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Overview of the COMPASS results on the nucleon spin

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Abstract

The COMPASS experiment [1] at CERN is one of the leading experiments studying the nucleon spin. These studies are being carried on since 2002, by measuring hadrons produced in deep inelastic scattering (DIS) of 160 GeV/c and 200 GeV/c polarised muons off different polarised targets (NH_3 for polarised protons and ^{6}LiD for polarised deuterons). One of the main goals is to determine how the total longitudinal spin projection of the nucleon, 1/2, is distributed among its constituents, quarks and gluons. We review here the recent results on the quark and gluon helicities obtained by COMPASS. The other major goal, whose fulfilment is needed for a complete understanding of the nucleon spin, is the determination of the transverse momentum dependent parton distributions (TMDs). Regarding this topic, the latest results on the Collins and Sivers asymmetries will be shown. The former is sensitive to the transverse spin structure of the nucleon, while the latter reflects the correlations between the quarks transverse momentum and the nucleon spin. This overview will conclude with a summary of the approved plans of COMPASS for the near future: the study of TMDs with a pioneering polarised Drell-Yan experiment and the measurement of generalised parton distributions (GPDs).

Keywords: Nucleon Spin, Quark Helicity, Gluon Helicity, TMDs, GPDs

1. Introduction

In perturbative QCD, the leading twist contribution to a parton distribution function (PDF) can be written in collinear approximation as

$$\Phi(x) = \frac{1}{2}[q(x) + \gamma_5 \Delta q(x) S_L + \gamma_5 \Delta_T q(x) S_T \gamma_1] \quad (1)$$

The quantity $q(x)$ describes the unpolarised parton distribution as a function of the fraction of longitudinal momentum carried by the parton, $\Delta q(x)$ ($\Delta_T q(x)$) represents the longitudinally (transversely) polarised parton distribution function and S_L (S_T) stands for the longitudinal (transverse) spin of the nucleon. In COMPASS, the polarised PDFs are investigated via DIS processes for all the light quarks (u, d and s). Concerning the polarised gluon distribution function, it is only investigated from longitudinally polarised targets by studying the next-to-leading order (NLO) interaction of photon-gluon fusion (PGF).

One of the major goals of COMPASS is to understand how the longitudinal spin projection of the nucleon, 1/2, is built up from its basic constituents:

$$\frac{S_z^N}{\hbar} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma\left(= \sum_q \Delta q\right) + L_z^q + \Delta G + L_z^g \quad (2)$$

$\Delta\Sigma$ (ΔG) represents the total quark (gluon) helicity and L_z^q (L_z^g) represents the orbital angular momentum (OAM) of quarks (gluons). The most recent results on the quark and gluon helicities are reviewed here. Measurements of transverse spin asymmetries leading to the determination of the transverse spin distributions of quarks and to the Sivers function are also discussed. The latter is sensitive to the OAM of quarks and, therefore, may be of crucial importance for the determination

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of one of the remaining unknowns in Eq. 2. This article will conclude with a summary of the future plans concerning the study of OAM, TMDs and GPDs.

2. Longitudinal Spin Structure of the Nucleon

The structure function describing the longitudinal spin of the nucleon, $g_1(x, Q^2)$, is determined at COMPASS by measuring the following inclusive spin asymmetry:

$$A_1 \equiv \left(\frac{\sigma_{\gamma^* N}^{\rightleftarrows} - \sigma_{\gamma^* N}^{\rightrightarrows}}{\sigma_{\gamma^* N}} \right) = \frac{g_1(x, Q^2)}{f_1(x, Q^2)} \quad (3)$$

The symbol $\rightarrow$ ($\Rightarrow$) indicate the direction of the virtual-photon (nucleon) polarisation, and f_1 represents the well known unpolarised structure function. The COMPASS results on g_1 (deuterons and protons) can be seen in Fig. 1:

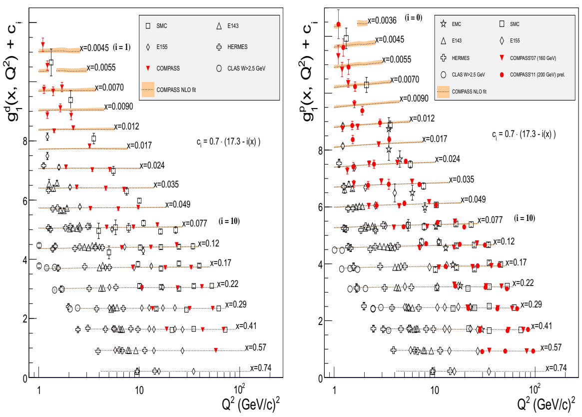

Figure 1: World data on g_1^d (left) and g_1^p (right). The COMPASS improvements in precision and in kinematic coverage are evident.

By using the world data on g_1^d and g_1^p, the total contribution of quarks to the nucleon spin can be obtained [2]. Without considering its own g_1^p data (non-existent at the time), COMPASS published the following results: $\Delta\Sigma = 0.30 \pm 0.01(stat.) \pm 0.02(syst.)$ and $(\Delta s + \Delta\bar{s}) = -0.08 \pm 0.01(stat.) \pm 0.02(syst)$. They indicate very clearly that the intrinsic spin of quarks contributes only with 30% to the total nucleon spin (with a slightly negative contribution from the strange sea). However, recently COMPASS refined the procedure of extracting the quark and gluon helicities from the g_1 data. Besides the inclusion of g_1^p, several systematic studies concerning the assumptions on the functional forms of the PDFs were performed. Note that the partonic helicities are obtained from a minimisation of the difference between the calculated and the measured g_1. In turn, the calculated g_1 results from a DGLAP evolution of an initial parametrisation of the partonic helicities. Therefore, it is clear the importance of a proper choice of the functional forms. The results are shown in Fig. 2. One can observe that there is still a small sensitivity to the light sea and gluon helicities. This fact is grounded on the existence of a rather limited kinematic coverage by the measurements of $g_1(x, Q^2)$. Concerning the total quark helicity, it is well constrained: $\Delta\Sigma = \int \Delta q(x)dx \in [0.256, 0.335]$.

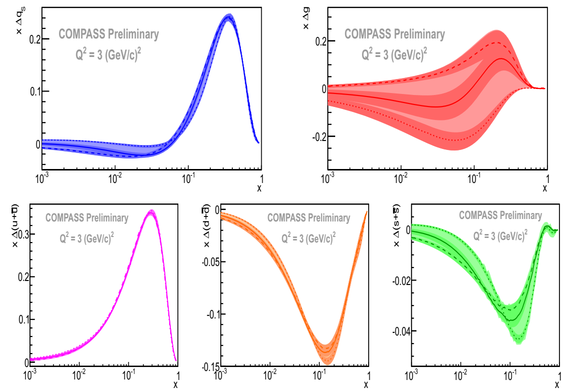

Figure 2: Top panels: Quark and qluon helicities resulting from QCD fits to the world data on g_1. Bottom panels: Quark helicities for all the light quark flavours. Each plot contains the results for 3 different scenarios (which cover all possible solutions): $\Delta G < 0$, $\Delta G = 0$ and $\Delta G > 0$. The shadowed bands represent the uncertainties arising from the choice of the functional forms.

2.1. *Quark Helicities from Semi-Inclusive DIS*

In addition to the analysis of the g_1 data, COMPASS also measures SIDIS asymmetries in order to improve our knowledge on the sea-quark helicities. In the LO approximation, this hadronic asymmetry is defined by

$$A_1^h = \frac{\sum_q e_q^2 \Delta q(x, Q^2) D_q^h(z, Q^2)}{\sum_q e_q^2 q(x, Q^2) D_q^h(z, Q^2)} \quad (4)$$

where e_q is the electric charge of a given quark flavour, Δq (q) the polarised (unpolarised) parton distribution function and D_q^h the fragmentation function (FF) of the struck quark to a hadron h. A total of 8 asymmetries are measured via SIDIS processes at COMPASS, namely $A_1^{\pi^+}$, $A_1^{\pi^-}$, $A_1^{K^+}$ and $A_1^{K^-}$ for both proton and deuteron targets. By taking also into account the 2 inclusive spin asymmetries, which were used for the extraction of g_1^d and g_1^p, one is able to determine the following quark helicities [3]: Δu, $\Delta\bar{u}$, Δd, $\Delta\bar{d}$ and Δs. These helicities were extracted from Eq. 4, using the DSS parametrisation for D_q and the MRST04 parametrisation for q, and are shown in Fig. 3:

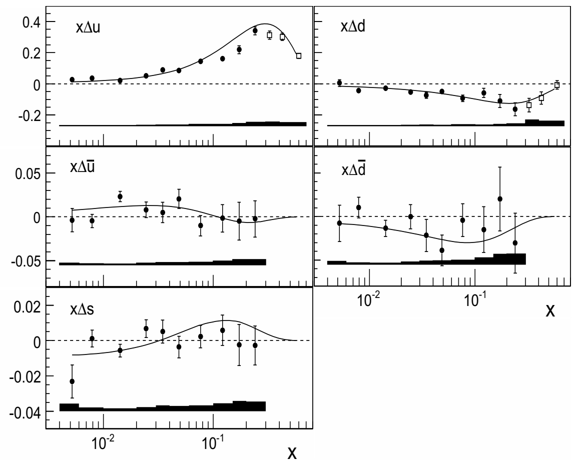

Figure 3: SIDIS results on the light quark helicities, under the assumption of $\Delta s = \Delta\bar{s}$, at $Q^2 = 3\ (GeV/c)^2$. The curves correspond to a global NLO fit obtained from DSSV [4].

From the above figure one obtains for the strange quark helicity a first moment of: $\Delta s = -0.01 \pm 0.01(stat.) \pm 0.01(syst.)$. The difference between this result and the one obtained from the inclusive asymmetries, $(\Delta s + \Delta\bar{s}) = -0.08 \pm 0.01(stat.) \pm 0.02(syst.)$, may have an explanation on the fragmentation function which was used in the SIDIS analysis. In order to clarify this small discrepancy, COMPASS is measuring hadron multiplicities (number of hadrons per DIS event) with the aim of constraining the needed FFs for Eq. 4:

$$\frac{dM^h}{dz} = \frac{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2)} \tag{5}$$

2.2. Gluon Polarisation

As we saw in Fig 2, the distribution of the gluon helicity extracted from the g_1 data is quite uncertain. Consequently, the determination of ΔG from QCD fits must be complemented by direct measurements of the gluon polarisation $\Delta g/g$ ($\Delta G = \int \Delta g(x)dx$). We measure the gluon polarisation instead of the gluon helicity because it is experimentally simpler.

In COMPASS two main analyses were followed: open charm and high p_T hadron pairs. The first method is free from physical background at LO. This fact is justified by a negligible quantity of intrinsic-charm in the nucleon in the COMPASS kinematic domain ($x_{Bj} < 0.1$) [5, 6]. The open charm is tagged by the invariant mass reconstruction of D^0 mesons, via detection of their hadronic decay products. Since these mesons can only result from interactions with a gluon inside the polarised nucleon (true at LO and with small exceptions at NLO), the extraction of $\Delta g/g$ can be performed using the following D^0 asymmetries at $\langle Q^2 \rangle = 13\ (GeV/c)^2$:

$$A^{D^0} = f P_t P_\mu \langle \hat{a}_{LL} \rangle \left(\frac{\Delta g}{g} \langle x \rangle \right) \tag{6}$$

$$\hat{a}_{LL} \equiv \frac{\Delta\hat{\sigma}_{\mu g}}{\hat{\sigma}_{\mu g}} = \left(\frac{\hat{\sigma}_{\mu g}^{\leftrightarrows} - \hat{\sigma}_{\mu g}^{\leftleftarrows}}{\hat{\sigma}_{\mu g}^{\leftrightarrows} + \hat{\sigma}_{\mu g}^{\leftleftarrows}} \right) \tag{7}$$

where f, P_t and P_μ are the fraction of polarisable material inside the target, the target polarisation and the beam polarisation respectively. The partonic asymmetry $\hat{a}_{LL}$ is obtained from a Monte Carlo simulation of the PGF process at COMPASS and, thereafter, it is parametrised by a Neural Network in order to allow us to use $\hat{a}_{LL}$ on data. In order to overcome the limited charm statistics at COMPASS, a weighted method was developed to minimise the statistical error of $\Delta g/g$ [7]. Since this method implies an event-by-event analysis, a Neural Network is used to distinguish the PGF events from the combinatorial background in the D^0 mass spectra. The open charm analysis is performed at LO and also at NLO in QCD. The result of the former analysis is shown in Fig. 4, while the result from the latter analysis is shown in Fig. 5 (for details see [7]).

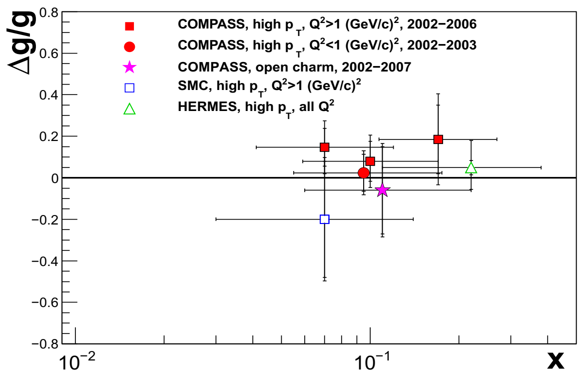

Figure 4: World data on $\Delta g/g$ obtained at LO in QCD. The COMPASS results are given by the color filled symbols.

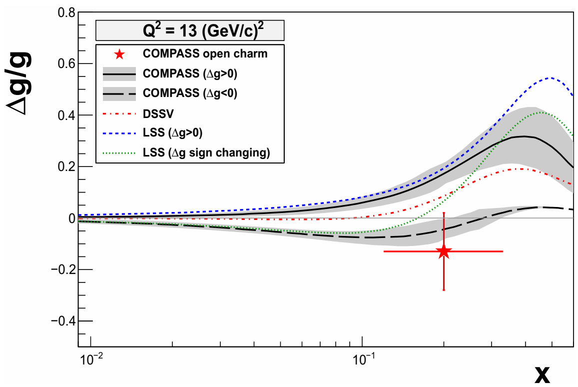

Figure 5: COMPASS result on $\Delta g/g$ obtained at NLO in QCD (first world measurement). The point can be compared with the existing QCD fits. The COMPASS fits are constrained by the experimental measurement.

In the second method hadron pairs with high transverse momenta p_T are selected. In this case there are several contributions to the measured asymmetries: LO processes, QCD Compton and PGF processes. For low Q^2 events there are also resolved photon contributions. The analysis is done independently for data with $Q^2 > 1$ (GeV/c)^2 and $Q^2 < 1$ (GeV/c)^2. Despite the large statistics available, this method has to face a more complicated analysis: in order to extract $\Delta g/g$ from the high-p_T asymmetries, we need to add to Eq. 6 as many terms as the existing physical processes (with $\Delta g/g$ replaced by A_1^{LO} and $A_1^{Compton}$). The partonic asymmetries, as well as the fractions corresponding to each physical process, are also determined from a Monte Carlo simulation of the COMPASS experiment [8]. The high-p_T results were only obtained at LO and are shown in Fig. 4. They agree with the open charm point from COMPASS and with the high-p_T points from SMC and HERMES. The most fair conclusion that one can draw from such plot is that the gluon polarisation is small and compatible with zero within $x_g \in [0.07, 0.2]$.

Still concerning this topic, we measured the longitudinal spin asymmetries for the polarised muon-deuteron and muon-proton interactions (cf. Fig. 6), $A_{LL} = A_1 \times D$, with D representing the polarisation transfer from the muon to the virtual-photon. With the goal of comparing our results with the theoretical calculations of A_{LL}, we measured these asymmetries from all events with a $Q^2 < 1$ (GeV/c)^2. The calculations, which are recently becoming available at the NLO approximation, assume different values for the gluon helicity ΔG (one calculation of A_{LL} for each assumed value of ΔG). Therefore, the above mentioned comparison can provide an indirect determination of ΔG. So far, there is not a single calculation capable of describing simultaneously our deuteron and proton data.

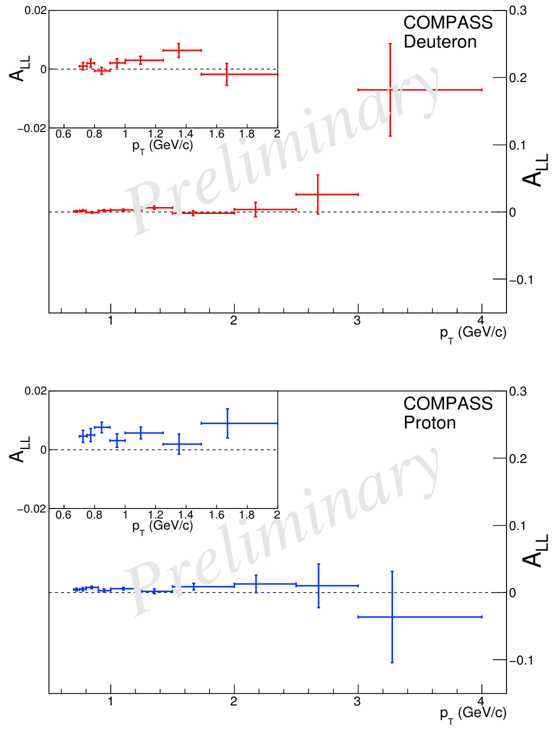

Figure 6: Top panel: COMPASS results on A_{LL}, using a deuteron target, obtained from all events with $Q^2 < 1$ (GeV/c)^2. Bottom panel: COMPASS results on A_{LL}, using a proton target, obtained from all events with $Q^2 < 1$ (GeV/c)^2.

3. Transversity and TMDs

Besides the longitudinally polarised structure function $g_1(x, Q^2)$ and the unpolarised structure function $f_1(x, Q^2)$, the Transversity function $h_1(x, Q^2)$ is the remaining necessary ingredient to describe the nucleon structure at leading twist. The function $h_1(x, Q^2)$ is linked to the distribution of transversely polarised partons and can be accessed in SIDIS when using a transversely polarised target. This is possible through a measurement of the so called Collins asymmetry, which is sensitive to the correlation between the outgoing hadron direction (in SIDIS) and the initial quark transverse spin. Therefore, the Collins asymmetry can be used to determine the quark transverse spin distributions $\Delta_T u(x)$ and $\Delta_T d(x)$. This asymmetry has a $\sin(\phi_h + \phi_S)$ modulation, where ϕ_h represents the azimuthal angle of the outgoing hadron and ϕ_S the azimuthal angle of the nucleon spin. It is measured simultaneously with other azimuthal asymmetries by fitting the various angular modulations of the outgoing hadron. The Collins asymmetry is defined by

$$A_{Coll} = \frac{\sum_q e_q^2 h_1^q(x, Q^2) \otimes H_{1q}^{\perp h}(z, , Q^2, p_T)}{\sum_q e_q^2 f_1^q(x, Q^2) \otimes D_{1q}^h(z, Q^2)} \quad (8)$$

Here, f_1^q represents the unpolarised structure function, D_{1q}^h the quark fragmentation function and $H_{1q}^{\perp h}$ is the so called Collins fragmentation function (depending on spin). The latest results from COMPASS on A_{Coll} can be seen in Fig. 7:

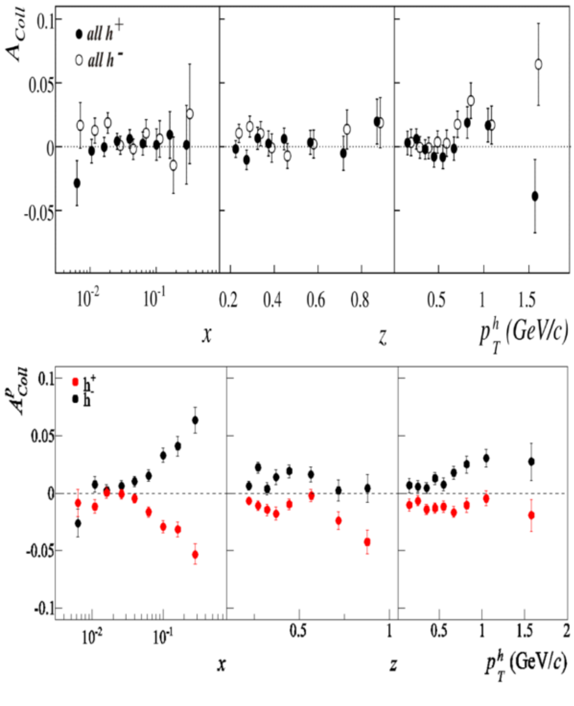

Figure 7: COMPASS results on the Collins asymmetry for deuterons (top) and protons (bottom).

One can confirm the existence of a large signal in the proton data. The zero compatible asymmetry which is seen in the deuteron data is understood as a cancellation between the u and d quarks in the deuteron molecule. More details can be found in [9]. In addition to the Collins asymmetries, COMPASS also have preliminary results on $h_1^u(x)$ and $h_1^d(x)$. These transversity functions were extracted from pion pair dihadron asymmetries, using the method described in [10], and are shown in Fig. 8. Concerning the u quark, a clear positive signal is observed at high x. For the d quark more data is needed to draw any conclusion.

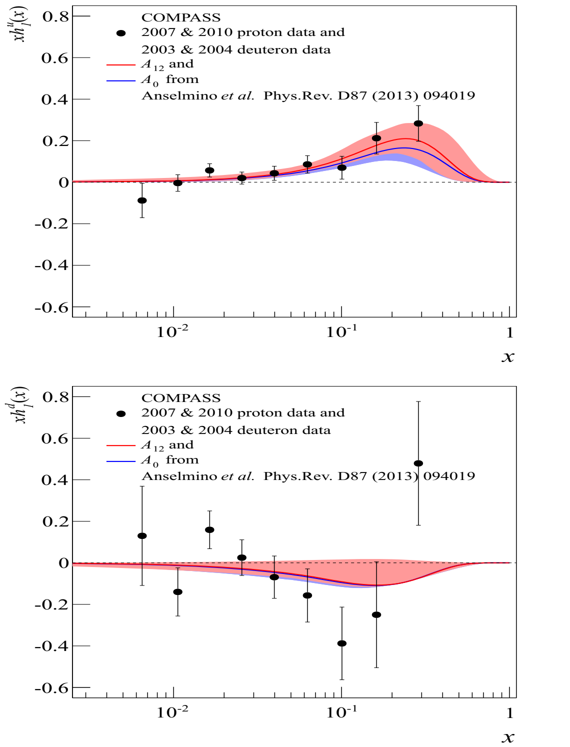

Figure 8: COMPASS results on the transversity function for the u (top) and d (bottom) quarks. A_{12} and A_0 were obtained from fits to the Belle data.

If one takes into account the intrinsic transverse momentum of partons, k_T, 5 additional TMDs are needed to describe the nucleon structure at leading twist. In particular, the Sivers TMD $f_{1T}^{\perp}(x, k_T)$ is of extreme importance. Since it correlates the nucleon transverse spin with the quarks k_T, this TMD is quite sensitive to the quarks OAM (one of the unknowns in Eq. 2). The Sivers function can be determined through a global analysis of the experimental Sivers asymmetry:

$$A_{Siv} = \frac{\sum_q e_q^2 f_{1T}^{\perp q}(x, Q^2, k_T) \otimes D_{1q}^h(z, Q^2)}{\sum_q e_q^2 F_1^q(x, Q^2) \otimes D_{1q}^h(z, Q^2)} \quad (9)$$

A_{Siv} is measured at COMPASS by fitting its specific $\sin(\phi_h - \phi_S)$ modulation. The results for quarks are shown in Fig. 9. This time a large signal is seen only for the positive hadrons of the proton data. For more details see [11]. Concerning the gluons, a preliminary result on the Sivers asymmetry was also made available by COMPASS. It was extracted from data by fitting the Sivers modulation of the dihadrons resulting from PGF processes. The obtained result, using only the deuteron data (so far), is:

$$A_{Siv}^{PGF} = -0.14 \pm 0.15 \pm 0.06 \quad @\langle x_g \rangle = 0.13 \qquad (10)$$

The gluon Sivers asymmetry is clearly compatible with zero. However, COMPASS is still improving the statistical precision of this particular measurement.

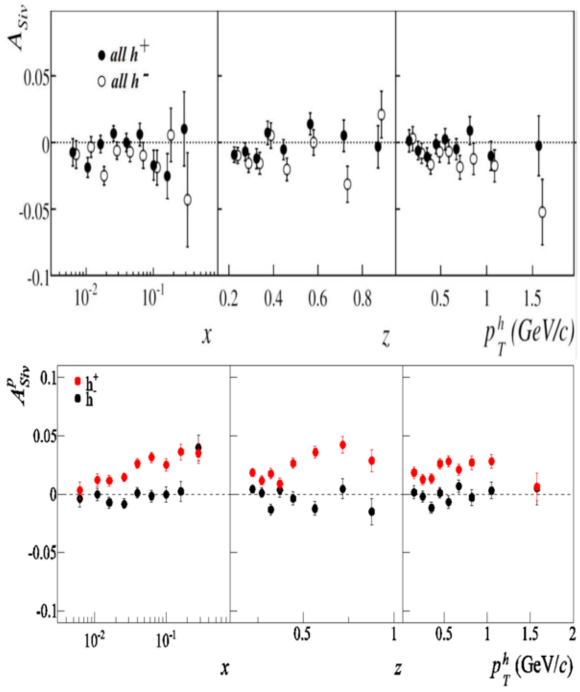

Figure 9: COMPASS results on the quark Sivers asymmetry for deuterons (top) and protons (bottom)

4. Outlook

From October 2014 onwards, two new topics will be investigated at COMPASS [12]. One of them is the study of 4 TMDs (Sivers, Boer-Mulders, Transversity and Pretzelosity) with the first ever polarised Drell-Yan experiment. The experiment will consist on a 190 GeV/c π^- beam scattering off a transversely polarised proton target (NH_3), and the analysis will be focused on the dimuon channel to take advantage of the excellent muon detection by the COMPASS spectrometer [1]. Besides the study of the TMDs distribution, the major goal is to verify the expected sign change of the Sivers and Boer-Mulders TMDs when accessed via SIDIS or Drell-Yan. The observation of the above mentioned sign change is crucial for our current understanding of TMDs and, by performing both measurements with the same spectrometer, COMPASS has privileged conditions to test this important QCD prediction. As a bonus the Drell-Yan experiment will also allow us to study the production mechanism and polarisation of the J/Ψ. These two goals can be achieved with the already approved one year of data taking in 2015. With a second year of data taking, possibly in 2018, it will be possible to study the TMDs as a function of x_F and p_T.

The other major topic will be investigated after the data taking of 2016 and 2017. The goal is the study of GPDs through the deeply virtual compton scattering (DVCS) of μ^+ and μ^- off a liquid hydrogen target. They will be determined from the analysis of the azimuthal dependence of the DVCS cross-section. Since the GPDs correlate the transverse spatial and the longitudinal momentum degrees of freedom, their knowledge will provide us the needed ingredients to obtain tomographic images of the proton. Besides this major breakthrough in the understanding of the nucleon structure, the GPDs are also the ideal tool to access the OAM of quarks via the Ji sum rule:

$$\begin{aligned} J^q &= \frac{1}{2}\Delta\Sigma + L^q \\ &= \frac{1}{2}\int_0^1 dx x[H^q(x,\xi,t) + E^q(x,\xi,t)] \qquad (11) \end{aligned}$$

where H^q and E^q represent two of the four GPDs that will be measured at COMPASS.

In parallel with the GPD programme, COMPASS will also perform two important measurements from unpolarised SIDIS events. The first one is the measurement of hadron multiplicities, using a proton target, to significantly improve our knowledge on fragmentation functions, $\Delta s(x)$ and $s(x)$ (specially at low x). The other major goal is the measurement of the Boer-Mulders TMD. The latter is of crucial importance to verify the sign change when compared to the Drell-Yan measurement.

5. Summary

The total quark contribution to the nucleon spin was measured with good precision and amounts only to 30%. The extraction of quark helicities was performed for all light flavours from SIDIS data and also from the NLO-QCD fits to the g_1 data. However, the role of $\Delta s(x)$ in the nucleon spin-puzzle is not yet clear. The contribution of the strange quark helicity to the nucleon spin is for sure small, but a more profound knowledge on fragmentation functions is required in order to have a precise determination of $\Delta s(x)$. To this end, i.e.

to improve our knowledge on fragmentation functions, COMPASS is measuring hadron multiplicities.

The gluon contribution to the nucleon spin was found to be small and compatible with zero in the x_g range covered by the measurements. Concerning the indirect extraction of the gluon helicity, more polarised data on $g_1(x, Q^2)$ is needed to reduce the ΔG uncertainty resulting from the NLO-QCD fits. Also, the existing calculations of A_{LL} for events with $Q^2 < 1$ (GeV/c)^2 are not capable of describing simultaneously the COMPASS measurements of A_{LL}(protons) and A_{LL}(deuterons). Note that there are several calculations of A_{LL}, at the NLO approximation, each one assuming a different value for ΔG.

Precise results on the Collins and Sivers asymmetries were shown (for quarks). By being non-zero, the latter points to a relevant contribution of the quarks OAM to the nucleon spin (and also to the importance of k_T in the description of the nucleon structure). Preliminary results on the transversity function, using pion pair dihadron asymmetries, were also presented for the valence quarks. A clear signal is seen for the u quark at high x. Concerning the gluons, a new measurement of the Sivers asymmetry was presented. The preliminary result, which was obtained only from deteron data, is compatible with zero.

An exciting physics program is in preparation for the near future. The expected outcome will be a kind of 3D imaging of the nucleon, both in the momentum space (TMDs) and in the position space (GPDs). A decisive step towards a proper understanding of the nucleon spin will also be given by determining the quarks OAM via the Ji sum rule.

Acknowledgments

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References

[1] COMPASS, P. Abbon et al., *The COMPASS experiment at CERN*, Nucl. Inst. Meth. A577, 455 (2007).

[2] COMPASS, V. Yu Alexakhin et al., *Spin asymmetry A_1^d and the spin-dependent structure function g_1^d of the deuteron at low values of x and Q^2*, Phys. Lett. B 647 (2007) 8.

[3] COMPASS, M. G. Alekseev et al., *Flavour Separation of Helicity Distributions from Deep Inelastic Muon-Deuteron Scattering* , Phys. Lett. B 680 (2009) 217.

[4] D. de Florian, R. Sassot, M. Stratmann and W. Vogelsang (DSSV), Phys. Rev. Lett. 101 (2008).

[5] Johan Alwall, *Quark Asymmetries and Intrinsic Charm in Nucleons*, Hep-ph/0508126.

[6] S. J. Brodsky, P. Hoyer, C. Peterson and N. Sakai, *The intrinsic charm of the proton*, Phys. Lett. B93 (1980) 451.

[7] COMPASS, M. G. Alekseev et al., *Leading and Next-to-Leading Order Gluon Polarisation in the Nucleon and Longitudinal Double Spin Asymmetries from Open Charm Muoproduction*, Phys. Rev. D 87 (2013) 052018.

[8] COMPASS, M. G. Alekseev et al. et al, *Leading order determination of the gluon polarisation from DIS events with high-pT hadron pairs*, Phys. Lett. B 718 (2013) 922.

[9] COMPASS, C. Adolph et al. et al, *Experimental investigation of transverse spin asymmetries in muon-p SIDIS processes: Collins asymmetries*, Phys. Lett. B 717 (2012) 376.

[10] Bacchetta A., Courtoy A. and Radici M. *First extraction of valence transversities in a collinear framework* JHEP (2013) 119

[11] COMPASS, C. Adolph et al. et al, *Experimental investigation of transverse spin asymmetries in muon-p SIDIS processes: Sivers asymmetries*, Phys. Lett. B 717 (2012) 383.

[12] COMPASS Collaboration, *COMPASS-II proposal*, CERN-SPSC.2010-014, SPSC-P-340, 17 May 2010.