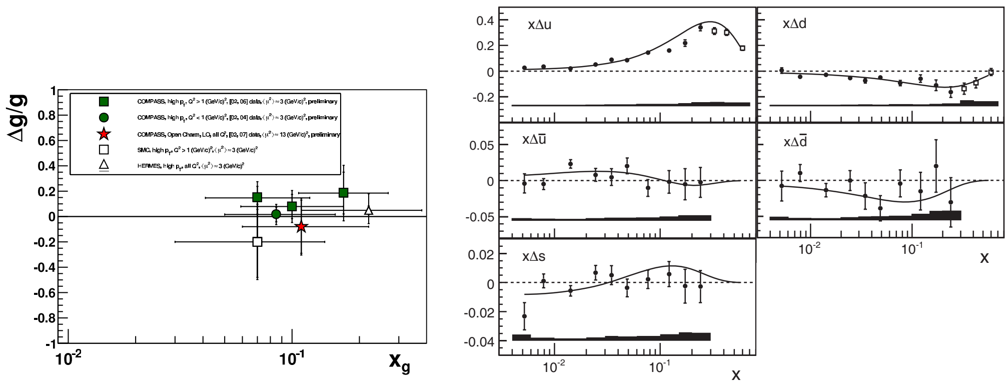

Fig. 1. – (a) The COMPASS results for $\Delta g/g$ compared with the measurements from SMC and HERMES experiments. (b) The quark helicity distributions $x\Delta u$, $x\Delta d$, $x\Delta\bar{u}$, $x\Delta\bar{d}$, $x\Delta s$ at $Q2 = (3\,\mathrm{GeV}/c)2$ as a function of x, extracted with a flavor separation analysis from COMPASS data.

other experiments and global fits. From the first moment of g_1, with the assumption of SU_3 symmetry and information from hyperon decay, it is also possible to extract the value of the strange quark contribution to the spin, that was found $\Delta s + \Delta\bar{s} = -0.08 \pm 0.01(\mathrm{stat}) \pm 0.02(\mathrm{syst})$.

Further information on the quark helicity distribution can be achieved from SIDIS channels, thanks to the correlation between the flavor of the struck quark and the produced hadron type, described by the fragmentation functions (FF). From the measurement of double spin asymmetries for different hadron types on different targets, the helicity Parton Distribution Function (PDF) for the different quark and antiquark flavors can be extracted.

In COMPASS the asymmetries on pions and kaons, identified with the RICH detector, have been measured both on the deuteron [5] and on the proton data [6]. The COMPASS result is the first measurement for the kaon asymmetries on proton. The good agreement with the existing asymmetries from the HERMES experiment, measured at a lower Q^2 value, implies a small Q^2 dependence at fixed x of the SIDIS asymmetries.

A flavor separation analysis at leading order has been performed using the COMPASS kaon and pion asymmetries, as well as the inclusive ones, on proton and deuteron targets [6]. The quark and antiquarks helicity PDFs have been extracted independently in the different x bins; the results are shown in fig. 1. The antiquark distributions are compatible with zero within the statistical accuracy; the strange quark helicity is also compatible with zero in the measured range, a result that is at variance with the inclusive measurement, giving a negative value. The apparent discrepancy is an interesting finding that could be explained with the present poor knowledge of the strange FF, that enter in the flavor separation analysis, or with a changing sign shape of the strange PDF, as used in some recent global fits of the DIS and SIDIS measurements. From the integrals of the helicity PDFs, a value of $\Delta\Sigma$ in agreement with the inclusive result is found.

2·2. *Measurements of* ΔG. – The gluon polarization can be measured in SIDIS reactions through Photon-Gluon Fusion (PGF) processes, in which a quark-antiquark pair is produced. To tag the PGF processes in the data, events with a charmed particle in the final state [7] namely D^0 meson, are selected. Even though the channel has limited

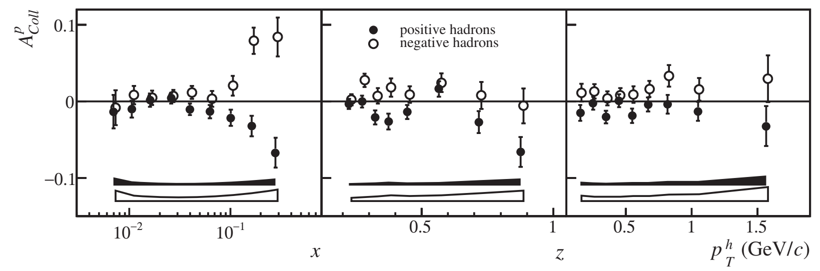

Fig. 2. – Collins asymmetries for positive and negative hadrons on proton target as a function of x, z and p_T.

statistics, it allows to access the PGF processes in a clean way, since the intrinsic charm in the nucleon is negligible. Another tag is done selecting in the final state two hadrons with high transverse momentum with respect to the virtual photon direction [8]; this channel has higher statistics with respect the open charm channel, but relies on a MC sample in order to evaluate the level of the background contribution.

The COMPASS results for $\Delta g/g$ are shown in fig. 1(a), compared with the other existing measurements from the SMC and the HERMES experiments. It can be seen that all values are compatible with zero within the statistical accuracy. Despite the limited covered range in x_g, spanning from 0.05 to 0.3, the measurements allow to exclude values for the integral ΔG larger than 0.3 in absolute value. A small contribution of the gluon polarization has been also confirmed independently by polarized proton collision experiments at RHIC.

3. – Transverse spin

A complementary and much recent development in spin physics is provided by the study of the transverse spin phenomena. In order to describe the inner structure of the nucleon, at leading order three PDFs are needed: the well-known momentum and helicity PDFs, and the transversity PDF, $\Delta_T q$. The transversity PDF describes the probability, in a transversely polarized nucleon, of finding a quark with spin parallel to the nucleon spin; it is different from the helicity PDF due to the relativistic motion of the light quarks. One way to access the transversity PDF is in SIDIS reactions, via the so-called "Collins effect", a left-right asymmetry in the hadron distribution produced by a transversely polarized quark. The Collins asymmetry is proportional to the transversity PDF convoluted with the Collins FF, describing the correlation between the quark spin and the momentum of the produced hadron.

In 2005 the HERMES experiment measured for the first time the Collins asymmetries on a proton target [9]; the asymmetries were found different from zero and provided the first evidence for the fact that both transversity and the Collins FF were different from zero. In parallel first measurement of Collins asymmetries on a deuterium target were provided by COMPASS [10-12]; the asymmetries were found to be compatible with zero within the statistical accuracy, at the level of 1%. The two different results from the experiments were explained in a single unified picture by a global fit [13], together with Belle asymmetries in e^+e^- reactions, giving an independent access to the Collins FF. More recently, COMPASS has provided also measurements on a proton target [14], shown in fig. 2 for positive and negative hadrons as a function of x, the relative energy of the hadron z and the transverse momentum p^h_T. At small x, a region uncovered by HERMES, the asymmetries are compatible with zero. In the valence region, the asymmetries are different from zero and of opposite sign for positive and negative hadrons. The results are compatible with those of HERMES, a non-obvious result due to the different kinematic range covered by the two experiments.

The Collins effect is not the only source of azimuthal asymmetries in SIDIS. When considering the quark intrinsic transverse momentum, other Transverse Momentum Dependent PDFs are needed in order to describe the hadron structure. These TMDs describe the correlations between the momentum and the spin of the parton or of the hadron, and give origin to different modulations in the SIDIS cross section, both in the unpolarized part and in the part depending on the target polarization. All these azimuthal modulations have been measured by COMPASS [15-17].

4. – Conclusions

After more than 20 years from the EMC result and the so-called spin crisis, the research in spin physics is still active and interesting. The quark contribution to the nucleon spin is known with a good level of precision, and SIDIS data allow the decomposition in different flavors. First direct measurements of the gluon polarization have been provided in the recent years, and give evidence of a small contribution of ΔG to the nucleon spin. Measurements of deeply Virtual Compton Scattering channels, also proposed by COMPASS in the near future [18], are promising in order to access the total angular momentum of quarks and gluons. Also, it has become clear that transverse spin and momentum effects are not negligible and give rise to sizeable azimuthal asymmetries in SIDIS reactions, for which the first experimental results have been provided in recent years.

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