Nucleon Spin Structure, experimental overview

F.Kunne

CEA Saclay, IRFU/SPhN, 91190 Gif/Yvette France

Abstract. An experimental overview on Nucleon Spin Structure studies is given. It covers results from HERMES, RHIC and COMPASS experiments. Latest results on quark and gluon helicities are discussed, as well as results on transversity. A brief presentation of future measurements is given.

Keywords: Spin of the Nucleon; gluon and quark helicity, transversity, polarization
PACS: 13.88.+e

INTRODUCTION

Much progress has been obtained recently on the study of the nucleon spin structure. We review here the results on the gluon and quark helicities obtained by HERMES, COMPASS, PHENIX and STAR. Measurements of transverse spin asymmetries, leading to the determination of the transverse spin quark distributions and to the Sivers functions are also discussed. In the last section we give a brief outlook on future projects.

LONGITUDINAL SPIN STRUCTURE OF THE NUCLEON

One of the main goals of the current experiments studying nucleon spin structure is to determine how the total longitudinal spin projection of the nucleon, 1/2, is distributed among its constituents: quarks, gluons and orbital angular momentum. This is summarized in the equation $1/2 = (1/2)\Delta\Sigma + \Delta G + L_z$, where $\Delta\Sigma$ is the contribution of the spin of all quarks (sum over $u, \bar{u}, d, \bar{d}, s, \bar{s}$). Old estimations from the naive quark parton model as well as from a QCD approach neglecting strange quark polarization, have predicted a large polarization of the quarks, *i.e.* $\Delta\Sigma = 0.6$. When EMC first measured a value of $\Delta\Sigma$ compatible with zero in 1987, this led to the nucleon "spin crisis". Since then, extensive measurements during the last decades have shown that the singlet axial matrix element a_0, which is related to $\Delta\Sigma$, is indeed small, of the order of 0.3, but not zero. In fact in some QCD schemes, $a_0 = \Delta\Sigma - (3\alpha_s/2\pi)\Delta G$. Thus a very large value of ΔG, several times the value of the nucleon spin, had even been advocated to possibly restore $\Delta\Sigma = 0.6$ when $a_0 = 0.3$.

Today, first results from lattice QCD calculations indicate in the contrary that the valence quark contributions to the nucleon spin could likely add up to a lower value of $\Delta\Sigma$ (restricted to u and d quarks) compatible with the latest measurements (0.3). They also indicate possible sizable individual quark contributions $L_{z(u)}$ and $L_{z(d)}$ to the total angular momentum L_z however opposite to each other for u and d and thus canceling in L_z. Not much is known theoretically on the gluon contribution ΔG, and in the last

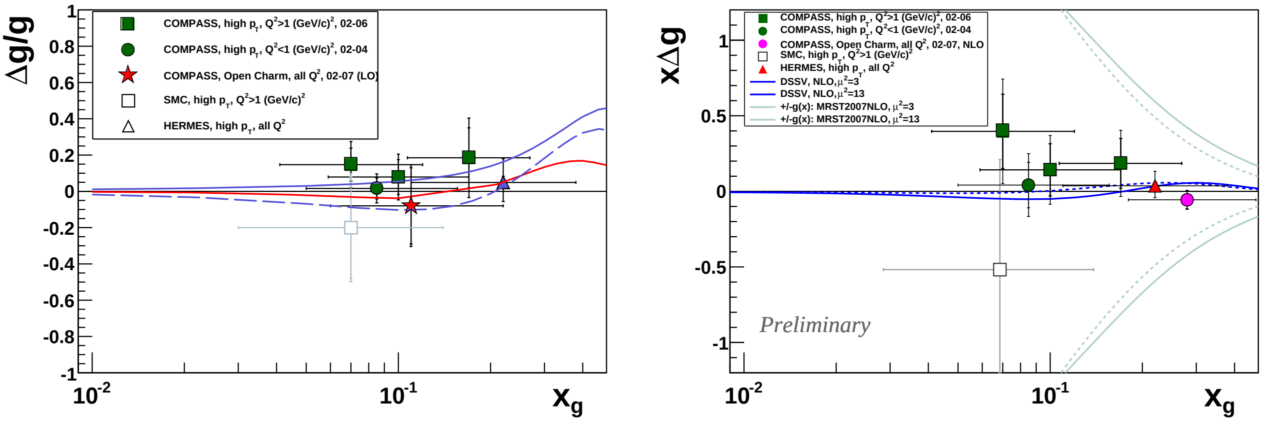

FIGURE 1. *left*: Direct measurements of the gluon polarization $\Delta g/g(x)$ from HERMES, COMPASS and SMC. All points are extracted at leading order (LO) in QCD. The curves are DSSV (lower red line) [4] and LSS (dashed and upper blue lines) [5] QCD fits at LO not including the data. *right*: same data but showing $x\Delta g$. The high p_T results are exactly the same, while the single point from the open charm channel (closed circle) has been extracted this time at next to leading order (NLO) and thus probes higher x(see text and [3]). The curves close to the zero axis show DSSV QCD fit at NLO at scales of 3 and 13 GeV^2. The external curves show the limits given by $\pm x_g(x)$. QCD scale is $\approx$ 3 GeV^2 for the high p_T data and 13 GeV^2 for the charm point.

15 years a large experimental effort has been undertaken for its measurement by various collaborations: HERMES at DESY, COMPASS at CERN, STAR and PHENIX at RHIC.

Gluon polarization

Experimentally, the gluon polarization can be determined by three different methods: (i) in polarized lepton nucleon SIDIS reactions, (ii) in polarized pp hard collisions, by choosing channels sensitive to the gluon distribution and measuring spin asymmetry of cross-sections, or (iii) through global QCD fits of polarized inclusive DIS data.

(i) By using polarized lepton beams, 27 GeV electron beam at HERMES or 160 GeV muon beam at COMPASS, scattered on polarized nucleons, direct measurements of ΔG are performed via the double spin asymmetry of cross sections for the photon gluon fusion (PGF) process $\gamma g \rightarrow q\bar{q}$. PGF events can be searched for in two channels: the "open charm channel" where a $c\bar{c}$ pair is produced and a charm quark is identified via the production of a D^0 meson, and the "high p_T hadron" channel, where outgoing quarks (likely light quarks) hadronize into hadrons, mainly pions, with high transverse momentum p_T. The open charm channel is only accessible at COMPASS thanks to the high energy of the CERN polarized muon beam. It provides a clean signature of the PGF but is a difficult channel requiring to count events with D^0 production over a large combinatorial background of π K pairs, leading to limited statistics. On the contrary, the high p_T channel, used at both COMPASS and HERMES, benefits from high statistics but

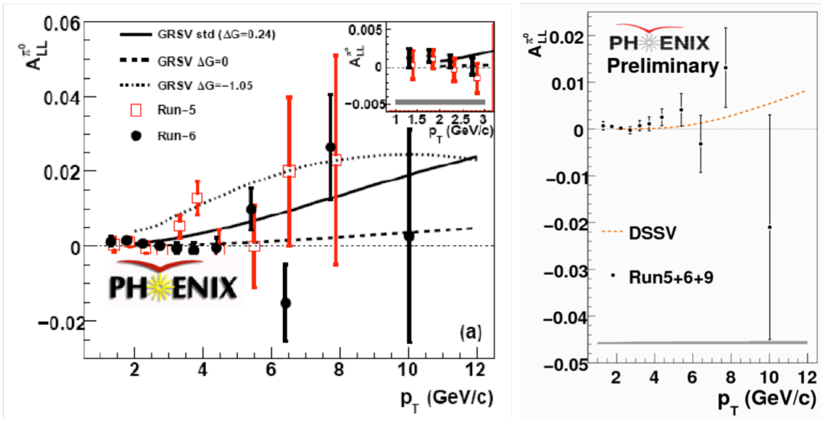

FIGURE 2. Double spin asymmetry $A_{LL}(p_T)$ for π_0 production at PHENIX. Data from runs 5 and 6 favor GRSV parametrization with $\Delta G = 0$ (*left*, dashed line). More precise data from run 9 (*right*) confirm the trend, they are compared to DSSV[4] parametrization corresponding also to a small value of ΔG, -0.08

suffers from competing background processes which have to be simulated and accounted for. Fig.1 *left* shows all existing direct measurements of the gluon polarization $\Delta G/G(x)$ extracted at leading order (LO) in QCD from the measured spin asymmetries in the high p_T and charm channels. COMPASS results [1] from the open charm (star) and high p_T (closed squares and circle) channels are shown together with HERMES (triangle)[2] and SMC (open square) results. The measurements probe x_g values of the gluon momentum fraction around 0.1-0.2 and give results compatible with zero in this kinematic range. The curves in Fig.1 *left* show parametrization from QCD analyses which do not include these data and which are discussed later. Fig.1 *right* shows the data this time plotted as $x\Delta G$. The high p_T results are exactly the same, while the single point from the open charm channel (closed circle) has been extracted this time at next to leading order (NLO)[3]. It has required the evaluation at NLO of the spin asymmetry (analyzing power a_{LL}) of the PGF process. The resulting value for ΔG is still compatible with zero, but the x_g range probed appears to be rather different, shifted towards higher values. This is partly due to the rapid variation including sign change, of $a_{LL}(x_g)$ causing a change in the relative weight of each event.

(ii) The other experimental studies of the gluon polarization are performed at the RHIC collider. Collisions of protons polarized longitudinally in opposite directions have been realized mainly at the energy of $\sqrt{s} = 200$ GeV, but also at 62 GeV and more recently 500 GeV, covering various kinematics ranges. Several channels are used to pin down the gluon polarization. The most abundant channels in term of statistics are the production of π^0 at PHENIX, and the production of jets at STAR [6]. In both cases, three different elementary processes (gg, gq and qq) contribute to the cross-section, so that the measured double spin asymmetries $A_{LL}$are sensitive to a combination of three quantities: $\Delta G(x_1).\Delta G(x_2)$, $\Delta G(x_1).\Delta q(x_2)$, and $\Delta q(x_1).\Delta q(x_2)$, where x_1 and x_2 are the fractions of momentum carried by the two colliding partons. For each physical channel (π^0, jets, etc.) the measured double spin asymmetry $A_{LL}(p_T)$ is compared to calculations where a given parametrization of $\Delta G(x)$ is assumed. The results [6] presented in Fig.2 for the π_0 channel and in Fig.3 for the single jet(left) and di-jet (right) channels show that

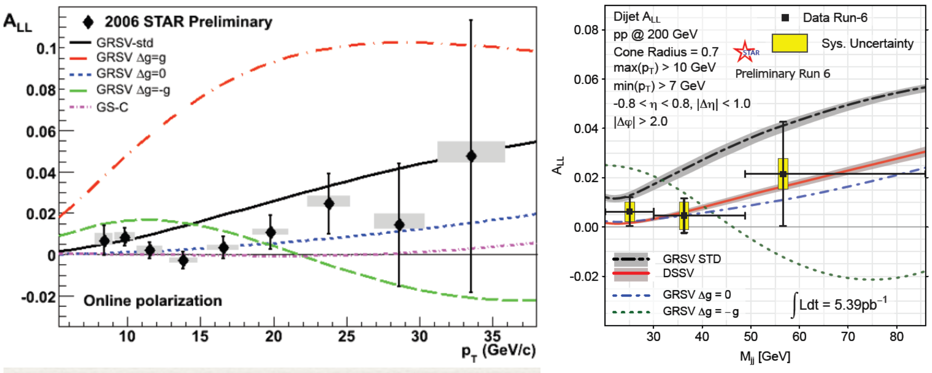

FIGURE 3. Double spin asymmetry $A_{LL}(p_T)$ for single jet (*left*) and di-jet (*right*) production at STAR. Data from favor GRSV parametrization with $\Delta G = 0$ (*left* blue dashed line, and *right* blue dot-dashed line), as well as DSSV parametrization (*right*, red full line) for which $\Delta G = -0.08$

all data favor parametrization with a gluon polarization close to zero. The data provide a strong constrain on the mean value of ΔG in the measured range $0.05 < x_g < 0.3$. Data taken at higher energy (500 GeV) are not yet included here. They will be helpful to constrain the lower x_g region.

(iii) The third way to determine -indirectly- the gluon contribution to the nucleon spin is to perform a global fit of polarized data, making use of the QCD Q^2 evolution equations which correlate g_1 and ΔG. Data on the longitudinal spin structure function g_1 exist for the proton, deuteron and neutron (^{3}He). They cover three decades in x and three in Q^2 (Fig.4). This is not quite sufficient to constrain severely enough $\Delta G(x, Q^2)$, however first results from global fits exist. To further constrain the fit, polarized pp data can be added [4]. As a result the polarized gluon distribution is severely constrained to values close to zero in the range $0.05 < x_g < 0.3$, as shown with the DSSV[4] fit plotted in Fig.1 *left* and *right*. For the future, precise g_1 data being taken now at COMPASS at 200 GeV incident muon energy will improve the quality of data at low x values.

Quark helicities

In parallel to the polarized inclusive DIS measurements, semi inclusive (SIDIS) events where an additional hadron tags the flavor of the struck quark, were recorded both at HERMES and COMPASS. The data from this reaction $\mu p \to \mu h X$ are used to extract at LO the helicity quark distributions for each quark flavor separately down to $x = 0.004$. This provides a wider picture of the nucleon spin, however requiring an additional input, the quark fragmentation functions (FF). COMPASS results [7] obtained using FFs from DSS [9] are shown in Fig.5 together with HERMES results[8] where FFs are extracted from the same HERMES data. The curve shows the global QCD fit of DSSV [4] at LO. Sea quark polarized distributions are found to be compatible with zero within the statistical errors. Concerning the strange quarks, note that the DSSV fit accommodates both the SIDIS data (COMPASS and HERMES data, shown here and compatible with zero), and the results from analyses of inclusive DIS data, which lead to a negative first

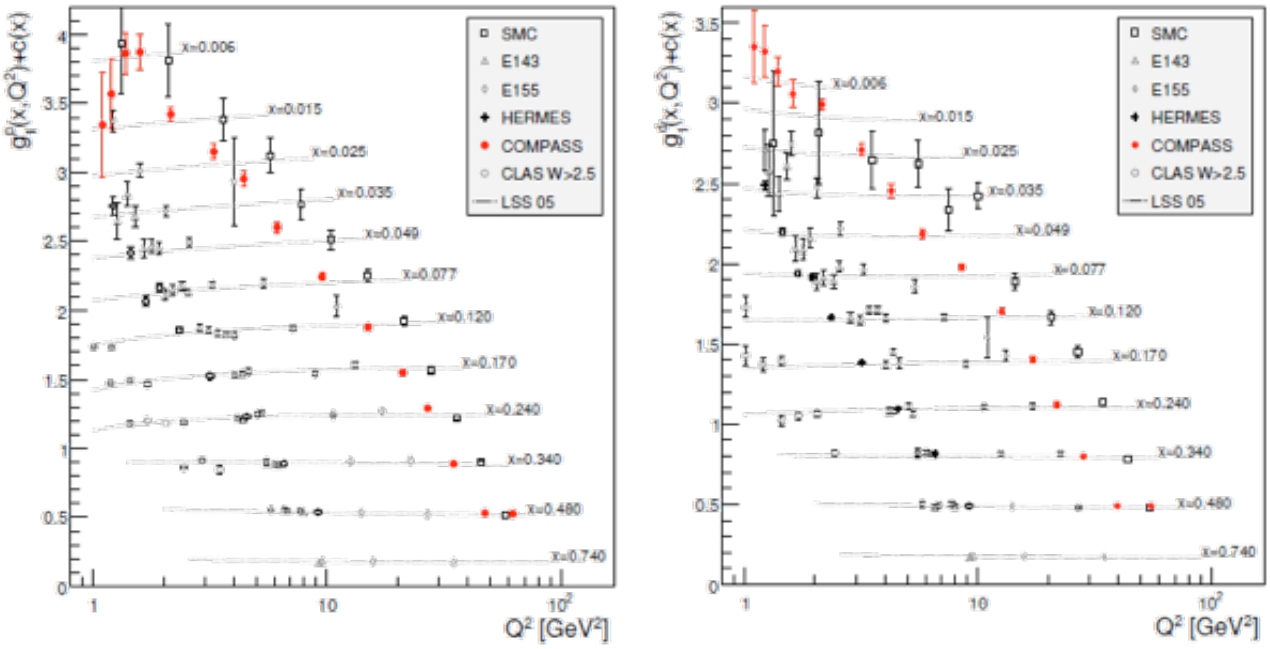

FIGURE 4. World data on longitudinal spin structure function g_1: proton (*left*) and deuteron (*right*)

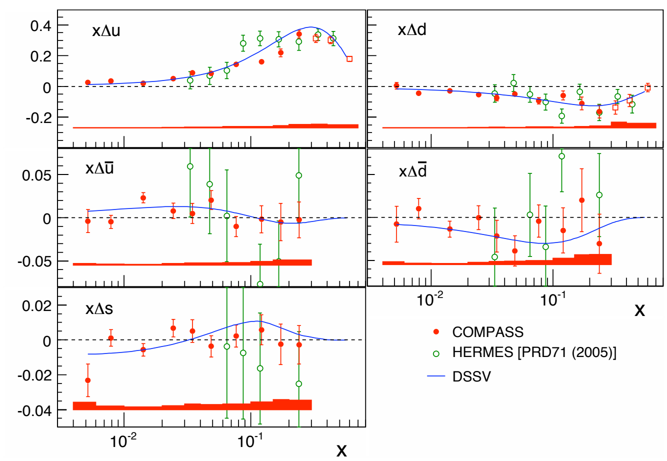

FIGURE 5. COMPASS (closed red points) and HERMES (open green points) results for the helicity quark distribution $x\Delta q(x)$ for five flavors compared to the global fit at NLO from DSSV[4].

moment for Δs (suggesting a negative contribution at low x). In the future, the SIDIS sector will benefit from more precise determination of quark FFs.

At RHIC, in a short exploratory run, first collisions at 500 GeV were performed. By studying the parity violating reaction $u+\bar{d} \to W^+ \to e^+ + \nu$ the quantity $\Delta\bar{d}/\bar{d} - \Delta u/u$ is probed (similarly $\Delta\bar{u}/\bar{u} - \Delta d/d$ via W^-). First results from PHENIX and STAR reporting asymmetries with signs as expected from SIDIS results, are very encouraging [10]. The advantage of this channel is that no FF are needed for the extraction of quark helicities.

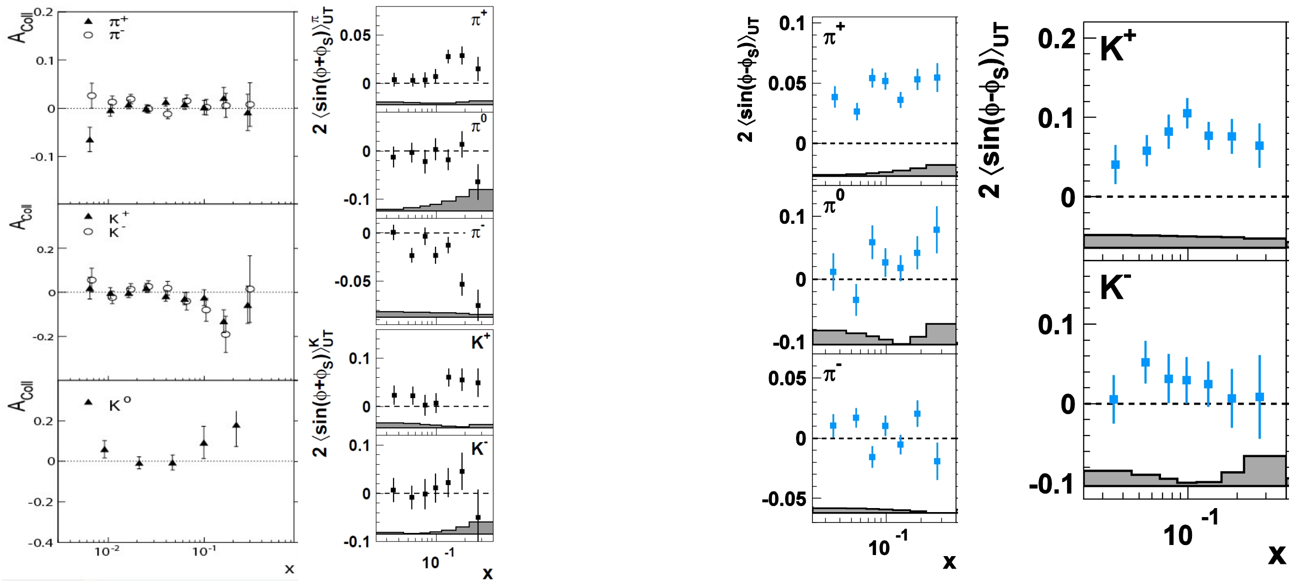

FIGURE 6. *Left*: Collins asymmetry for $\pi^{+/-}, K^{+/-}, K^0$ from COMPASS deuteron target data (first column) and Collins asymmetry for $\pi^+, \pi^0, \pi^-, K^+, K^-$ from HERMES proton target data (second column). Note no signal in $\pi^{+/-}$ deuteron, while there is signal in $\pi^{+/-}$ proton. *Right*: Sivers asymmetry for π^+, π^0, π^- (third column) and K^+, K^- (fourth column) from HERMES proton target data[**?**]. Note signal in π^+, and even larger signal in K^+.

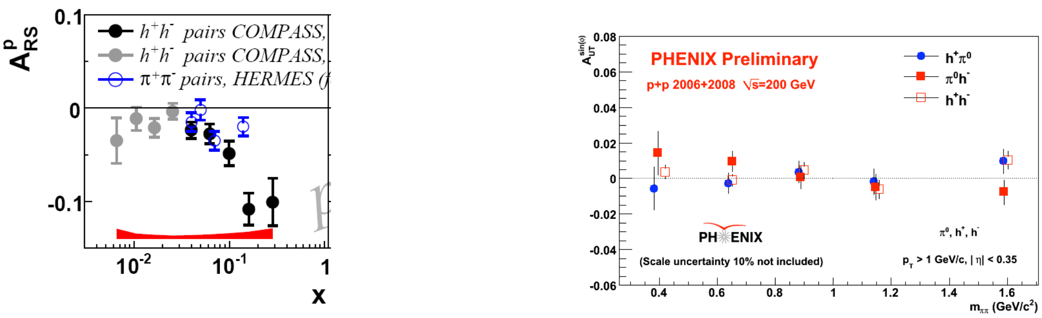

FIGURE 7. *Left*: COMPASS (closed points) and HERMES (open points) results for the ”hadron pair azimuthal asymmetry”, an alternative way to probe transversity; note the large signal at high x. *Right*: PHENIX results for the ”hadron pair azimuthal asymmetry”, probing a region more sensitive to gluons

TRANSVERSITY AND TMD

Three structure functions are necessary to describe the nucleon at leading twist: $F_1(x), g_1(x)$ and $h_1(x)$. If one does not integrate over the transverse momentum dependent (TMD) distributions of the partons, more structure functions are needed. $h_1(x)$ is linked to the distribution of transversely polarized partons and can be accessed in SIDIS. The experiment requires a lepton beam, a transversely polarized nucleon target and the detection of an outgoing hadron $lp \Uparrow \rightarrow lph^{+/-}$. The Collins and Sivers asymmetries as well as other azimuthal asymmetries are measured simultaneously by looking at various modulations of the outgoing angle of the hadron. The Collins asymmetry is sensitive to the correlation between the outgoing hadron direction and the initial quark transverse spin. Thus it can provide a determination of the quark transverse spin distributions $\Delta_T u$ and $\Delta_T d$. The Sivers asymmetry, obtained from a different angular modulation, is sensitive to a TMD that correlates the nucleon spin and the transverse momentum of the parton k_T. Collins and Sivers asymmetries were measured both at HERMES and COMPASS using a transversely polarized proton target, and in addition at COMPASS using a deuteron target. Mainly because of cancelations between u and d quark contributions, the data on deuteron give asymmetries compatible with zero [11] for both Collins (Fig 6 *left-first column)* and Sivers (not illustrated here). On the contrary signals are observed with the proton target for the Collins asymmetry [13] for all charged hadrons (Fig 6 *left-second column*) and for the Sivers one for positive hadrons (Fig 6 *right*). COMPASS data on the proton [12] (not shown in the figures) are in excellent agreement with HERMES data for Collins, and give slightly smaller signal for Sivers. More statistics will be available soon from COMPASS 2010 data. An early global analysis[14] using the first HERMES proton data combined with the COMPASS deuteron data and the BELLE fragmentation function data, led to the extraction of $\Delta_T u$ and $\Delta_T d$. They were shown to be opposite to each other in sign, and smaller in size than the helicity distributions. The extracted u and d Sivers functions are also opposite in sign. The forthcoming data will help disentangle the dependence on the various kinematic variables x, z, p_T.

An alternative method to probe quark transverse spin distributions $\Delta_T u$ and $\Delta_T d$ is to study azimuthal asymmetries from hadron pairs. Data from HERMES and COMPASS (Fig.7 *left*) confirm the signal of transversity at high x. HERMES data were used for a first direct extraction of transversity [15] at LO. A similar approach with hadron pair production is followed at RHIC (Fig.7 *right*) but there, the asymmetries are compatible with zero. Note that the kinematic range is different there, likely dominated by gluons.

Single spin asymmetries in $pp \Uparrow \rightarrow \pi^{+/-/0} + X$ are studied at RHIC in the BRAHMS, PHENIX and STAR experiments[16]. They confirm that the large asymmetries seen in the past at much smaller energies, do persist at 62 and 200 GeV. The mechanisms involved, Collins, Sivers or higher twist contributions are being investigated.

As a conclusion, it must be noted that there has been major progress in measurements on transversity and transverse momentum dependent (TMD) distributions [17]. These TMDs constitute a powerful tool to understand the correlations. They are complemented by lattice calculations which start to quantify correlations observed between spin, position and momentum of the partons.

OUTLOOK

There are very good perspectives for spin physics studies at existing and future facilities. After the current program, RHIC prepares upgrades both on the accelerator and on the detectors. On the machine side, higher polarization (0.65 instead of 0.50) and higher luminosity ($3.10^{31} cm^{-1} s^{-1}$, *i.e.* three times higher than today) are foreseen for 2014, while STAR and PHENIX upgrades should be completed already by 2012. In parallel a new polarized Drell-Yan experiment *AnDY* dedicated to transverse spin is being prepared. The major physics goals for the years to come at RHIC are the measurements of helicity distributions in polarized W-production, the measurement of the gluon polarization at lower x values from di-jets and di-hadrons, the Sivers asymmetries in Drell-Yan where the sign change versus SIDIS is expected, and Collins asymmetries using di-hadron fragmentation functions and hadrons in jets.

In the COMPASS-II experimental program, foreseen for 2012 onwards, two new sectors will be studied: the transverse imaging of the nucleon with the measurement of generalized parton distributions (GPDs) via exclusive processes, and the TMD distributions via polarized Drell-Yan reactions. In parallel to the GPD program where the DVCS $\mu p \to \mu p \gamma$ process will be measured, high statistics on SIDIS reactions $\mu p \to \mu p h$ will be recorded. Azimuthal hadron asymmetries will give access to several TMDs. In addition, a full mapping of pion and kaon multiplicities will serve as input to global QCD analyses of quark FF on one side and on PDFs on the other one. The polarized Drell-Yan program will use high energy pion beam in conjunction with a transversely polarized NH_3 target. Spin asymmetries sensitive to various TMDs like the Sivers and Boer-Mulders ones, will provide a test of the factorization approach: the sign of the Sivers function is expected to be opposite in the DY and SIDIS reactions and this has never been tested experimentally.

Future projects, described in dedicated contributions to this conference, like JLab-12 GeV and the long term project of an electron ion collider EIC or ENC, will contribute to the common effort to study nucleon spin, opening new kinematical ranges.

REFERENCES

1. COMPASS, C.Marchand et al., *these proceedings*
2. HERMES, JHEP 08 (2010) 130, arXiv:1002.3921
3. COMPASS, K.Kurek et al., *these proceedings*
4. D. de Florian, R. Sassot, M. Stratmann and W. Vogelsang (DSSV) *Phys. Rev. Lett.* 101 (2008) 072001; see also M. Stratmann et al. *these proceedings*,
5. E. Leader, A. Sidorov, D. Stamenov (LSS), *Phys. Rev. D* 82 (2010) 114018
6. PHENIX *Phys. Rev. Lett.* 103 (2009) 012003; STAR *Phys. Rev. Lett.* 100 (2008) 232003; see also contributions of A. Datta, M.Walker, P. Djawotho *these proceedings*
7. COMPASS *Phys. Lett. B* 693 (2010) 227
8. HERMES, *Phys. Rev. D* 71 (2005) 012003; see also *Phys. Lett. B* 666 (2008)466
9. D. de Florian, R. Sassot and M. Stratmann (DSS) *Phys. Rev. D* 75 (2007) 114010
10. PHENIX *Phys. Rev. Lett.* 106 (2011) 062001; STAR *Phys. Rev. Lett.* 106 (2011) 062002; see also contributions from R. Towel, J. Seele *these proceedings*.
11. COMPASS *Phys. Lett. B* 673 (2009) 127
12. COMPASS *Phys. Lett. B* 692 (2010) 240
13. HERMES *Phys. Rev. Lett.* 103 (2009)152002
14. M. Anselmino et al., *arXiv:0812.4366*
15. A.Courtoy, A.Bachetta et al., *these proceedings*
16. PHENIX and STAR, see contributions of F.Wei, R.Fersch, *these proceedings*
17. HERMES and COMPASS, see contributions of L.Pappalardo, C.Schill, *these proceedings*