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Transverse Spin and Transverse Momentum Effects at COMPASS

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The study of transverse spin and transverse momentum effects is part of the scientific program of COMPASS, a fixed target experiment at the CERN SPS. For these studies, a 160 GeV/c momentum muon beam is scattered on a transversely polarized nucleon target, and the scattered muon and the forward going hadrons produced in DIS processes are reconstructed and identified in a magnetic spectrometer. The measurements have been performed on a deuteron target in 2002, 2003 and 2004, and on a proton target in 2007. The main results obtained measuring single spin asymmetries are reviewed, with particular emphasis on the most recent proton measurements. After two years of spectroscopy measurements with hadron beams, in 2008 and 2009, the Collaboration will resume measurements with the muon beam and a transversely polarized target in 2010.

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1. Introduction

The quark structure of the nucleon is fully specified at the twist-two level by three parton distributions: the momentum distributions $q(x)$, the helicity distributions $\Delta q(x)$ and the transverse spin distributions $\Delta_T q(x)$, where x is the Bjorken variable. The latter distribution, often referred to as transversity, is chiral-odd and thus not directly observable in deep inelastic lepton-nucleon scattering (DIS). In 1993 Collins suggested that transversity could be measured in semi-inclusive DIS (SIDIS) thanks to a mechanism involving in the hadronisation another chiral-odd function [1], known as the "Collins function" $\Delta_T^0 D_q^h$, i.e. a possible spin dependent part of the usual fragmentation function D_q^h. The mechanism is expected to lead to an azimuthal asymmetry A_{Coll} (the "Collins asymmetry") in the distribution of the inclusively produced hadrons. At leading order A_{Coll} can be written as

$$A_{Coll} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}\,, \tag{1}$$

and should show up as the amplitude of a $\sin\Phi_C$ modulation in the hadron azimuthal distribution. The Collins angle $\Phi_C = \phi_h + \phi_s - \pi$ is the sum of the azimuthal angles of the hadron transverse momentum $\vec{p}_T^{\,h}$ (ϕ_h) and of the spin direction of the target nucleon (ϕ_s) with respect to the lepton scattering plane, as measured in the Gamma-Nucleon System. Since this workshop honours Anatoli, I'd like to remind that he has been a pioneer in trying to directly measure this Collins function by looking for a possible correlation between the azimuthal angles of the hadrons in the two jets resulting from the $e^+e^- \rightarrow hadrons$ annihilations at high energy. The statistics of the DELPHI collaboration data at LEP which were looked at [2] was not sufficient to unambiguously show up the effect. Recently, however, measurements of the reaction $e^+e^- \rightarrow hadrons$ by the Belle Collaboration have established directly that this Collins fragmentation function is sizable [3]. Also, the non-zero Collins asymmetries for the proton observed by HERMES [4] require both non-vanishing Collins fragmentation and transversity functions.

An alternative way to address the transversity distribution has also been suggested [5,6,7,8]. Very much like for the Collins case, the fragmentation of a transversely polarized quark into a pair of distinguishable hadrons h_1 and h_2 is expected to show an azimuthal modulation of the type $A_{\Phi_{RS}}\, sin\Phi_{RS}$, where $\Phi_{RS} = \phi_R + \phi_s - \pi$. The angle ϕ_R is defined introducing the vector $\vec{R} = (z_2\vec{p}_1 - z_1\vec{p}_2)/(z_1 + z_2)$, where $\vec{p}_1$ and $\vec{p}_2$ are the momenta in the laboratory frame of h_1 and h_2 respectively, and z_1 and z_2 are the fractions of the virtual photon energy carried by the two hadrons. ϕ_R is the azimuthal angle between the transverse component of $\vec{R}$ and the lepton scattering plane in the Gamma-Nucleon system. Also in this case a non-zero asymmetry amplitude $A_{\Phi_{RS}}$ has been measured, so that an alternative way to measure transversity is at reach.

If the quarks are assumed to be collinear with the parent nucleon (no intrinsic quark transverse momentum $\vec{k}_T$), or after integration over $\vec{k}_T$, the three distributions $q(x)$, $\Delta q(x)$ and $\Delta_T q(x)$ exhaust the information on the internal dynamics of the nucleon. However, admitting a finite $\vec{k}_T$ a total of eight transverse momentum dependent (TMD) distribution functions are needed for a full description of the SIDIS cross-section [9]. All these functions lead to azimuthal asymmetries in the distribution of produced hadrons and can be disentangled in SIDIS using their different angular modulations. In between these TMD PDFs, of particular interest is the Sivers function which arises from a correlation of the transverse momentum of an unpolarised quark in a transversely polarised nucleon and the nucleon polarisation vector. Neglecting the hadron transverse momentum with respect to the fragmenting quark, this $\vec{k}_T$ dependence could cause the "Sivers asymmetry"

$$A_{Siv} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h} \tag{2}$$

in the distribution of the hadrons resulting from the quark fragmentation with respect to the nucleon polarization. The Sivers asymmetry could be revealed as a $\sin\Phi_S$ modulation in the number of produced hadrons, where $\Phi_S = \phi_h - \phi_s$ and ϕ_h

and ϕ_s are the azimuthal angles which enter in definition of Φ_C. Measuring SIDIS on a transversely polarized target allows the Collins and the Sivers effects to be disentangled, as shown by the COMPASS and the HERMES experiments.

All in all, understanding the transverse spin structure of the nucleon has gained considerable momentum in the recent ten years, and the COMPASS experiment has given, is still giving, and will give an important contribution in this direction.

Recently, considerable attention has also been devoted to the investigation of exclusive channels in high-energy lepton - nucleon scattering. Processes like Deeply Virtual Compton Scattering (DVCS) or Deeply Virtual Exclusive Meson Production (DVEMP) can give access to Generalized Parton Distributions (GPDs) and consequently to a wealth of information on the nucleon structure. In particular vector meson production on a transversely polarized target is sensitive to the nucleon helicity-flip GPD E [10] which allows through the Ji sum rule [11] to access in a unique way the orbital angular momentum carried by the partons in the proton. This new line of investigation benefits of a rigorous theoretical background, and the perspectives for a complete 3-D description of the nucleon have propagated much excitement in the scientific community. While new experiments are being planned to measure GPDs, the existing DIS experiments, like HERMES, COMPASS, and the experiments at JLab, have already started to look at exclusive processes.

In the talk I gave at this workshop I briefly mentioned all the results we have obtained scattering a 160 GeV μ^+ beam on transversely polarized deuteron and proton targets, namely:

- single spin asymmetry (SSA) for inclusive single hadron production;
- SSA's for pairs of inclusive hadrons;
- SSA's for exclusive ρ's;
- inclusive Λ polarization;
- azimuthal hadron asymmetries ("Cahn asymmetries") for unpolarized nucleons.

At COMPASS the measurements on the transversely polarised ^{6}LiD target have been performed in 2002, 2003 and 2004 In those data no appreciable asymmetries were observed within the accuracy of the statistical errors of the measurements [12,13,14]. The deuteron data are still to-day the only SIDIS data ever taken on a transversely polarized target, and provide important constraints to the contribution of the d-quark. Together with the HERMES data on a transversely polarized proton target and the $e^+e^- \rightarrow hadrons$ Belle data they have allowed to perform the first global analysis and extract the transversity distributions and the Sivers functions for the u- and d-quarks [15,16,17]. Most of the results on the deuteron target have already been published. In this written report therefore I will concentrate only on our recent measurements on the proton target, which have been collected in 2007.

2. The COMPASS Experiment

The COMPASS spectrometer [18] is in operation in the North Hall (Hall 888) of CERN since 2002. To ensure large angular acceptance and dynamical range it is a two-stage magnetic spectrometer, and to cope with the different requirements of location accuracy and rate capability at different angles it uses a variety of tracking detectors. Particle identification is provided by a large acceptance RICH detector, by calorimeters, and by muon filters. Major upgrades have been executed in 2005, and the phase space of the proton target data is larger than that of the deuteron data. The main changes concern the polarised target, the tracking system, the RICH detector, and the electromagnetic calorimeter. A major difference in the spectrometer with respect to its initial configuration is given by the use of a new target solenoid magnet (PTM) which has an acceptance of ± 180 mrad as seen from the upstream end of the target (it was ± 70 mrad with the previously used magnet). To polarize the target material and to hold the polarisation in the longitudinal mode the solenoid provides a field of 2.5 T, with an excellent homogeneity of $\pm 2 \cdot 10^{-5}$ over the whole target volume. Very much as the old magnet, the new magnet is also equipped with two sets of saddle-shaped coils which can provide a 0.6 T vertical field, which is used either to rotate the target nucleon spin or to hold the polarisation vertical for the transversity measurements. The polarised target consists of three cylindrical cells, 4 cm diameter: one central cell, 60 cm long, and two other ones, each 30 cm long, separated by 5 cm. Neighboring cells are polarised in opposite directions, so that data from both spin directions are recorded at the same time. In the deuteron measurements, a configuration of two cells, each 60 cm long, was used, but the much larger acceptance of the new PTM suggested the three-cell configuration, which further reduces false asymmetries. The target material (NH_3) is first longitudinally polarised in the solenoidal field with the method of dynamical nuclear polarisation (DNP). The maximum polarisation value achievable in the three cells ranges between 0.80 and 0.90, depending slightly on the sign of the polarisation and on the cell location. About 48 hours are necessary to reach 95% of the maximal polarisation. When the desired polarisation value is reached, the radio frequency system is switched off, the target spins get frozen, the magnetic field is lowered to 0.6 T and adiabatically rotated to the vertical direction by suitably varing the solenoid and the dipole fields. In the frozen spin mode and with the holding field at its operational value (0.6 T) the relaxation time of the polarisation exceeds 3000 hours.

In 2007 data have been taken at a mean beam intensity of $7 \cdot 10^6$ μ/s (typically $2 \cdot 10^8$ μ/spill, for a spill length of 4.8 s every 16 s). About $12 \cdot 10^9$ events, corresponding to 440 TB of data, have been collected, using up $4 \cdot 10^{13}$ muons, in six separate periods. In each period, after 4-5 days of data taking, a polarisation reversal was performed by changing the microwave frequencies in the three cells, always keeping the central cell oppositely polarised with respect to the external ones.

In the data analysis, in order to ensure a DIS regime, only events with a photon virtuality $Q^2 > 1$ (GeV/c)^2, a fractional energy of the virtual photon $0.1 < y < 0.9$, and a mass of the hadronic final state $W > 5$ GeV/c^2 are considered.

The transverse spin asymmetries are obtained by comparing, cell by cell, the azimuthal distributions of the detected hadrons as measured in the first half of a period with the corresponding distributions of the second half. Since the two sets of data are taken typically one week apart, the stability of the apparatus is crucial and has been carefully checked. As a result of the quality control, only the data collected in the last 3 periods have been used in so far for the extraction of the Sivers asymmetry. The Sivers asymmetry shows up as a modulation of the azimuthal angle of the hadron transverse momentum with respect to the target spin, and is very sensitive to any instability of the spectrometer. Due to the commissioning of several new counters and new trigger elements the spectrometer was not stable enough in the first part of the run, thus those data have not been used to produce the preliminary results we have released in so far. On the contrary, the Collins asymmetry is an asymmetry in the azimuthal angle between the hadron transverse momentum and a direction which depends on the target spin direction and the lepton scattering plane, which is different for each event. All the tests on the data quality and stability have not revealed any systematic effects on the extraction of the Collins asymmetry, and all the six periods have therefore been used for the extraction of the Collins asymmetry results.

The same argument holds for the hadron pair asymmetry $A_{\Phi_{RS}}$: it is also defined with respect to the lepton scattering plane, thus it also turned out to be not sensitive to small variations in acceptance of the spectrometer, and all the six periods of data have been used to extract the preliminary results.

3. Results

The Collins and Sivers asymmetries have been evaluated for positive and negative hadrons in bins of the three kinematic variables x, z and p_T^h. The raw asymmetries have been extracted for each data taking period and have been divided for the dilution factor, the target polarisation and, in the case of the Collins analysis, for the D_{NN} kinematical factor. The dilution factor of the ammonia target has been evaluated for each bin; it is constant at a value of 0.15 in z and p_T^h bins, while it increases with x from 0.14 to 0.17. The target polarisation was measured individually for each cell and each period, with a 5% uncertainty. Finally, the weighted mean of the asymmetries measured in each period has been performed. The systematic errors have been evaluated as a fraction of the statistical error and are 0.4 and 0.6 for the Collins and Sivers asymmetries respectively.

Preliminary results for the Collins asymmetries on about half of the collected statistics have been first shown at Transversity 2008 [19]. In Fig. 1 I show the results on the full statistics, which have first been presented at DIS 2009 [20]. The asymmetries shown in Fig. 1 are given as function of x, z, and p_h^T, for positive and negative hadrons. The error bars are only statistical. As clear in Fig. 1, the Collins asymme-

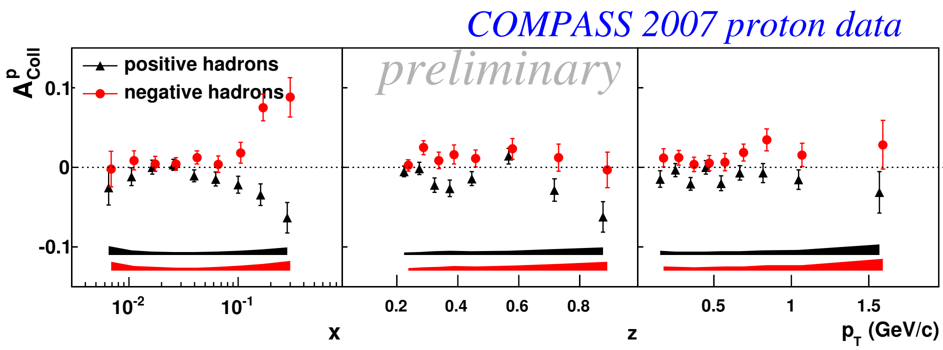

Fig. 1. Collins asymmetry as function of x, z, and p_h^T, for positive and negative hadrons.

try has a strong x dependence. It is compatible with zero at small x and increases up to 0.10 in the valence region ($x > 0.1$). The values agree both in magnitude and in sign with the previous measurements of HERMES [4], which have been performed at a considerably lower electron beam energy. Also, as shown in Fig. 3, they agree with the predictions of the global analysis of ref. [16] I mentioned in the introduction which, using the proton HERMES preliminary data, the deuteron COMPASS data, and the Belle data, allowed a first extraction of the u- and d-quark transversity PDF. The nice agreement of this analysis with the previous measurements, which have been used as input to the fit, and with the present proton results is a strong

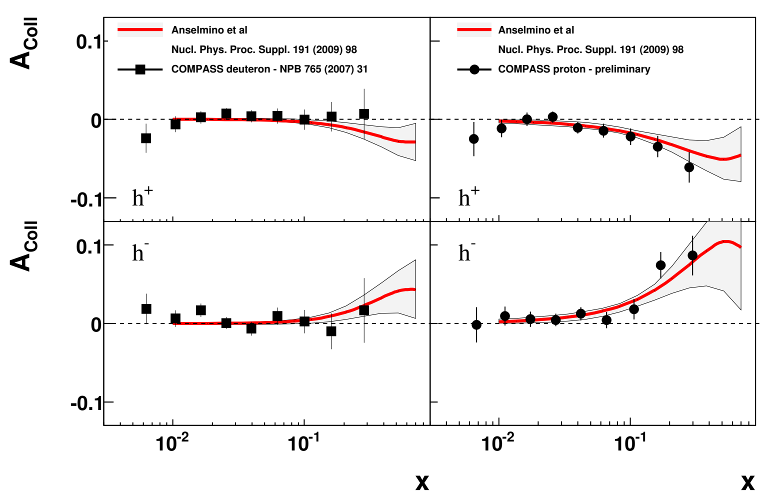

Fig. 2. Comparison of the global fit results of ref. [16] with the COMPASS Collins asymmetries on deuteron (left) and proton (right).

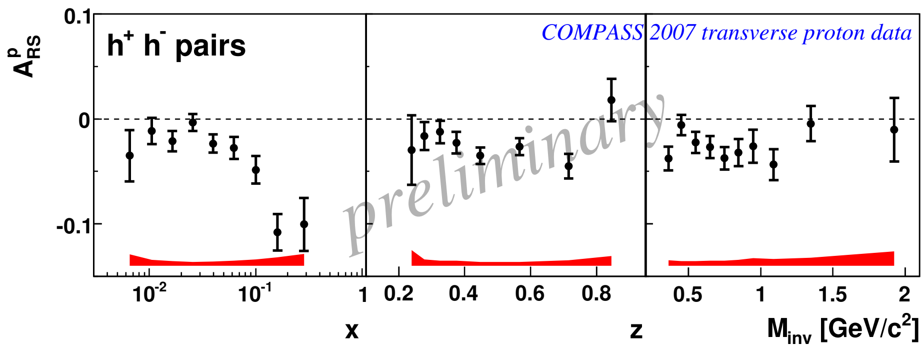

Fig. 3. Hadron pair asymmetry as function of x, Z and M_{inv} for positive and negative hadrons.

support to the underlying interpretation of the Collins asymmetry in term of $\Delta_T q$, the third twist-two parton distribution function, and of a left-right asymmetry in the fragmentation of a transversely polarised quark. Both these properties now seem to be firmly established.

Complementary evidence on the non-zero value of the transversity distributions at large x comes from the hadron pair asymmetries. Our preliminary results for $A_{\Phi_{RS}}$ have been presented for the first time at DIS 2009 [21] and are shown in Fig 3, as a function of x, Z (the sum of the z-values of the two hadrons) and M_{inv}, the invariant mass of the two-hadrons system. In the large x-region we measure a strong asymmetry, which is a clear indication that both the transversity distribution and the interference fragmentation function $H_1^{\angle}$ are non-zero. A non-zero hadron pair asymmetry on a transversely polarized proton target has already been detected by the HERMES Collaboration [22], whose data are in nice agreement with a model predictions of Bacchetta and Radici [8]. Most interesting, our measured asymmetries are a good factor of three larger than those measured by HERMES, very likely because of the different phase space of the experiments. It will be of the greatest interest to look at the forthcoming data on the two-hadron interference fragmentation function which are being worked upon by the Belle Collaboration, and perform another global analysis with the COMPASS, HERMES and Belle data to extract both $\Delta_T q$ and $H_1^{\angle}$.

The results for the Sivers asymmetry were presented for the first time at Transversity 2008 [19] and are given in Fig. 4. Very much as for the deuteron case, no non-zero asymmetry shows up, within the statistical accuracy of the measurements, neither for the positive, nor for the negative hadrons. This result is unexpected and intriguing. It is unexpected when compared with the HERMES results, which in the case of positive pions and kaons show large positive Sivers asymmetries in the valence region. It is intriguing because in the framework of the present understanding of the Sivers mechanism, the difference in phase space due to the different beam momenta (28 and 160 GeV/c) does not seem to be large enough to justify

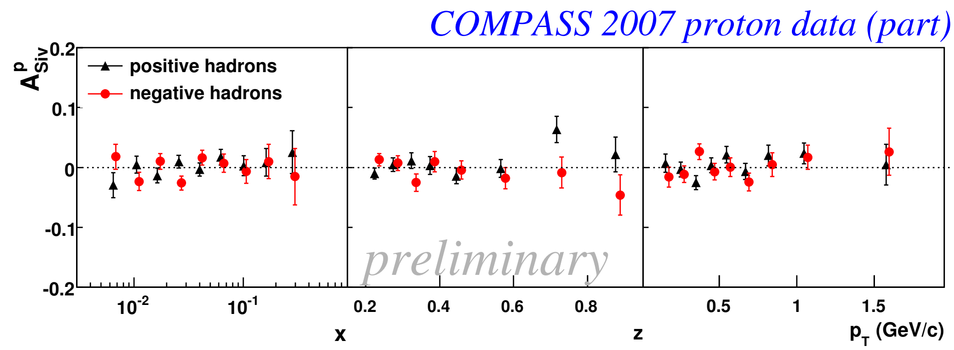

Fig. 4. Sivers asymmetry as function of x, z, and p_h^T, for positive and negative hadrons.

the difference. The asymmetry is expected to decrease with increasing Q^2, but the dependence is logarithmic, and even in the last x bins the mean Q^2 values of COMPASS and HERMES differ by factors of only 4 to 5. Our data points are affected by relatively large error bars, and the discrepancy with HERMES is statistically marginal, of the order of a few percent CL. More high energy data are needed to further investigate the energy dependence suggested by our results, which is a crucial issue for the present description of the transverse momentum structure of the nucleon. The COMPASS Collaboration has already decided to resume the measurement with the transversely polarized target in 2010, for one full year [23], and the corresponding proposal has been recommended by the CERN SPSC Committee and accepted by the CERN Research Board.

The same data collected in 2007 on the transversely polarized proton target have been used to study the exclusive reaction $\mu + N \to \mu' + \rho^0 + N'$, where N is a proton from the NH_3 target material. To select such events we require incident and scattered muon tracks, with two additional tracks, corresponding to charged π's from the decay of the ρ^0. To select exclusive events, cuts are applied on the missing energy in the reaction, as well as on the transverse momentum of the ρ^0 with respect to the virtual photon direction. Since the recoil proton cannot be detected in our experiment, the final sample of events still contain a considerable background of non-exclusive events, about 30%, which will be subtracted in the final analysis.

By expressing the event rate as a function of the azimuthal angle between the spin of the target (ϕ_S) and the production plane (ϕ), a transverse spin asymmetry can be constructed $A_{UT}^{sin(\phi-\phi_S)}$ which represents a cross-section asymmetry between the ($\phi - \phi_S$) direction and the opposite ($\phi - \phi_S + \pi$) direction. A preliminary analysis of the 2007 data has provided for this asymmetry the values which are shown in Fig. 3, which are all consistent with zero in the Q^2, x and p_T^2 range investigated. A similar result was obtained using the deuteron target data collected

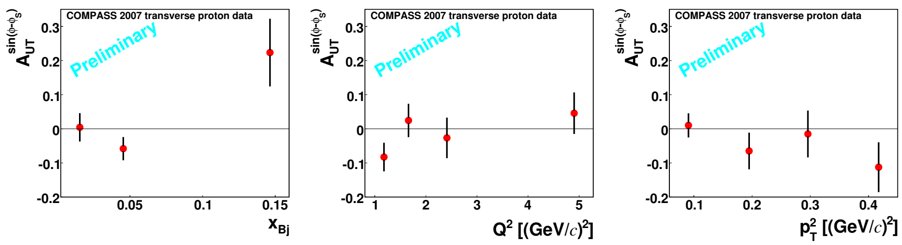

Fig. 5. Transverse proton target spin asymmetries in exclusive ρ^0 production as a function of x (left), Q^2 (middle), and p_T^2 (right).

in 2002, 2003 and 2004, but in that measurement cancellation between proton and neutron could be expected. The present result shows that also the asymmetry on the proton is small, compatible with zero within the error bars. Our result which was first shown at DIS 2009 [24], is in agreement with a similar measurement by the HERMES collaboration [25], and with the theoretical prediction of Goloskokov and Kroll[26]. The calculation of Goloskokov a nd Kroll gives for ρ^0 production on the proton a very small asymmetry $A_{UT}^{sin(\phi-\phi_S)}$, about -0.02, which certainly agrees with our measurement.

4. Conclusions

Transverse spin and transverse momentum effects in lepton nucleon scattering offer new tools to unveil the structure of the nucleon. COMPASS has given its share by executing a first round of exploratory measurements scattering 160 GeV/c muons on transversely polarized deuteron and proton targets. When our data are combined with the proton data of HERMES and with the $e^+e^- \to hadrons$ data analyzed by the BELLE Collaboration new properties of matter emerge, which nicely fit in a new theoretical framework in which the transverse momentum of partons is there from the very beginning, thus going beyond the collinear parton model.

Along this path, Anatoly Efremov has been a main actor and a friend. Since many years by now we have been discussing about transverse spin phenomena, and personally I pushed very strongly to have him join our COMPASS Experiment. Since the time he became a COMPASS member, I discovered he is not only good in theory, but also in data analysis! Not to mention his major role as an organizer of the series of Workshops on High Energy Spin Physics in Dubna. I wish him to maintain his interest in what we are doing and keep contacts with us for many years to come.

In the long term, the investigation of the spin structure of the nucleon will necessitate a major investment, to build a high luminosity electron-proton collider in which polarized electrons and polarized proton will collide at high energy. Projects are ongoing since some time at JLAB, at BNL, and, more recently, in Europe, where ideas to use the HESR antiproton storage ring of FAIR at GSI to store polarized protons are being put forward. The construction of a new polarized electron ring of suitable energy is not for free, but feasibility studies are ongoing. In the meantime, only JLAB and COMPASS can contribute to this field. JLAB experiments are unbeatable in statistical precision, but the interpretation of the data requires also measurements at high Q^2 which can only be performed using high energy beams. From this point of view, I think COMPASS should stay on the stage for several years, profit of the accelerator complex upgrade which is being carried on at CERN and thus increase its luminosity, and bridge the colleagues who are interested in this field across the time gap from now to the day the future collider will enter into operation.

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