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Spin physics at COMPASS

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Abstract. Results for the spin structure of the nucleon from the COMPASS data taking periods 2002 to 2004 are presented. The quark contribution to the nucleon spin, following from a QCD fit to the new data, turns out to be significantly larger than it was derived from the previous world data. The new data favour, on the other side, a comparatively small gluon polarisation in the range $x_g \approx 0.1$. In the data taken with the deuteron target polarised transversely the related asymmetries are found to be small on the level of accuracy reached so far, indicating a cancellation of the proton and neutron contributions. This is in agreement, for both the Collins and the Sivers asymmetry, with recent theoretical calculations. Also, a step towards the understanding of angular-momentum contributions with COMPASS is taken by the evaluation of asymmetries in exclusive vector meson production.

PACS. 25.30.Mr Muon scattering (including the EMC effect) – 21.10.Hw Spin, parity, and isobaric spin – 24.85.+p Quarks, gluons, and QCD in nuclei and nuclear processes – 13.60.-r Photon and charged-lepton interactions with hadrons

1 Introduction

Since many years the understanding of the structure and the spectrum of hadrons is a central goal of particle physics. As initialised by Hofstadter's results on the proton radius, dating now 50 years ago, a complete description of the underlying strong interaction is still a challenging task on both the experimental and theoretical sides. While in the sector of high-energetic collisions, perturbative quantum chromodynamics (QCD) is a powerful tool, for the low-energy processes and bound-state properties the effective degrees of freedom cannot be directly derived from the presumably underlying theory.

The COmmon Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS) at the Super Proton Synchrotron (SPS) at CERN is devoted to this field with a broad variety of measurements, using different beams and spectrometer setups. While measurements with pion and proton beams will explore hadron spectroscopy, the data taking up to now has been focused on spin physics with a muon beam in deep inelastic scattering (DIS, for momentum transfer $Q^2 > 1\,\mathrm{GeV}^2/c^2$) as well as in quasi-real photo-production ($Q^2 < 1\,\mathrm{GeV}^2/c^2$) processes. During the data taking periods 2002–2004, the muon momentum was $160\,\mathrm{GeV}/c$ and the beam intensity $4 \cdot 10^7$ muons/s.

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2 The COMPASS spectrometer

COMPASS [1] is a 2-stage magnetic spectrometer equipped with modern detector and data acquisition technology for large-acceptance measurements with high-intensity beams and high interaction rates. The tracking system is based on silicon microstrip detectors, together with scintillating fiber detectors, for high-precision tracking in the target region, the novel technologies of Micromegas and GEM detectors are employed for the small-area tracking, and drift chambers, straw tubes and wire chambers are used for the large-area tracking. A large-acceptance ring-imaging Cherenkov (RICH) detector in the first spectrometer stage provides charged-particle identification. Both stages are equipped with hadronic calorimeters, providing further particle identification. Their signals are also used in the trigger system, which is based on scintillator hodoscopes selecting the signals from scattered muons. The muons are identified throughout the apparatus in detectors behind hadron absorbers.

The target system [2] is equipped with two 60 cm long cells filled with solid ^{6}LiD. The cells are polarised oppositely by separate RF cavities. The target magnet provides a 2.5 T longitudinal solenoid field and a 0.4 T transverse dipole field, where the latter is used during the adiabatic field rotations and also as holding field during running with the target spin oriented transverse to the beam. The polarisable part of the ^{6}Li nucleus represents with good

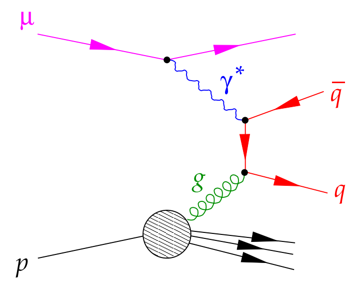

Fig. 1. The photon-gluon fusion process. The dependence of the production amplitude on the relative polarisation of the muon and the nucleon gives access to the gluon polarisation in the nucleon.

accuracy an additional deuteron, so the presented asymmetries are effectively measurements on the deuteron, and the target material has a favorable dilution factor of ~ 0.4. Polarisations to about 50% are reached.

The resulting trigger rate of about 20 kHz is handled by custom-made frontend electronics for the 250000 readout channels and transfered through a farm of event builder computers to tape at a rate of about 5 TB per day.

3 Results on spin physics

3.1 Composition of the nucleon spin

In QCD, the spin of the nucleon can have four contributions,

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g, \qquad (1)$$

where $\Delta\Sigma$ is the quark contribution, ΔG the gluon contribution, and L_q, L_g are the respective angular momenta.

Using the $\overline{MS}$ renormalisation scheme, the contribution of the quarks is given by the observable singlet axial current, $\Delta\Sigma = a_0$. This value has been extracted, using the new 2002–2004 COMPASS data only,

$$a_0(Q^2 = 3\,\mathrm{GeV}^2/c^2) = 0.35 \pm 0.03_{\mathrm{stat}} \pm 0.05_{\mathrm{syst}}, \qquad (2)$$

the details of this analysis being given in a separate contribution to these proceedings [3] and also in [4]. The integral over g_1^N is performed by summing the obtained data points, with a small correction for the $x_{Bj} \to 0$ and 1 limits taken from a QCD fit to the world data , and the evolution to a fixed Q^2. The difference with respect to the former SMC analysis [5], leading to a significantly smaller value, mainly stems from the values at small Bjorken $x < 0.02$, where the new COMPASS data are well compatible with zero.

This method, even allowing the sign of the gluon contribution ΔG to be positive or negative within its systematic error [3], restricting only the absolute value to 0.2–0.3. With COMPASS this quantity can be accessed by the study of the photon-gluon fusion (PGF) process, depicted in fig. 1. The photon carries a well-determined fraction of the known incoming muon polarisation, while

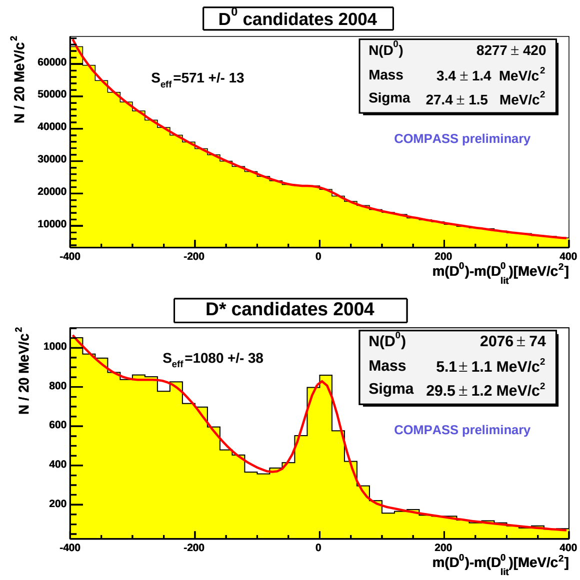

Fig. 2. D-meson signals from the COMPASS 2002–2004 data. The upper plot shows all reconstructed D^0-mesons, the lower plot the D^0 tagged by a $D^* \to D\pi$ decay.

the gluon polarisation, as related to the incoming proton polarisation, is the quantity of interest. There are two ways of extracting the process in COMPASS: The production of a $c\bar{c}$ pair not forming a bound system (open charm), which is intrinsically a small-scale process due to the high charm mass, and by this the theoretically favorable channel. The second possibility is the production of light quarks, $q = u, d, s$, where the PGF process is enriched by choosing a small spatial scale by either selecting $Q^2 > 1\,\mathrm{GeV}^2/c^2$, or by ensuring that the outgoing hadrons have high transverse momenta, $\Sigma p_T^2 > 2.5\,\mathrm{GeV}^2/c^2$.

3.2 Open-charm analysis

The production of charm quarks via photon-gluon fusion is observed through D-mesons, which are reconstructed from the tracks of their decay particles. The channels investigated so far are the decay $D^0 \to \pi^+ K^-$, as well as the same decay preceded by an original $D^* \to D\pi_{\mathrm{slow}}$ decay. The statistics and purity of the two channels as measured in the runs 2002 to 2004 is presented in fig. 2. While the available statistics is much higher for the D^0, the D^* sample is of higher purity, resulting in comparable uncertainties on the extracted asymmetry in the two cases.

The photon-nucleon asymmetry $A^{\mu N}$ is obtained by correcting the obtained experimental asymmetry A^{exp}:

$$A^{\mu N} = \frac{1}{P_B P_T f D}\frac{S+B}{S}A^{exp} \qquad (3)$$

for the beam and target polarisations P_B, P_T, for the material dilution factor f, which accounts for the fact that not all nucleons in the target are polarised, the depolarisation factor D for the virtual photon, and the dilution factor due to the admixture of unpolarised combinatorial background B under the signal S. A possible background asymmetry due to other spin-dependent processes is assumed to be much smaller than the statistical uncertainty obtained so far. For the extraction of ΔG, the respective analysing power $a_{LL} = \Delta\sigma(\gamma^* g \to c\bar{c}X)/\sigma(\gamma^* g \to c\bar{c}X)$, only accessible via a model-dependent simulation, must be used, leading to

$$\frac{\Delta G}{G} = \frac{1}{P_B P_T f D\ a_{LL}} \frac{S+B}{S} A^{exp}. \qquad (4)$$

Since part of the factors have a different value for each event, the asymmetry is finally obtained by the method of event weighting. Combining the values for the two examined channels, the preliminary result from open charm is

$$\frac{\Delta G}{G} = -0.57 \pm 0.41_{\mathrm{stat}} \qquad (5)$$

for the gluon momentum fraction centered at $x_g \approx 0.15$ with an RMS width of 0.08, the scale of the process being centered around $13\,\mathrm{GeV}^2/c^2$.

3.3 High-p_T pairs

The leading deep inelastic process is given by the virtual photon colliding with a quark, which recoils and fragments into a hadron mainly in the direction of the initial photon. Choosing two hadrons with both having a large transverse momentum $p_{T,i} > 0.7\,\mathrm{GeV}/c$ and $\Sigma_i p_{T,i}^2 > 2.5\,\mathrm{GeV}^2/c^2$, enhances strongly the contribution where the photon hits a virtual $q\bar{q}$ pair carrying the information of a single gluon; in COMPASS kinematics this reaches a contribution up to 30%. The sample is purified by taking only hadrons identified in the hadron calorimeters, and further restricted to masses for the 2-hadron system $> 1.5\,\mathrm{GeV}$, suppressing contributions from resonances.

The first option in order to obtain a result for $\Delta G/G$ is to choose events with $Q^2 > 1\,\mathrm{GeV}^2/c^2$, since then the only competing processes to PFG are the leading-order deep inelastic process and QCD-Compton interaction, as shown in fig. 3 on the left side. These two competing processes are sensitive to the quark polarisation, whose contribution to the asymmetry can be neglected after further restricting the events to $x < 0.05$, given the smallness of A_1 in this region. Then, the asymmetry in 2-hadron production with high p_T can be connected with $\Delta G/G$,

$$A^{\gamma^* N \to hh} = R_{PGF}\ a_{LL}^{PGF} \frac{\Delta G}{G}. \qquad (6)$$

The ratio $R_{PGF} = 0.34 \pm 0.07$ is taken from the COMPASS Monte Carlo simulation using the LEPTO 6.5.1 generator, which is suited for physics at high Q^2, and from the 2002–2003 data the preliminary value

$$\frac{\Delta G}{G} = 0.06 \pm 0.31_{\mathrm{stat}} \pm 0.06_{\mathrm{syst}} \qquad (7)$$

is obtained at scale $\mu^2 = 3\,\mathrm{GeV}^2/c^2$ and an average $x_g \approx 0.13$ with an RMS of 0.08.

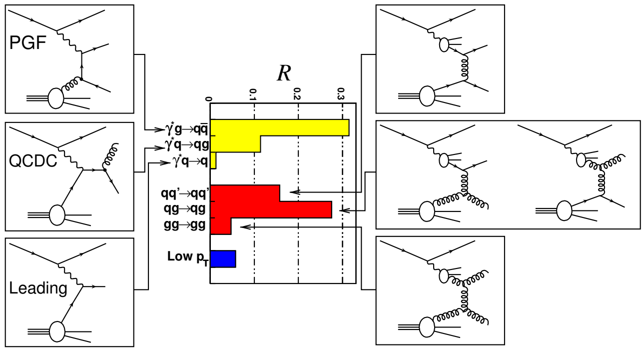

Fig. 3. Contributions of different processes as in the PYTHIA sample of events with $Q^2 < 1\,\mathrm{GeV}^2/c^2$.

The selection of quasi-real photo-production with $Q^2 < 1\,\mathrm{GeV}^2/c^2$, has about a factor of 10 more statistics, but now the asymmetry is more difficult to interpret, since also processes with resolved photons, as presented in fig. 3 on the right side, have to be taken into account. Those processes involving the hadronic part of the photon are estimated in [6] and used in the PYTHIA 6.2 [7] Monte Carlo generator for incorporation of these effects. The details of this analysis for the 2002–2003 data is given in [8], including the 2004 data the new preliminary value

$$\frac{\Delta G}{G} = 0.016 \pm 0.058_{\mathrm{stat}} \pm 0.055_{\mathrm{syst}} \qquad (8)$$

is extracted at $x_g = 0.095$ and the scale $\mu^2 = 3\,\mathrm{GeV}^2/c^2$.

3.4 Results for $\Delta G/G$

The three preliminary COMPASS values for $\Delta G/G$ are summarized in fig. 4, together with the data previously obtained by SMC [9] and HERMES [10]. They are compared with the parametrisation given by GRSV [11] in

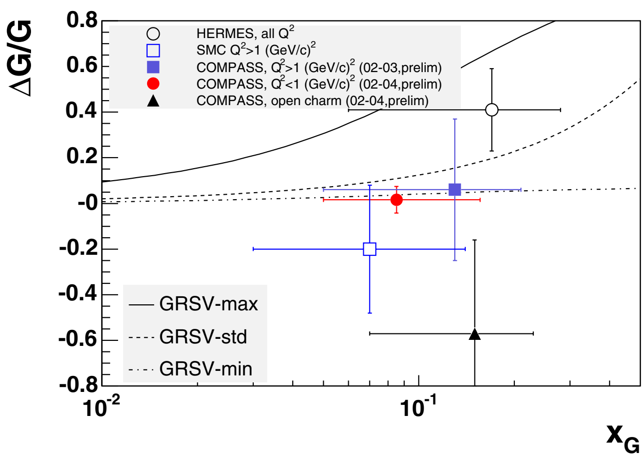

Fig. 4. Gluon polarisation of the nucleon as obtained in the different COMPASS analysis, compared to earlier measurements and theoretical distributions from [11] as discussed in the text.

the scenarios of maximal, best fit and minimal integrated value for ΔG being 2.5, 0.62 and 0.16, respectively. While the experimental values of the high-p_T analysis have been obtained at the same scale as the calculation was carried out, *i.e.* $Q^2 = 3\,\mathrm{GeV}^2/c^2$, the open-charm data refer to a much higher scale $\mu^2 = 13\,\mathrm{GeV}^2/c^2$.

3.5 Transversity

For the description of the quark state of a nucleon at twist-two level, in addition to the $q(x)$ and $\Delta q(x)$ distributions also the transverse spin distributions $\Delta_T q(x)$ contribute [12,13]. The sparseness of available data is explained by the fact that these *transverse distributions* are not observables in inclusive deep inelastic scattering due to their chiral-odd nature.

COMPASS runs about 20% of the beam time with the target transversely polarised in order to measure transversity asymmetries in semi-inclusive deep inelastic muon scattering. The produced hadrons exhibit azimuthal asymmetries with respect to the transverse target polarisation. Two possible angular correlations are discussed, depending on whether the hadron azimuthal angle is observed with respect to the azimuthal angle of the initial or fragmenting quark spin as depicted in fig. 5, defining the Sivers $(\phi_h - \phi_s)$ or Collins $(\phi_h - \phi'_s)$ angle, respectively.

In case of the Collins asymmetry, the chiral-odd distribution $\Delta_T^0 D_q^h$, describing the spin dependence of the hadronization of the transversely polarised quark q into the hadron h, contributes together with the transverse-distribution function $\Delta_T q$ to the asymmetry

$$A_{Coll} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}, \tag{9}$$

where the Collins angle Φ_C is contained in the azimuthal dependence of $\Delta_T^0 D_q^h$ [14].

In case the initial nucleon spin direction is correlated to an intrinsic transverse momentum k_T of an unpolarised quark in the transversely polarised nucleon, the quark distribution could be written [15] as

$$q_T(x, \boldsymbol{k}_T) = q(x, k_T) + \Delta q_0^T(x, k_T) \cdot \sin \Phi_S \tag{10}$$

and leads to a Sivers asymmetry

$$A_{Siv} = -\frac{\sum_q e_q^2 \cdot \Delta q_0^T \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}, \tag{11}$$

a convolution of the Sivers distribution function Δq_0^T and the unpolarised fragmentation function D_q^h. So, the Sivers asymmetry is not connected to transversity, *i.e.* the transverse-distribution function $\Delta_T q$.

The analysis of these quantities from the COMPASS 2002–2004 transversity data is performed with DIS cuts ($Q^2 > 1\,\mathrm{GeV}^2/c^2$, $W > 5\,\mathrm{GeV}$, $0.1 < y < 0.9$) and a cut on the transverse momentum of the hadrons, $p_T > 0.1\,\mathrm{GeV}/c$, ensuring the angles Φ_C and Φ_S to be well defined. The asymmetry is extracted either from all hadrons

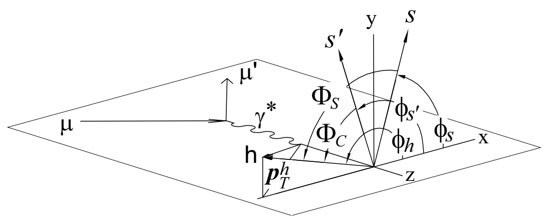

Fig. 5. Azimuthal angles used in the extraction of Collins and Sivers asymmetries.

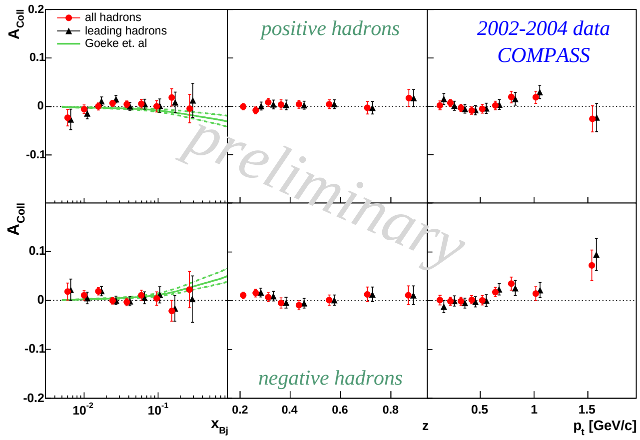

Fig. 6. Collins asymmetry from the COMPASS 2002–2004 data, compared in the x_{Bj}-dependence to a recent theoretical calculation [18].

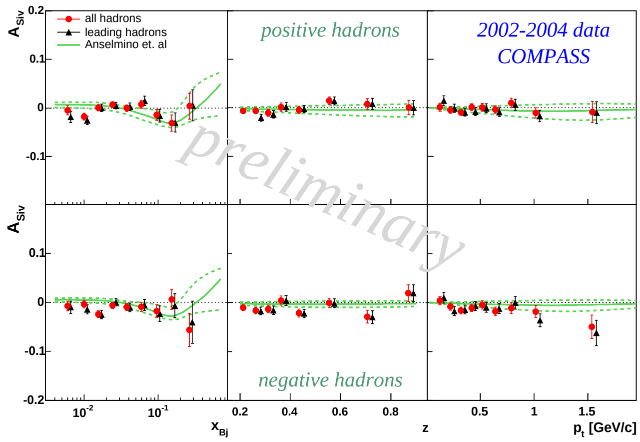

Fig. 7. Sivers asymmetry from COMPASS 2002–2004 data, shown together with a theoretical description [19] as discussed in the text.

with $0.2 < z < 1$, z being the fraction of the photon energy carried by the hadron, or from only the hadrons with highest momentum if they have $z > 0.25$. Further details of the analysis and systematic studies can be found in [16] and [17].

The results are presented for both options, in fig. 6 for the Collins asymmetry and in fig. 7 for the Sivers asymmetry. In case of the Collins asymmetry, the x_{Bj}-dependence is compared to a recent theoretical calcula-

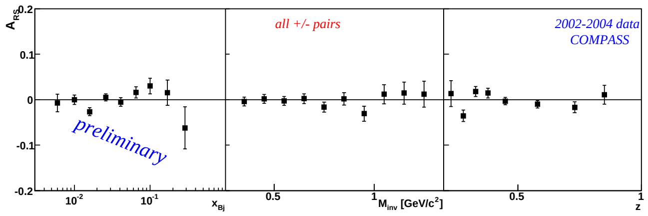

Fig. 8. Transverse asymmetry determined from hadron pairs.

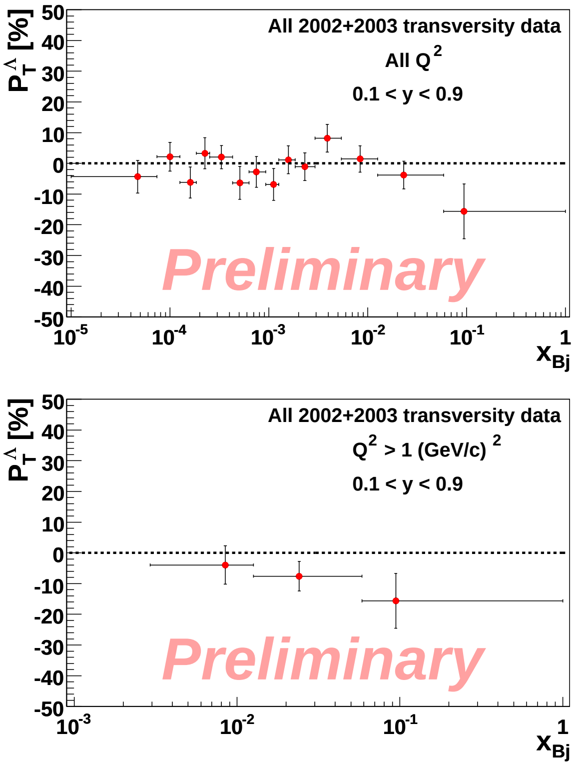

Fig. 9. Transversity from Λ polarisation.

tion [18] using transversity distributions from the chiral quark-soliton model, which has been found in agreement also with other experiments. In order to disentangle the transversity distributions from the transverse fragmentation function $\Delta_T^0 D_q^h$, this quantity must be determined by another method, as for example done with the analysis of spin asymmetries in $e^+e^- \to 2h$ reactions studied by the BELLE Collaboration.

The measured Sivers asymmetry is compared to the theoretical analysis [19] in dependence on the kinematical variables x_{Bj}, z and p_T. This analysis takes into account these new COMPASS data together with the HERMES data on protons within the leading-order parton model including transverse quark motions.

Compared to the sizable asymmetries measured on the proton [20], the presented asymmetries on the deuteron are much smaller, which would follow if $\Delta_T u$ and $\Delta_T d$ had opposite sign like the helicity distributions, and so the contributions from the proton and neutron mainly cancel.

Also other ways of accessing the transverse spin distribution $\Delta_T q(x)$ are studied on the COMPASS data.

In the production of hadron pairs, the angle of the two-hadron plane with respect to the fragmenting quark spin may be defined analogously to the Collins case, giving rise to an asymmetry proportional to the convolution of the transverse spin distribution $\Delta_T q(x)$ and a two-hadron fragmentation function, referred to as interference fragmentation function $H_q^{\angle h}(z, M_h)$. The resulting transverse asymmetry is shown in fig. 8 in dependence of x_{Bj}, the invariant mass of the 2-hadron system, and z. The asymmetry is found to be small, so either both or one of the functions $\Delta_T q(x)$ and $H_q^{\angle h}(z, M_h)$ are small on the achieved level of accuracy, as in the case of single-hadron studies.

The last channel presented here in order to access transversity is the study of the transverse polarisation of Λ hyperons. Here, the measured Λ polarisation is expected to depend on $\Delta_T q(x)$. In fig. 9 the dependence of x_{Bj} for all measured Q^2 and with a cut on deep inelastic kinematics $Q^2 > 1\,\mathrm{GeV}^2/c^2$ is presented. The data from the 2002–2003 data taking for DIS kinematics may indicate a non-zero value, however at the statistical limit of data analysed so far. Including the 2004 data will increase the statistics by a factor of 2.

3.6 Exclusive ρ-production

Incoherent exclusive ρ^0 production on polarised deuterons, $\mu + N \to \mu + N + \rho$, is also studied at COMPASS at

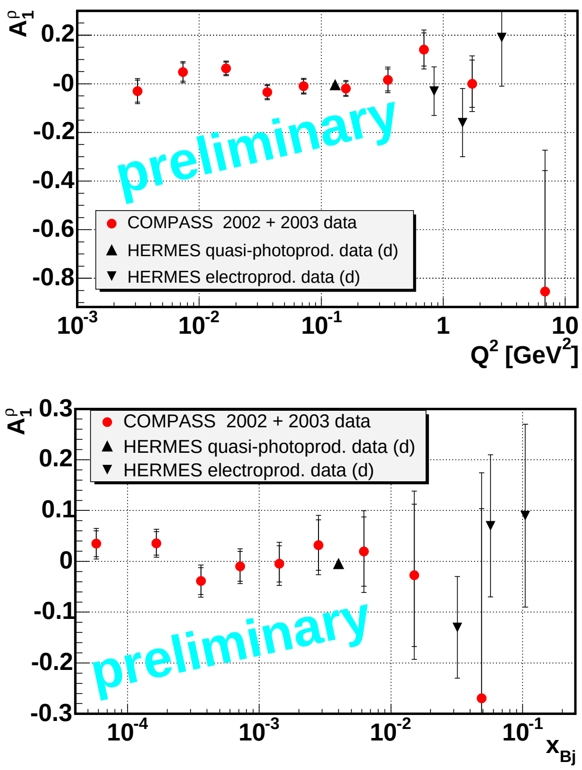

Fig. 10. Exclusive ρ production asymmetry, shown together with the results from HERMES [22].

$\langle W \rangle = 10\,\text{GeV}$ over a wide kinematical range: $3 \times 10^{-3} < Q^2/(\text{GeV}^2/c^2) < 7$ and $5 \times 10^{-5} < x_{Bj} < 0.05$.

For the analysis two hadron tracks are required, which correspond to charged pions from the ρ^0 decay. A cut on the invariant mass is applied: $0.5 < M_{\pi\pi}/\text{GeV} < 1$. As slow recoil target particles are not detected in the current setup, in order to select exclusive events we used cuts on the missing energy, $-2.5 < E_{\text{miss}}/\text{GeV} < 2.5$, and on the transverse momentum of ρ^0 with respect to the virtual-photon direction, $p_t^2 < 0.5\,\text{GeV}^2/c^2$. Coherent interactions on the target nuclei are suppressed by a cut $p_t^2 > 0.15\,\text{GeV}^2/c^2$.

The longitudinal double-spin asymmetry A_1^ρ from the COMPASS 2002 and 2003 data [21] is reported as a function of Q^2 (upper panel) and x_{Bj} (lower panel) in fig. 10. Comparison with the HERMES results [22] is also shown. For the whole kinematical range A_1^ρ is consistent with zero. This indicates that the role of unnatural-parity exchanges, like π- or A_1-Reggeon exchange, is small in that kinematical domain, which is to be expected if diffraction is the dominant process. At $Q^2 > 1\,\text{GeV}^2/c^2$ a non-zero asymmetry would indicate sensitivity to spin-dependent generalized parton distributions [23] but more data are needed to clarify this issue.

4 Summary and outlook

COMPASS contributes to a broad variety of questions around the spin riddle of the nucleon, where possibly the gluon contribution will turn out to be smaller than it was speculated at some point. The transversity phenomena are studied with dedicated data-taking periods, and have delivered first results for the deuteron. The ongoing analysis will increase the statistics in many channels, and lead to more precise information.

Apart from the aspects presented here, the huge data set collected with muon beam allows to also contribute to aspects of hadron spectroscopy, as the exclusion of a $\Xi^{--}(1860)$ pentaquark [24] on a high statistical level demonstrates.

The 2004 data taken with a pion beam have revealed the possibilities that the very flexible setup of the experiment offers, switching to soft hadronic and Primakoff reactions within a few days.

The preparation for the 2007 run is ongoing, where for the first time a polarised hydrogen target will allow at COMPASS transversity measurements on the proton, before the first measurements with hadron beam for central production are started.

In longer terms, an upgraded COMPASS spectrometer with even higher beam flux is discussed, aiming at the still unknown orbital angular momenta of the partons in the nucleon. This will be addressed, for example, by the determination of GPDs via deep virtual Compton scattering and hard exclusive vector meson production.

References

1. COMPASS proposal, CERN/SPSLC96-14 (1996).
2. J. Ball *et al.*, Nucl. Instrum. Methods A **498**, 101 (2003).
3. A. Korzenev (for the COMPASS Collaboration), these proceedings.
4. COMPASS Collaboration (V. Alexakhin *et al.*), Phys. Lett. B **647**, 8 (2007).
5. SMC Collaboration (B. Adeva *et al.*), Phys. Rev. D **58**, 112001 (1998).
6. M. Glück, E. Reya, C. Sieg, Eur. Phys. J. C **20**, 210 (2001).
7. T. Sjöstrand *et al.*, Comput. Phys. Commun. **138**, 238 (2001).
8. COMPASS Collaboration (E. Ageev *et al.*), Phys. Lett. B **633**, 25 (2006).
9. SMC Collaboration (B. Adeva *et al.*), Phys. Rev. D **70**, 012002 (2004).
10. HERMES Collaboration (A. Airapetian *et al.*), Phys. Rev. Lett. **84**, 2584 (2000).
11. M. Glück, E. Reya, M. Stratmann, W. Vogelsang, Phys. Rev. D **63**, 094005 (2001).
12. J.P. Ralston, D.E. Soper, Nucl. Phys. B **152**, 109 (1979).
13. V. Barone *et al.*, Phys. Rep. **359**, 1 (2002).
14. J. Collins, Nucl. Phys. **396**, 161 (1993).
15. D. Sivers, Phys. Rev. D **41**, 83 (1990).
16. COMPASS Collaboration (V. Alexakhin *et al.*), Phys. Rev. Lett. **94**, 202002 (2005).
17. COMPASS Collaboration (E. Ageev *et al.*), Nucl. Phys. B **765**, 31 (2007).
18. A.V. Efremov, K. Goeke, P. Schweitzer, Phys. Rev. D **73**, 094025 (2006).
19. M. Anselmino *et al.*, *Proceedings to Transversity 2005, Como, Italy* (World Scientific Publishing, 2006) ISBN 981-256-846-8, hep-ph/0511249.
20. HERMES Collaboration (A. Airapetian *et al.*), Phys. Rev. Lett. **94**, 012002 (2005).
21. A. Sandacz (for the COMPASS Collaboration), Nucl. Phys. B, Proc. Suppl. **146**, 58 (2005).
22. HERMES Collaboration (A. Airapetian *et al.*), Eur. Phys. J. C **29**, 171 (2003).
23. S.V. Goloskokov, P. Kroll, Eur. Phys. J. C **42**, 281 (2005).
24. COMPASS Collaboration (E. Ageev *et al.*), Eur. Phys. J. C **41**, 469 (2005).