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Nucleon Spin Structure- Experimental overview

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We review here the results on the gluon helicity and quark helicities in the nucleon. They contribute to solve the problem of the decomposition of the ½ spin of the nucleon among its constituents. Data were obtained by the HERMES and COMPASS collaborations using longitudinally polarized lepton beams and polarized nucleon targets, and at PHENIX and STAR using colliding polarized proton beams. Some results on transversity are also shown. They were obtained with transversely polarized targets and lead to the determination of the transverse spin quark distributions. In the last section we give a brief outlook on short term future plans.

XV International Conference on Hadron Spectroscopy (Hadron 2013)
November 4-8 2013
Nara, Japan

http://pos.sissa.it

PoS(Hadron 2013)027

1. Introduction

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 and antiquarks. 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 $\Delta\Sigma$=0.6. When EMC first measured a value of $\Delta\Sigma$ compatible with zero in 1987, this led to the nucleon ”spin crisis”. Extensive measurements during the last decades have shown that the singlet axial matrix element a_0, which is related to $\Delta\Sigma$, is small, of the order of 0.3, but not zero. 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 been advocated to restore $\Delta\Sigma$ = 0.6 when a_0=0.3. Today, first results from lattice QCD indicate in the contrary that the valence quark contributions to the nucleon spin could add up to a lower value of $\Delta\Sigma$ (u and d only) compatible with the latest measurements (~0.3). They also indicate sizable quark contributions $L_z(u)$ and $L_z(d)$ to the angular momentum Lz however opposite thus canceling in L_z. Not much is known theoretically on ΔG, and in the last 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 BNL.

2.Gluon polarization

The gluon polarization can be determined by three different methods: (i) in polarized lepton nucleon 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 e^- at HERMES or 160 GeV μ at COMPASS, scattered on polarized nucleons, direct measurements of $\Delta G/G$ are performed via a double spin asymmetry of cross sections for the photon gluon fusion (PGF) process $gg \rightarrow qq$. PGF events are searched for in two channels: the ”open charm channel” where a cc pair is produced and a c quark is identified via the production of a D^0 meson, and the ”high p_T hadron” channel, where outgoing lighter quarks hadronize into 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 statistics is limited and D^0 events suffer from a large combinatorial background of πK pairs. On the contrary, the high p_T channel benefits from high statistics but suffers from competing background processes which have to be simulated. Fig.1 shows all existing direct measurements of the gluon polarization $\Delta G/G(x)$ extracted at leading order (LO) in QCD. 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 gluon momentum fraction x_g around 0.1 and give results compatible with zero. The curves show parameterizations from QCD analyses which do not include these data and which are discussed later.

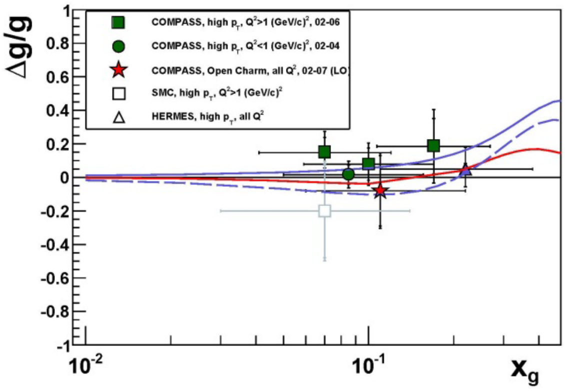

Figure 1: World direct measurements gluon polarization $\Delta g/g(x)$:COMPASS (4 green points from high p_T and red star from open charm), HERMES and SMC, all at LO. The curves are DSSV (red) [3] and LSS (blue) [4] QCD fits at LO, at Q^2=3 GeV^2, and not including the data.

(ii) At RHIC, collisions of longitudinally polarized protons have been realized mainly at $s^{1/2}$ = 200 GeV, but also at 62 GeV and more recently 500 GeV. Several channels are used to pin down the gluon polarization. The most abundant ones in terms of statistics are the production of π^0 at PHENIX and of a single jet at STAR [5]. 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 colliding partons. For each channel (π^0, jets, etc.) $A_{LL}(p_T)$ is compared to calculations where a given parameterization of

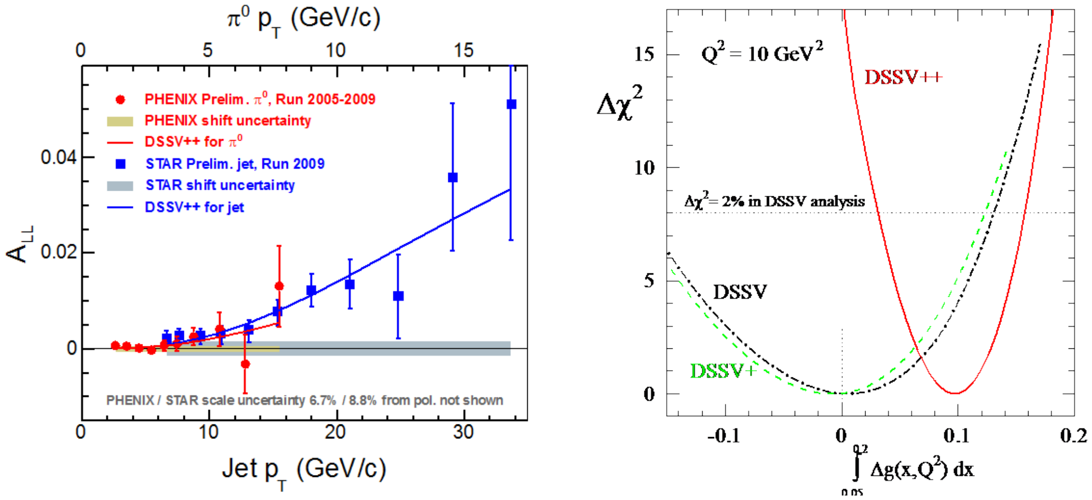

Figure 2: *Left:* $A_{LL}(p_T)$ for π^0 (PHENIX) and jet production (STAR) [5] including 'run 9' data. *Right:* 'DSSV++' fit (in red), vs old DSSV one (in black). χ^2 is now minimum for ΔG~0.1 for 0.05 <x_g< 0.2.

$\Delta G(x)$ is assumed. RHIC 'run 9' (2009) data are shown in Fig.2 *left* for the π^0 and jet channels. The data provide a strong constraint on $<\Delta G>$ in the range $0.05 < xg < 0.2$. The DSSV++ fit including these data indicates a positive value $<\Delta G>\sim 0.1$ in this x interval (Fig.2 *right*). Higher energy (500 GeV) data, not yet included here, will constrain a 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 the longitudinal spin structure function g_1 and ΔG. Data exist for the proton, deuteron and neutron (^{3}He). The data set includes recent COMPASS g_1^p data at 200 GeV, and it covers three decades in x and three in Q^2 (Fig.3). This is not sufficient to constrain severely $\Delta G(x,Q^2)$. When polarized pp data are added [3], $<\Delta G>$ is constrained in the range $0.05< x_g<0.2$.

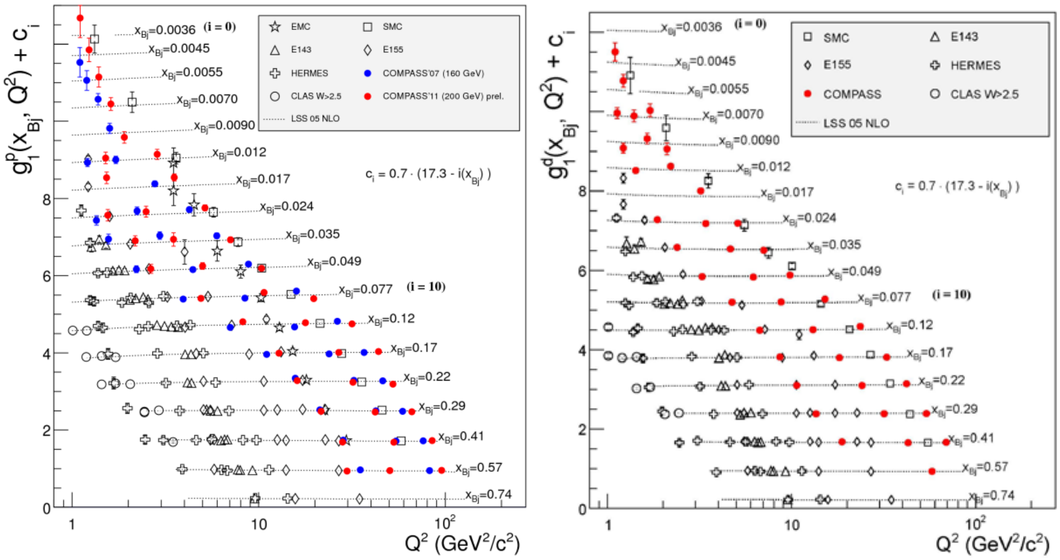

Figure 3. World data on longitudinal spin structure function g_1 for proton (left) and deuteron (right)

3.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 the reaction, $\mu p \rightarrow \mu hX$, are used to extract at LO the helicity quark distributions for each quark flavor separately down to $x = 0.004$. This provides a broader picture of the nucleon spin, but requires an additional input, the quark fragmentation functions (FF). COMPASS results [6] obtained using FFs from DSS [8] are shown in Fig.4 *left* together with HERMES results [7] 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

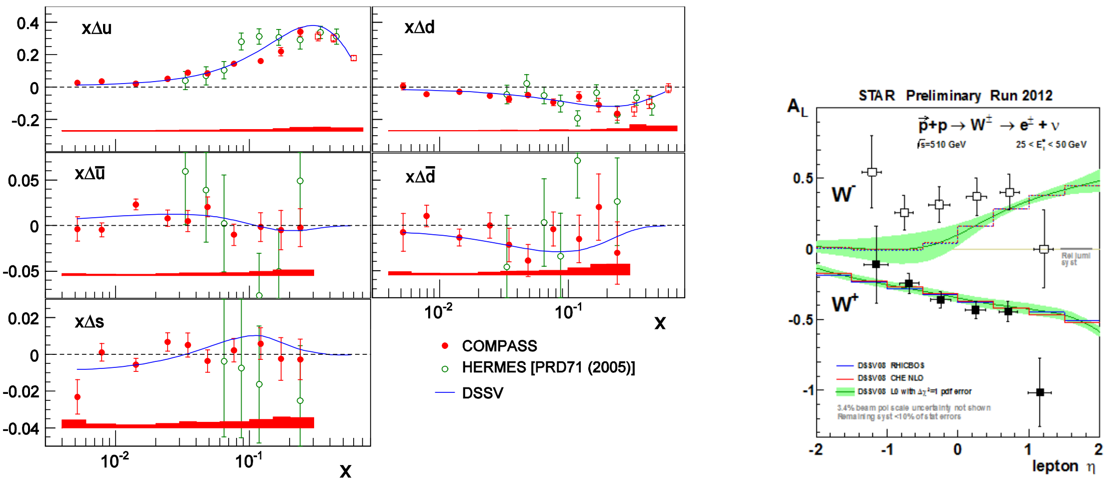

Figure 4. *Left:* COMPASS (closed red points) and HERMES (open green points) results for the helicity quark distributions $x\Delta q(x)$ for five flavors compared to the global fit at NLO from DSSV [4]. *Right:* STAR data on the spin asymmetry for W production.

and compatible with zero), and the results from analyses of inclusive DIS data, which lead to a negative first 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, first polarized pp collisions at 500 GeV were analyzed. By studying the parity violating reaction u d-bar $\rightarrow W^+ \rightarrow e^+ \nu$, the quantity Δd-bar/d-bar − Δu/u is probed (similarly Δu-bar/u-bar − Δd/d via W^-). First results from STAR ‘run 12’ are shown in Fig.4 *right* [9]. They constrain Δu-bar and Δd-bar. This channel probes a high energy scale and no FF are needed.

4.Transversity

Three structure functions are necessary to describe the nucleon at leading twist: F_1 (unpolarised), g_1 (longitudinal spin) and h_1 (transverse spin). If one does not integrate over the parton transverse momentum k_T, more structure functions are needed: the parton Transverse Momentum Dependent (TMD) distributions. h_1 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 *h* in the reaction $lp \rightarrow lh^{+/-}$. Collins, Sivers and other azimuthal asymmetries are measured simultaneously by looking at various modulations of the outgoing hadron angle. The Collins asymmetry is sensitive to the correlation between the outgoing hadron direction and the initial quark transverse spin. It provides a determination of the quark transverse spin distributions $\Delta_T u(x)$ and $\Delta_T d(x)$. The Sivers asymmetry is sensitive to a TMD distribution that correlates the nucleon spin and k_T. Collins and Sivers asymmetries were measured both at HERMES (p data) and COMPASS (p and d) using transversely polarized targets.

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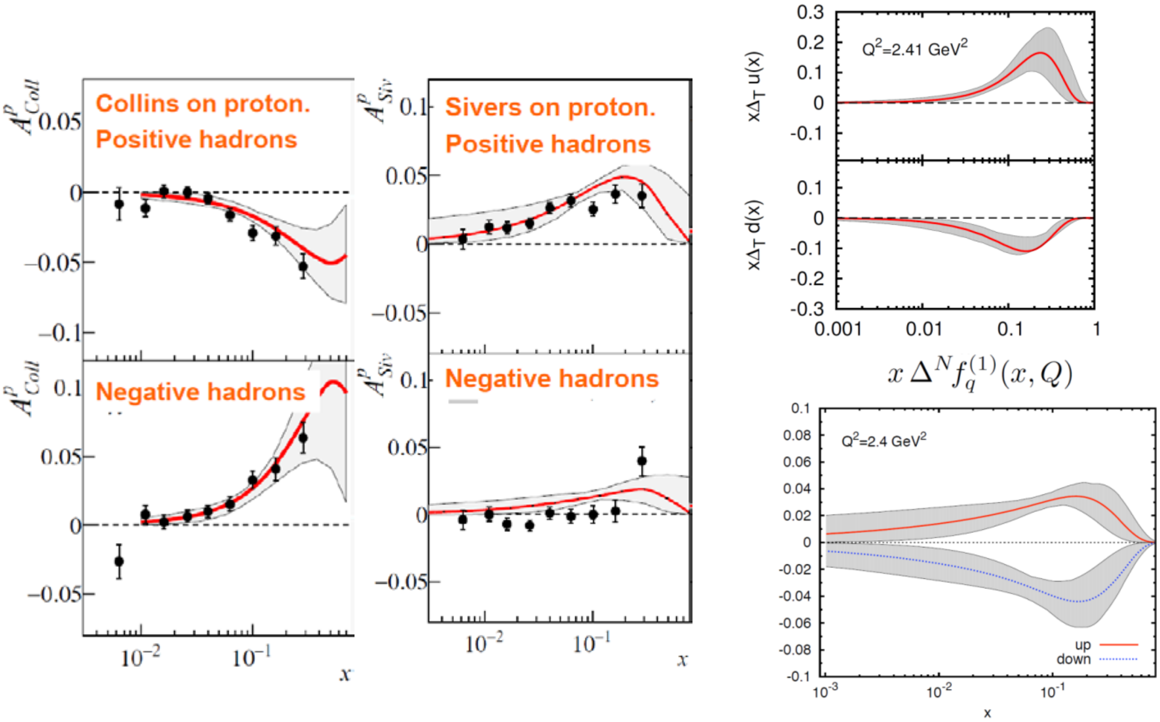

Figure 5. *Left:* Collins asymmetry on proton target, for positive *(top)* and negative *(bottom)* hadrons, COMPASS 2007+2010 data. *Center:* same for Sivers asymmetry. *Right T*ransversely polarized parton distributions *(top)* and Sivers functions *(bottom)* for u and d flavors, extracted from a global QCD analysis of HERMES, COMPASS and Belle data.

Mainly because of cancelations between u and d quark contributions, the data on deuteron give asymmetries compatible with zero [10] for both Collins and Sivers (not illustrated here). On the contrary signals are observed with the proton target for the Collins asymmetry [10] for charged hadrons (Fig.5 *Left*) and for the Sivers one for positive hadrons (Fig.5 *Center)*. Taken at an average Q^2 about 3-4 times higher than HERMES, COMPASS data on the proton are in excellent agreement with HERMES for Collins, but give slightly smaller signal for Sivers. Global analyses as in [11] (Fig.5 *Right*) using the HERMES p data combined with the COMPASS p and d data and the Belle FF data, lead to the extraction of $\Delta_T u(x)$ and $\Delta_T d(x)$. They are 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 [11] (Fig.5 right). More data are needed to disentangle the dependence on the various kinematic variables x, z and p_T. As a conclusion, there has been major progresses in measurements of transversity and TMD distributions which 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.

5. Outlook

At RHIC, higher beam polarization and higher beam luminosity (3. 10^{31}cm^{-1}s^{-1}, *i.e.* three times higher than today) are foreseen for 2014. At COMPASS, two new sectors will be studied: the TMD distributions via polarized Drell-Yan reactions and the transverse imaging of the nucleon with the measurement of Generalized Parton Distributions (GPDs) via exclusive processes. In parallel to the GPD program, high statistics on SIDIS reactions $\mu\, p \rightarrow \mu'\, h$ will be recorded both to access several TMDs and to perform a full mapping of pion and kaon multiplicities which will serve as input to global QCD analyses of quark FFs and PDFs. Future projects 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.

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