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Spin Physics at COMPASS

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Abstract. The COMPASS experiment is a fixed target experiment at the CERN SPS using muon and hadron beams for the investigation of the spin structure of the nucleon and hadron spectroscopy. The main objective of the muon physics program is the study of the spin of the nucleon in terms of its constituents, quarks and gluons. COMPASS has accumulated data during 6 years scattering polarized muons off longitudinally or transversely polarized deuteron (^{6}LiD) or proton (NH_3) targets.

Results for the gluon polarization are obtained from longitudinal double spin cross section asymmetries using two different channels, open charm production and high transverse momentum hadron pairs, both proceeding through the photon-gluon fusion process. Also, the longitudinal spin structure functions of the proton and the deuteron were measured in parallel as well as the helicity distributions for the three lightest quark flavours.

With a transversely polarized target, results were obtained with proton and deuteron targets for the Collins and Sivers asymmetries for charged hadrons as well as for identified kaons and pions. The Collins asymmetry is sensitive to the transverse spin structure of the nucleon, while the Sivers asymmetry reflects correlations between the quark transverse momentum and the nucleon spin.

Recently, a new proposal for the COMPASS II experiment was accepted by the CERN SPS which includes two new topics: Exclusive reactions like DVCS and DVMP using the muon beam and a hydrogen target to study generalized parton distributions and Drell-Yan measurements using a pion beam and a polarized NH_3 target to study transverse momentum dependent distributions.

1. Introduction

COMPASS is a fixed target experiment at the CERN SPS accelerator with a wide physics program focused on the nucleon spin structure and on hadron spectroscopy. COMPASS investigates the spin structure of the nucleon in semi-inclusive deep-inelastic scattering. A longitudinally polarized 160 GeV muon beam is scattered off a longitudinally or transversely polarized NH_3 or ^{6}LiD target. The scattered muon and the produced hadrons are detected in a 50 m long wide-acceptance forward spectrometer with excellent particle identification capabilities [1]. A variety of tracking detectors are used to cope with the different requirements of position accuracy and rate capability at different angles. Particle identification is provided by a large acceptance RICH detector, two electromagnetic and hadronic calorimeters, and muon filters.

The polarized ^{6}LiD target is split into two cylindrical cells along the beam direction. The two cells are polarized in opposite direction. The polarized NH_3 target consists of three cells (upstream, central and downstream) of 30, 60 and 30 cm length, respectively. The upstream and downstream cells are polarized in the same direction while the middle cell is polarized oppositely.

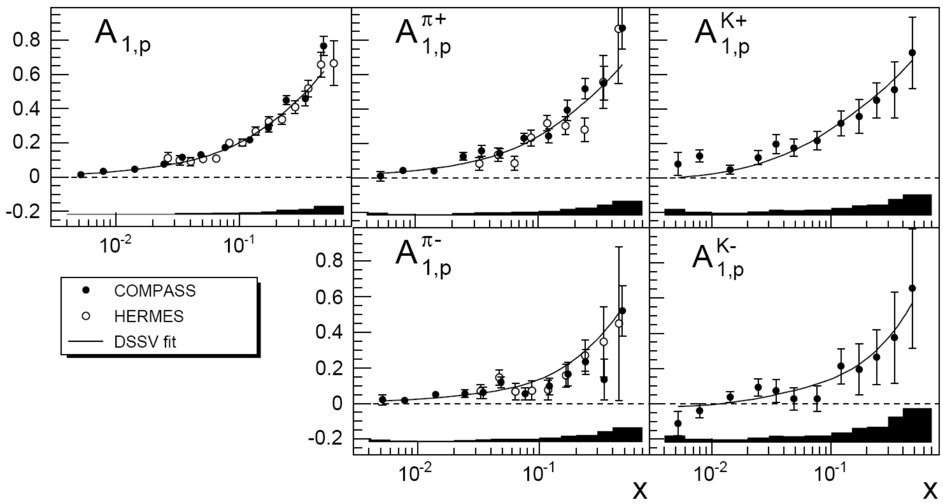

Figure 1. Inclusive, $\pi^{\pm}$ and $K^{\pm}$ longitudinal double-spin asymmetries on the proton (filled circles: COMPASS results from Ref. [2]). For comparison the HERMES results from Ref. [4] (open circles) and the DSSV fit prediction from Ref. [6] are shown.

2. Longitudinal Spin Structure of the Nucleon

The longitudinal spin structure of the nucleon is investigated by measuring double spin asymmetries in inclusive (DIS) and semi-inclusive (SIDIS) deep-inelastic scattering on a longitudinally polarized target. SIDIS asymmetries, where pions and kaons are detected, are sensitive to the individual quark flavours. The most recent proton asymmetries measured in 2007 [2, 3] are shown in figure 1 together with the results from the HERMES experiment [4, 5].

From the semi-inclusive asymmetries, a leading order QCD extraction of the polarized parton distribution functions is possible. The measured asymmetries $A_1^h(x, z)$ for a hadron h can be written as the product of polarized parton distribution functions $\Delta q(x)$ and fragmentation functions $D_q^h(z)$, summed over all quark q and anti-quark $\bar{q}$ flavours:

$$A_1^h(x, z) = \frac{\sum_{q,\bar{q}} e^2 \cdot \Delta q(x) \cdot D_q^h(z)}{\sum_{q,\bar{q}} e^2 \cdot q(x) \cdot D_q^h(z)} \tag{1}$$

The fragmentation functions are taken from the parametrization of DSS [8]. For the unpolarized parton distribution functions $q(x)$ in the denominator the MRST parametrization [9] is used.

In a least-squares fit to the ten inclusive and semi-inclusive asymmetries from proton- and deuteron data, the quark helicity distributions for $u-$, $d-$ and $s-$quarks are extracted. Since it was observed that in the measured x-range the extracted strange and anti-strange quark helicity distributions are compatible, the assumption $\Delta s = \Delta \bar{s}$ has been made to further reduce the number of parameters. The results of the fit are then shown in figure 2. The curves in figures 1 and 2 are the results of a global fit of the DSSV group using previously existing data at Next-to-Leading Order (NLO) [6, 7].

The u-quark helicity distribution is positive with its maximum in the valence quark region and the d-quark distribution is negative in the same x-region. The anti-quark distributions $\Delta\bar{u}$ and $\Delta\bar{d}$ do not show a significant x-dependence. $\Delta\bar{u}$ is consistent with zero, while $\Delta\bar{d}$ is slightly negative. The flavour asymmetry of the helicity distribution of the sea, $\Delta\bar{u} - \Delta\bar{d}$ has been extracted from the fit. The first moment determined in the x-range of the experimental data, is

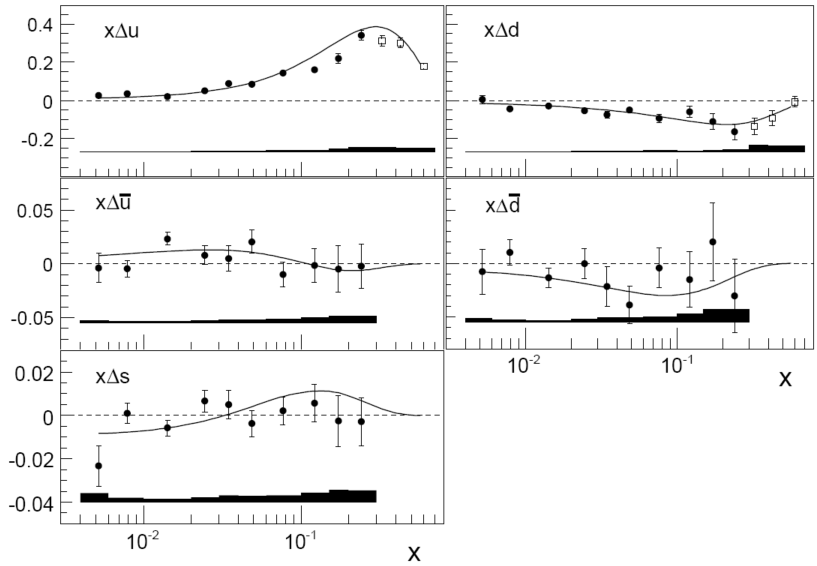

Figure 2. Quark helicity distributions $x\Delta u$, $x\Delta d$, $x\Delta\bar{u}$, $x\Delta\bar{d}$ and $x\Delta s$ at $Q_0^2 = 3$ (GeV/c)^2 as a function of x. The bands show the systematic uncertainty of the measurement. The curves are predictions of DSSV calculated at NLO [6].

found to be

$$\int_{0.004}^{0.3}(\Delta\bar{u} - \Delta\bar{d})dx = -0.03 \pm 0.03(stat.) \pm 0.01(syst.) \quad (2)$$

and therefore compatible with zero. The model prediction $\Delta\bar{u} - \Delta\bar{d} \simeq \bar{d} - \bar{u}$ of [10, 11] is not confirmed by the experimental data. New COMPASS data on a longitudinally polarized proton target have been collected in 2011 and will allow the statistical precision of the measurements to be increased.

3. Gluon polarization in the nucleon

At COMPASS, the gluon polarization is directly measured by determining the longitudinal double-spin asymmetry in the photon-gluon fusion process (PGF). PGF events are searched for in two different channels: the open charm production channel, where an outgoing charm quark is identified by the production of D^0 mesons and the high-p_T hadron pair channel, where the two outgoing quarks hadronize with high transverse momentum. The open charm channel provides a clean signature of PGF but with limited statistics. For the high-p_T channel, statistics is large, but the background from other processes is higher.

Open-charm events are selected by reconstructing D^0 and D^* mesons from their decay products. For this analysis, all data collected on ^{6}LiD and NH_3 from 2002 until 2007 have been used. The particle identification is performed using the RICH detector. For the D^* sample, the D^0 mesons are tagged by the detection of a low momentum pion from the $D^* \rightarrow D^0 + \pi_S$ decay. For untagged events, the decay channel $D^0 \rightarrow K+\pi$ has been used. The total number of D^0 mesons is about 14.000 (10.000) and 46.000 (19.000) in the D^* and D^0 samples collected on ^{6}LiD (NH_3) targets.

The final result for the gluon polarization from open charm production is given by the weighted mean of the results for D^0 and D^* as [12]

$$\Delta g/g = -0.08 \pm 0.21(stat.) \pm 0.11(syst.) \quad (3)$$

with $< x >= 0.11$ at a scale $\mu^2 \approx 13$ (GeV/c)^2.

In the high-p_T hadron pair channel, other competitive processes contribute to the asymmetry. These are the leading order process $\gamma+q \rightarrow q$ and the QCD-Compton process $\gamma+q \rightarrow \gamma+q(g+q)$.

Resolved photons are strongly suppressed by selecting events with $Q^2 > 1$ (GeV/c)^2. A neural network is then used to assign for each event a probability for the three processes (PGF, QCD-Compton or LO), trained on the results of a Monte Carlo simulation [13]. The preliminary result for the gluon polarization for high-p_T hadron pairs with $Q^2 > 1(\mathrm{GeV/c})^2$ is

$$\Delta g/g = 0.13 \pm 0.06(stat.) \pm 0.06(syst.) \tag{4}$$

at $< x_g >= 0.09^{+0.8}_{-0.4}$ at an average scale of $\mu = 3(\mathrm{GeV/c})^2$. The result has been measured in three bins of x_g to check for a possible x_g dependence of the gluon polarization. It is displayed in figure 3 together with the measurements of SMC [14] and HERMES [15, 16] and two parameterizations from a COMPASS NLO QCD analysis of the world data [17]. The results favor small values of $\Delta g/g$.

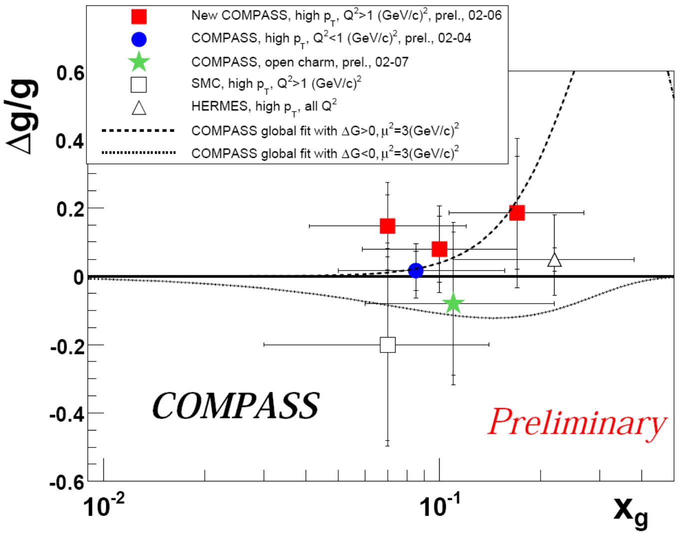

Figure 3. $\Delta g/g$ measurements from open-charm and high-p_T hadron pairs as a function of x. The COMPASS results are compared to results of SMC [14] and HERMES [15, 16]. The curves are two parameterizations from a COMPASS NLO QCD fit with $\Delta g > 0$ (dashed line) and $\Delta g < 0$ (solid line) [17].

4. Transversity and TMDs

Single spin asymmetries in semi-inclusive deep-inelastic scattering (SIDIS) off transversely polarized nucleon targets have been under intense experimental investigation over the past few years [18, 19, 20, 21, 22]. They provide new insights into QCD and the nucleon structure. For instance, they allow the determination of the third leading-twist quark distribution function $\Delta_T q(x)$, the transversity distribution [23, 24]. Additionally, they give insight into the parton transverse momentum distribution and angular momentum [25].

The measurement of transverse spin effects in semi-inclusive deep-inelastic scattering is an important part of the COMPASS physics program. In part of the years 2002-2004 data were taken by scattering a 160 GeV muon beam on a transversely polarized deuteron target. In 2007 and 2010, additional data were collected on a transversely polarized proton target.

In semi-inclusive deep-inelastic scattering the transversity distribution $\Delta_T q(x)$ can be measured in combination with the chiral odd Collins fragmentation function. According to Collins, the fragmentation of a transversely polarized quark into an unpolarized hadron generates an azimuthal modulation of the hadron distribution with respect to the lepton scattering plane [23].

In Fig. 4 the results for the Collins asymmetry on the proton target are shown as a function of x, z, and p_T for positive and negative hadrons [18]. For small x up to $x = 0.05$ the measured asymmetry is small and statistically compatible with zero, while for the last points an asymmetry

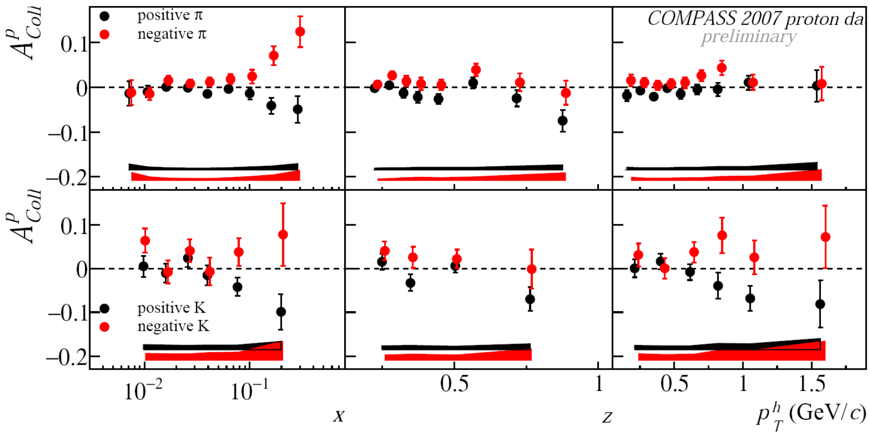

Figure 4. Collins asymmetry on a proton target for pions (upper row) and kaons (lower row) as a function of x, z and p_T [18]. The bands show the systematic uncertainty of the measurement.

different from zero is visible. The asymmetry increases up to about 8% with opposite sign for negative and positive hadrons. This result confirms the measurement of a sizable Collins function and transversity distribution.

COMPASS has measured the Collins asymmetries on a deuteron target as well. They are all compatible with zero [21]. From this measurement the opposite sign of u- and d- quark transversity has been derived. Both, proton and deuteron data sets have been employed in global fits taking into account the Collins fragmentation function from BELLE and the Collins asymmetries from COMPASS and HERMES to obtain constrains to the transversity distribution for u- and d-quarks [26].

Another azimuthal asymmetry is related to the Sivers effect. The Sivers asymmetry arises from a coupling of the intrinsic transverse momentum $\overrightarrow{k}_T$ of unpolarized quarks with the spin of a transversely polarized nucleon [27]. The correlation between the transverse nucleon spin and the transverse quark momentum is described by the Sivers distribution function $\Delta_0^T q(x, \overrightarrow{k}_T)$. Since the Collins and Sivers asymmetries are independent azimuthal modulations of the cross section for semi-inclusive deep-inelastic scattering, both asymmetries are determined experimentally from the same dataset.

In Fig. 5 the results for the Sivers asymmetry on the proton are shown as a function of x, z, and p_T. The Sivers asymmetry for negative hadrons is small and statistically compatible with zero. For positive hadrons the Sivers asymmetry is positive [18]. The Sivers asymmetry on the deuteron target is small and compatible with zero, which is due to the opposite sign of the $u-$ and $d-$quark Sivers function [21].

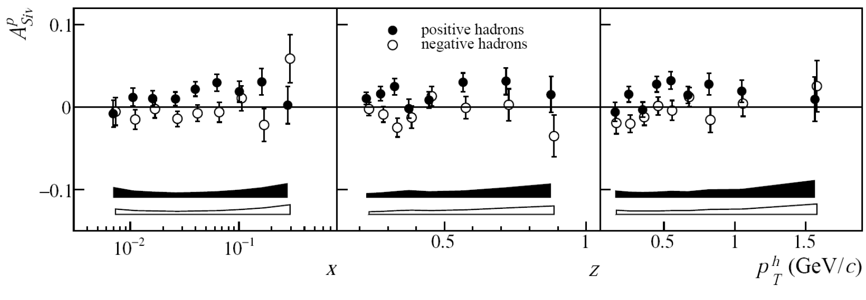

Figure 5. Sivers asymmetry on a proton target for positive and negative hadrons as a function of x, z and p_T from [18].

5. Outlook

Recently, the COMPASS II proposal [28] was submitted to improve the knowledge of the momentum structure of the nucleon towards a three dimensional picture. For this a series of new measurements is planned. A study of generalized parton distributions (GPD) will be done using exclusive reactions like deeply virtual Compton scattering (DVCS) and deeply virtual meson production (DVMP) [29, 30]. Drell-Yan processes will be used for a complementary study of transverse momentum dependent distributions (TMD) using a transversely polarized target [31]. At very low momentum transfers Primakoff reactions can be used to extract pion and kaon polarizabilities. The COMPASS II proposal was approved on December 2010 for an initial data taking of three years.

Acknowledgments

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