The Spin Physics Results from COMPASS

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Abstract. COMPASS (**CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy) is a fixed target experiment at CERN dedicated to studies of the spin structure of the nucleon and of the spectroscopy of hadrons. During the years 2002-2004, 2006-2007 and 2010-2011 the COMPASS collaboration has collected a large amount of data by scattering polarized 160(200) GeV/c muons on polarized ^{6}LiD and NH_3 targets. The COMPASS results on quark and gluon helicities are discussed, as well as results on transverse spin and transverse momentum effects in semi-inclusive deeply inelastic scattering.

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THE COMPASS EXPERIMENT

The COMPASS experiment at CERN investigates how nucleons and other hadrons are built up from quarks and gluons. The main physics observables studied by the Collaboration are the polarization of the constituents of a polarized nucleon, the mass and decay patterns of the light hadronic system with either exotic quantum numbers or strong gluonic excitation.

The COMPASS set-up was designed for beams of 100 to 200 GeV/c and was built around two large dipole magnets, defining two consecutive spectrometers, covering large and small scattering angles separately. Particle identification is performed using a RICH counter and both electromagnetic and hadron calorimeters. Until 2006, the polarized target was filled with a ^{6}LiD target material (mainly deuterium), for which polarization better than 50% were routinely achieved. In 2007 we began using ammonia (NH_3, mainly proton), reaching a polarization of 90% and higher. A full description of the spectrometer can be found in [1].

Longitudinal spin structure of the nucleon

The gluon polarization measurement

Worldwide experimental efforts in the last few decades have led to numerous results extending our knowledge of the nucleon spin structure. But major challenges like the "spin crisis" still remain since 1988, when the EMC experiment found that only a small fraction of the nucleon spin is carried by the quarks: $\Delta\Sigma = 12 \pm 9 \pm 14\%$ [2]. The EMC result has been confirmed by a series of deep inelastic scattering experiments giving, on average, a contribution from the quarks $\Delta\Sigma$ to the nucleon spin of $\sim 30\%$.

The spin 1/2 of the nucleon can be decomposed as $1/2 = 1/2\Delta\Sigma + \Delta G + L_{q+g}$ and one can conclude that the missing contribution to the nucleon spin must come from the gluons ΔG, and/or from the orbital angular momenta L_{q+g}. The gluon polarization can be directly measured via the spin asymmetry of the Photon-Gluon Fusion (PGF) process. The fragmenting $q\bar{q}$ pairs are then detected with two different, but complementary methods. In the first method ("open charm"), the events where the charmed quark hadronized into a D^0 or a D^* meson are selected. In the second method ("high-p_T pairs"), the PGF events are identified by requiring that two oppositely charged high-transverse momentum hadrons are detected in coincidence.

All gluon polarization measurements performed at COMPASS are summarized in Fig.1(left) together with the SMC [3] and HERMES [4] results. The world results for direct measurements of $\langle \frac{\Delta g}{g} \rangle$ are dominated by COMPASS and indicate a small value of ΔG, the first moment Δg. This was confirmed by the COMPASS "open charm" result at NLO [5], which also predicts a small value for the gluon spin contribution to the nucleon Fig.1(right).

It should be noted that a new LO extraction of the gluon polarization from COMPASS DIS data was done recently [6]. An evaluation of the gluon polarization $\langle \frac{\Delta g}{g} \rangle$ was done using the all-p_T method and $Q^2 > 1$ (GeV/c)^2 events. This new method is based on a combination of neural network approach with a simultaneous extraction of A_1^{LO}

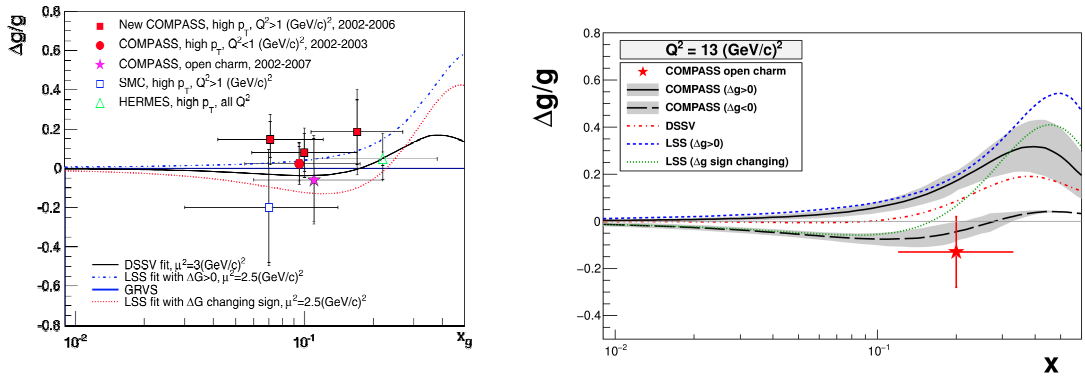

FIGURE 1. Left: Summary of the world efforts for the direct $\langle \frac{\Delta g}{g} \rangle$ measurement at LO in QCD. Right: NLO QCD result of COMPASS.

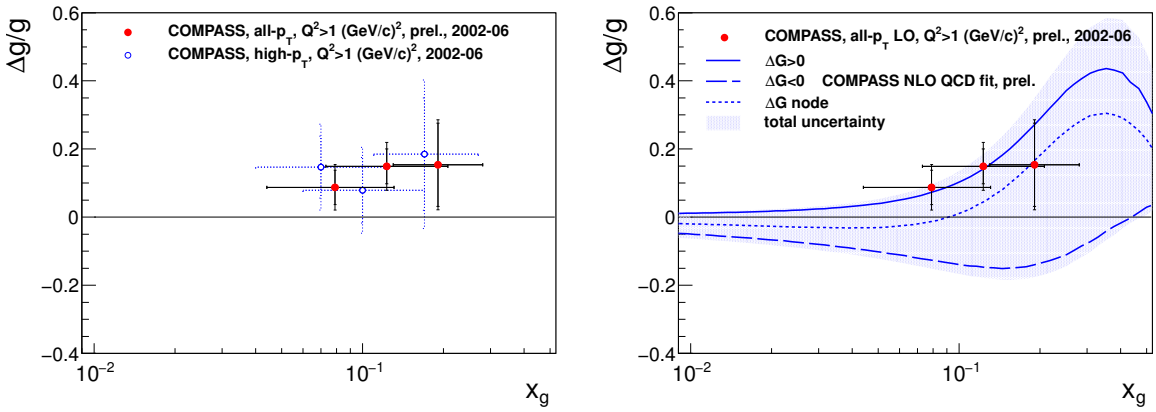

FIGURE 2. Left: Comparison of old and new results of $\langle \frac{\Delta g}{g} \rangle$ in three x_g bins. Right: Comparison of the new results with the newest COMPASS NLO QCD fit.

and the gluon polarization. The resulting value, from 2002-2006 data, is $\langle \frac{\Delta g}{g} \rangle = 0.113 \pm 0.038 \pm 0.035$, at $\langle x_g \rangle = 0.10$. Results of $\langle \frac{\Delta g}{g} \rangle$ in three x_g intervals were also calculated Fig.2(left). A reduction of both systematic and statistical uncertainties by more than 50% was achieved comparing to the already published value using the same data [7]: $\langle \frac{\Delta g}{g} \rangle = 0.125 \pm 0.060 \pm 0.063$, at $\langle x_g \rangle = 0.09$. The comparison of the new results with the newest COMPASS NLO QCD fit is shown in Fig.2(right).

Global NLO QCD fits to world data on g_1

A new global NLO QCD fit of world data on g_1^p, g_1^d, g_1^n including the latest g_1^p COMPASS data which extend the kinematic domain to a lower value of x and higher values of Q^2 was done [8]. These g_1^p measurements were obtained from the 2011 data with an incident muon beam energy of 200 GeV/c on a polarized NH_3 target. The NLO pQCD fit including the world data on g_1 is used to extract a parametrization of the spin singlet, non-singlet and gluon distribution functions as functions of x and Q^2. Different scenarios of polarized parton distributions were investigated. A detailed study of systematic effects was done. The largest uncertainty arises from the choice of the functional forms. At the end, three scenarios cover all possible results with $\Delta G < 0$, $\Delta G \sim 0$ and $\Delta G > 0$ respectively. They lead to values of $\Delta\Sigma$ between 0.256 and 0.336 at $Q^2 = 3$ (GeV/c)^2. All fits in Fig.3 are performed in $\overline{MS}$ renormalization and factorization scheme.

In addition, the 2011 g_1^p data allow an update of the test of the Bjorken sum rule connecting the ratio of the weak

coupling constants to the first moment of the non-singlet spin structure function g_1^{NS}. A value of $1.219 \pm 0.052 \pm 0.095$ is found for g_A/g_V in NLO, which is in excellent agreement with the results obtained from neutron β decay measurements.

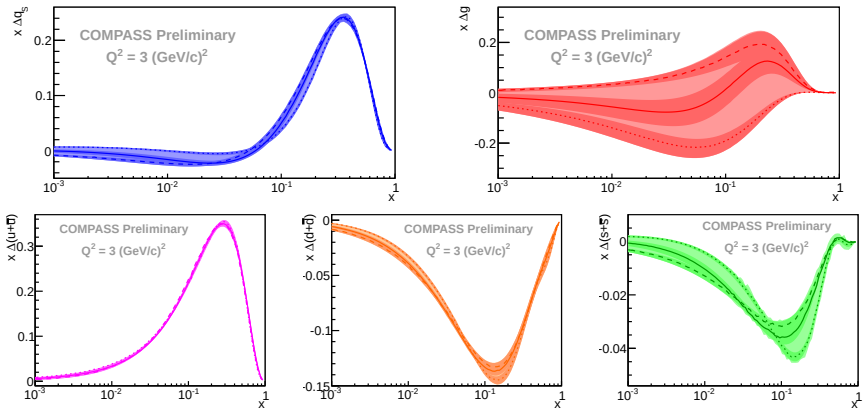

FIGURE 3. Results from the QCD fits of g_1 world data at Q^2=3 (GeV/c)^2. Top left: Quark spin distribution $x\Delta\Sigma$. Top right: Gluon spin distribution $x\Delta g(x)$. Bottom: $x(\Delta q + \Delta\bar{q})$ for u, d and s flavour going from left to right. For each distribution, the three solutions corresponding to the three different hypotheses of functional forms are shown

Transverse spin and momentum structure of the nucleon

The description of the partonic structure of the nucleon is one of the central problems of hadronic physics. In the present theoretical framework, eight transverse momentum dependent parton distribution functions (TMD PDFs) are required at leading twist for each quark flavour. They describe all possible correlations between the transverse momentum and spin of the quarks and the spin of the nucleon. When integrating over the quark transverse momentum five of these functions vanish, while three of them give the well known number, helicity and transversity distribution functions. Among these last three functions, the transversity distribution, which is the analogon of the helicity PDFs in the case of transversely polarized nucleons, was thoroughly studied only in the 90s and experimentally it is the least known one. On the experimental side, semi-inclusive deeply inelastic lepton scattering (SIDIS) is today the major source of information to access the TMD PDFs. The clear non-zero spin asymmetries recently measured in SIDIS off transversely polarized targets by both HERMES at DESY and COMPASS at CERN at different beam energies, can be described quite well with the present formalism, and thus give much confidence in the overall picture [9].

Collins and Sivers asymmetries

The results on azimuthal asymmetries in the reaction $\mu N \to \mu' h^{\pm} X$ were extracted from data collected in semi-inclusive deep inelastic scattering using a 160 GeV/c positive muon beam and a transversely polarized NH_3 target. The Collins and Sivers asymmetries of the proton were extracted in the Bjorken x range $0.003 < x < 0.7$. These asymmetries were extracted as a function of Bjorken x, the relative hadron energy z and the hadron transverse momentum p_T^h .

The Collins asymmetries (Fig.4) for negative and positive hadrons are similar in magnitude and opposite in sign. They are compatible with model calculations in which the u-quark transversity is opposite in sign and somewhat larger than the d-quark transversity distribution function. These studies confirm the leading-twist nature of the Collins asymmetry. The correlations between the Collins asymmetries measured along x, z and p_T^h respectively, and the correlations between the Collins and Sivers asymmetries have been investigated and found to be small.

The Sivers asymmetries (Fig.5) was found to be compatible with zero for negative hadrons and positive for positive hadrons, a clear indication of a spin-orbit coupling of quarks in a transversely polarized proton. As compared to measurements at lower energy, a smaller Sivers asymmetry for positive hadrons is found in the region $x > 0.03$. The asymmetry is different from zero and positive also in the low x region, where sea-quarks dominate. The kinematic dependence of the asymmetry has also been investigated and results are given for various intervals of hadron and virtual photon fractional energy. In contrast to the case of the Collins asymmetry, the results on the Sivers asymmetry suggest a strong dependence on the four-momentum transfer to the nucleon, in agreement with the most recent calculations. In the light of the most recent theoretical advances refined combined analyzes to evaluate the Sivers function and its

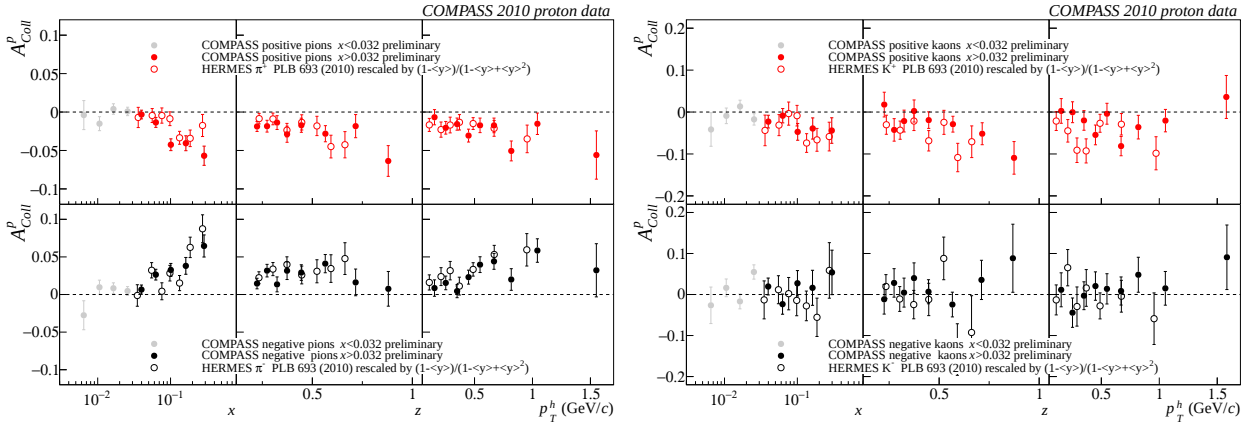

FIGURE 4. Comparison of the Collins asymmetries for charged pions and kaons as a function of x, z and p_T^h as measured by COMPASS (closed points) and HERMES [10] (open points). A cut on $x > 0.032$ has been applied to COMPASS data.

dependence on the SIDIS variables are required in order to understand the role of the Sivers function in the various transverse spin phenomena observed in hadron-hadron collisions and in future Drell-Yan measurements

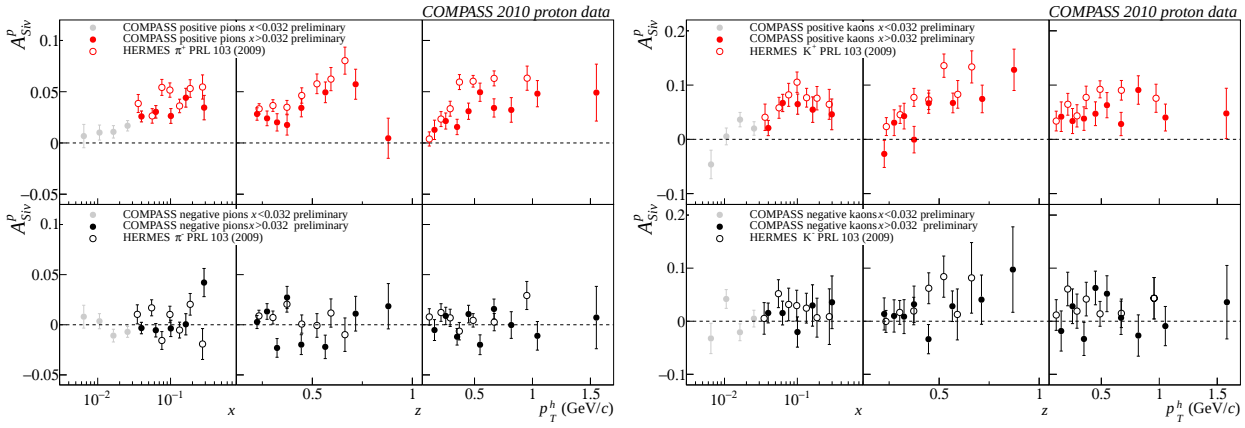

FIGURE 5. Comparison of the Sivers asymmetries for charged pions and kaons as a function of x,z and p_T^h as measured by COMPASS (closed points) and HERMES [11] (open points). A cut on $x > 0.032$ has been applied to COMPASS data.

Dihadron asymmetry and transversity PDF

An alternative to the Collins asymmetry approach to access the transversity PDF in SIDIS utilizes the transverse spin asymmetry in the production of pairs of oppositely charged hadrons, in the process $\mu N \to \mu' h^+ h^- X$ [12]. In this reaction a new chiral-odd fragmentation function appears, the dihadron Fragmentation Function (DiFF), which describes the spin-dependent part of the fragmentation of a transversely polarized quark into a pair of unpolarized hadrons describing a correlation of quark transverse spin with the normal pseudo-vector to the dihadron momenta plane.

The obtained asymmetry [13] is shown in Fig.6 as a function of x, z and $M_{\rm inv}^{\pi^+\pi^-}$. Large negative asymmetry amplitudes are observed in the high x region, which implies that both, the transversity distributions and the spin-dependent dihadron fragmentation functions do not vanish. Over the measured range of the invariant mass $M_{\rm inv}^{\pi^+\pi^-}$ and z, the asymmetry is negative and shows no strong dependence on these variables.

The extracted transversity PDF are shown in Fig.7 demonstrate very good agreement for the u-quark transversity with the global fit and fair agreement for the d-quark. An approximate equality of the Collins asymmetry and the dihadron asymmetry is observed, suggesting a common physical mechanism in the underlying fragmentation.

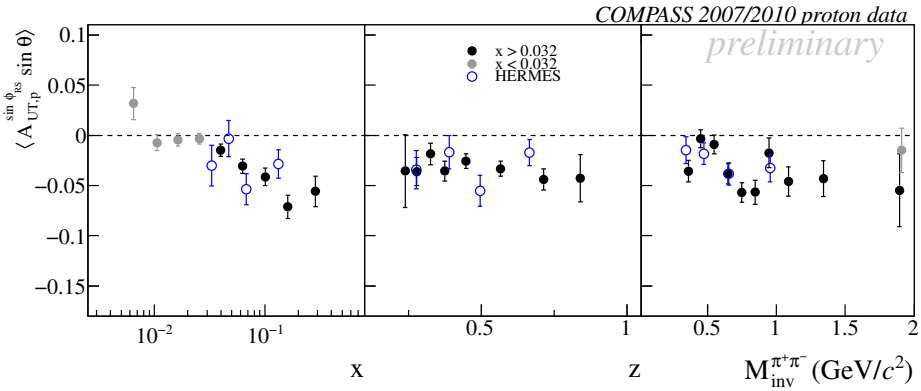

FIGURE 6. The $\pi^+\pi^-$ pair asymmetries of combined 2007/2010 proton COMPASS data in comparison with results from the HERMES experiment [14] scaled with $\frac{1}{D_{nn}}$ and sign changed.

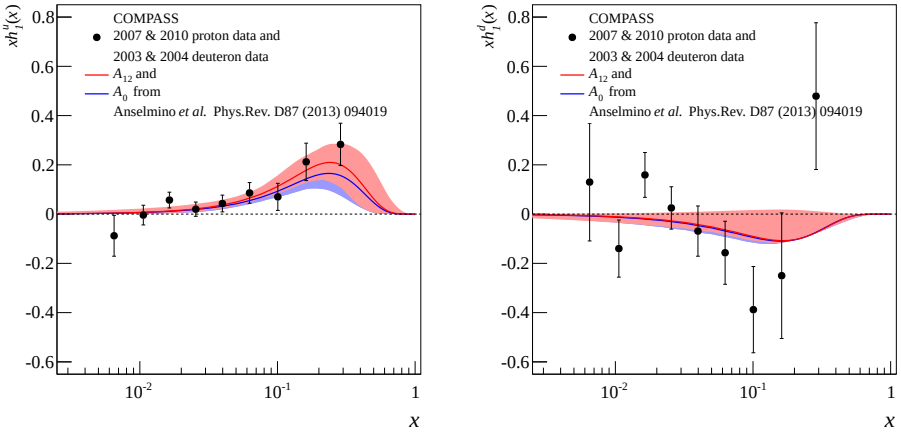

FIGURE 7. Comparison the results for u and d valence quarks transversity extracted from the 2003/2004 deuteron and the 2007/2010 proton pion-pair asymmetries with the single hadron Collins asymmetry global fit by [15].

REFERENCES

1. P. Abbon et al., *Nucl. Instr. Meth.* **A577** 455-518 (2007).
2. J. Ashman et al., *Phys. Lett.* **B206** 364-382 (1988).
3. B. Adeva et al., *Phys. Rev.* **B70** 012002-13 (2004).
4. A. Airapetian et al., *Phys. Rev. Lett.* **84** 2584-2588 (2000).
5. C. Adolph et al., *Phys. Rev.* **D87** 052018-22 (2013).
6. M. Stolarski, *DIS2014* Warsaw Poland 28 April - 2 May 2014.
7. C. Adolph et al., *Phys. Lett.* **B718** 922-930 (2013).
8. M. Wilfert, *DIS2014* Warsaw Poland 28 April - 2 May 2014.
9. C. A. Aidala, S. D. Bass, D. Hasch and G. K. Mallot, *Rev. Mod. Phys.* **85** (2013) 655-691 (2013); V. Barone, F. Bradamante and A. Martin, *Prog. Part. Nucl. Phys.* **65** 267-333 (2010).
10. A. Airapetian et al., *Phys. Lett.* **B693** 11-16 (2010).
11. A. Airapetian et al., *Phys. Rev. Lett.* **103** 152002-152008 (2009).
12. J. C. Collins, S. F. Heppelmann and G. A. Ladinsky, *Nucl. Phys.* **B420** 565-582 (1994).
13. C. Braun, *Transversity* Cagliari Italy 9-13 June 2014.
14. A. Airapetian et al., *J. High Energy Phys.* **0806** 017-035 (2008).
15. M. Anselmino et al., *Phys. Rev.* **D87** 094019-15 (2013).