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COMPASS RESULTS ON TMD OBSERVABLES

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The study of the transverse spin and transverse momentum structure of the nucleon is an important part of the scientific program of COMPASS, a fixed target experiment taking data at the CERN SPS since 2002. In these ten years COMPASS has produced a number of interesting results by measuring the forward going hadrons produced in deep inelastic scattering of a 160 GeV muon beam off polarized deuteron and proton targets. The COMPASS contribution to the understanding of the transverse structure of the nucleon, and the possible future contributions, are briefly reviewed here.

Keywords: Transverse nucleon structure; SIDIS; experimental results.

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1. Introduction

The transverse spin effects in hard processes discovered 40 years ago have triggered a huge amount of theoretical and experimental work aimed at the understanding of the transverse spin structure of the nucleon and of the role of the transverse momentum and orbital angular momentum of the partons. In the last twenty years enormous progress has been achieved On the experimental side, the large transverse spin effects observed at lower energy in different processes, like pp scattering, have been found to persist even at the highest energies of RHIC, and clear new effects have been measured in semi-inclusive lepton-nucleon deep inelastic scattering (SIDIS). On the theory side, completely new concepts have been introduced in the framework of QCD (see e.g. Ref. [1] and references therein). Since the 90's it is well known that to fully specify the quark structure of the nucleon at the twist-two level in the collinear case three parton distribution functions (PDFs) are necessary for each (anti)quark flavor q. Two of them are the already well know momentum distributions f_1^q (or q) and helicity distributions g_1^q (or Δq). The third one is a new PDF, the transversity distributions h_1^q (or $\Delta_T q$). It gives the correlation between the transverse polarisation of the quarks and the transverse polarisation of the parent nucleon and has many interesting properties, in particular its first moments are

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the tensor charges. Transversity is chiral-odd and thus not directly observable in inclusive DIS. Its measurement has been the main motivation for the transverse spin measurements in pp scattering at RHIC and in SIDIS at HERMES and COMPASS. In SIDIS transversity can be measured thanks to a mechanism involving in the hadronisation of transversely polarised quarks a chiral-odd fragmentation function (FF) called Collins function. This mechanism leads to an azimuthal transverse spin asymmetry (the "Collins asymmetry") in the distribution of the inclusively produced hadrons. Other channels giving access to transversity in SIDIS are the transverse spin asymmetries in hadron pair production and Λ polarisation.

These three PDFs depend on the Bjorken variable x and the squared four momentum transferred Q^2, and are integrated over the intrinsic transverse momentum of the quarks $\vec{k}_T$. When $\vec{k}_T$ is taken into account, other six so-called transverse momentum dependent (TMD) distributions are needed for a full description of the nucleon. They are also twist-two, but average to zero after integration over $\vec{k}_T$. They have all a clear interpretation in the parton model, and give the correlations between nucleon spin, quark spin and quark transverse momentum. Historically the first TMD PDF to be introduced was the Sivers function which arises from a correlation between the transverse momentum of an unpolarised quark in a transversely polarized nucleon and the nucleon polarization vector. Due to its T-odd nature it was initially believed to be zero, but ten years after it was proven that this is not the case thanks to final (or initial) state interactions. Another T-odd (and chiral-odd) TMD distribution is the Boer-Mulders function $h_1^\perp$ which describes the correlation between transverse momentum and transverse spin of a quark inside an unpolarised nucleon. Recent theoretical developments have led to specific predictions, in particular an opposite sign for the T-odd functions measured in SIDIS and in Drell-Yan (DY) processes is expected. Today, all the TMD PDFs are regarded as extremely interesting and in this context SIDIS plays a very special role being the process which allows the most direct access to all of them.

The differential SIDIS cross-section for unpolarised and longitudinally or transversely polarised targets contains 14 independent modulations in azimuthal angles which are linear combinations 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) measured with respect to the lepton scattering plane in the gamma-nucleon system. The amplitudes of six of these modulations are convolutions over transverse momenta of the transversity and of the TMD PDFs with the Collins or the unpolarised FFs. All the 14 amplitudes (or the corresponding azimuthal asymmetries obtained dividing the amplitudes by the integrated unpolarised cross-section and eventually by kinematical factors) can be measured from data collected with polarised lepton beams and unpolarised and polarised targets. Thus SIDIS gives access to transversity and to all the TMD PDFs. Information on the different quark flavor PDFs are then obtained using p and n (or d) targets and identifying the final state hadrons. Today the available SIDIS data set on TMD observables is quite complete and cover a considerable region of the $x-Q^2$ plane thanks to the measurements at different energies of COMPASS, HERMES and Jefferson Lab experiments. In the future, other results will come from these experiments and, on a longer time scale, from the new facilities, namely Jefferson Lab 12 GeV and the polarised electron-proton colliders.

In the following, after a brief description of the experiment, the COMPASS results on TMD observables both from unpolarised and from transversely polarised targets data are described. For reasons of space, the asymmetries measured in so far using the longitudinally polarized deuteron target data,[2] are not discussed here.

2. The COMPASS Experiment

The COMPASS experiment has a wide physics program which includes several measurements to study hadron spectroscopy and the nucleon spin structure, and, in particular, the direct measurement of the gluon contribution to the nucleon spin. The COMPASS spectrometer[3] was designed to satisfy the requirements of all those measurements and was built to have large angular acceptance and dynamical range, and to work with high intensity beams. It is a two-stage magnetic spectrometer equipped with many different tracking detectors in order to cope with the required location accuracy and rate capability in the different regions. Particle identification is provided by a large acceptance RICH detector, by calorimeters, and by muon filters. To study the nucleon structure a 160 GeV longitudinally polarised μ^+ beam impinging a 120 cm long solid state polarised target has been used. From 2002 to 2004 data were collected with the deuteron (^{6}LiD) target polarised either transversely or longitudinally with respect to the beam direction. During the 2005 shut-down of the CERN accelerators the large acceptance ($\pm 180^o$) polarised target magnet was installed and data taking was resumed in 2006, with the longitudinally polarised deuteron target. Data with the polarised proton (NH_3) target were collected in 2007 (transverse and longitudinal polarisation), in 2010 (transverse polarisation) and in 2011 (longitudinal polarisation, 200 GeV beam energy).

3. Results from Unpolarised SIDIS

In so far several spin-averaged observables, and in particular azimuthal asymmetries and hadron multiplicities versus transverse momentum, have been measured at COMPASS. The measurements have been performed using the deuteron (^{6}LiD) data collected in the year 2004. The choice of the data set is due to the fact that, at variance with the measurement of spin asymmetries, here the measured azimuthal distributions have to be corrected for the apparatus acceptance evaluated using Monte Carlo simulations. The spectrometer performances in 2004 are quite well understood and a good description of the measured distributions has been obtained already since some time. For all the measurements, the data collected with the opposite target polarisation have been combined in such a way that the spin effects cancel. As for the other SIDIS measurements, the events and the final state charged hadrons are usually selected requiring $Q^2 > 1$ (GeV/c)^2, a fractional energy of the virtual photon $0.1 < y < 0.9$, a mass of the hadronic final state system $W > 5$ GeV/c^2, a transverse momentum of the hadrons with respect to the virtual photon direction $P_T^h > 0.1$ GeV/c, and hadron energies corresponding to a fraction of the available energy $z > 0.2$ These cuts are the standard ones in COMPASS, and the resulting hadron sample will be referred as standard sample in the following.

Three modulations in the azimuthal distribution of the inclusively produced hadrons are expected in the SIDIS cross-section: a cosϕ_h, a cos2ϕ_h and a sinϕ_h modulation, which correspond to the $A^{UU}_{cos\phi_h}$, $A^{UU}_{cos2\phi_h}$ and $A^{LU}_{sin\phi_h}$ azimuthal asymmetries corrected for the kinematical y dependent factors (the superscripts indicate the target nucleon and the incoming lepton polarisation). The $A^{UU}_{cos\phi_h}$ asymmetry is expected to be dominated by the so called Cahn effect, a pure kinematical effect in the elastic scattering between the incoming lepton and the struck quark, while the Boer-Mulders function, convoluted with the Collins FF, is expected to contribute at higher twist only. The opposite happens in the case of $A^{UU}_{cos2\phi_h}$ which should mainly be due to the Boer-Mulders function since the Cahn effect is kinematically suppressed by a factor $1/Q$ and the perturbative QCD contributions are expected to be small at least at small P_T^h. $A^{LU}_{sin\phi_h}$ is a higher-twist term with no clear interpretation in the parton model.

The asymmetries have been measured[4] using the standard hadron sample with some additional cut ($x < 0.13$, $y > 0.2$, $z < 0.85$, $P_T^h < 1.0$ GeV/c, a virtual photon polar angle calculated with respect to the beam direction < 60 mrad) mainly applied in order to avoid large acceptance corrections, and separately for positive and negative hadrons as functions of x, z and P_T^h. The $A^{LU}_{sin\phi_h}$ asymmetries show a slightly positive signal for the positive hadrons and are compatible with zero for the negative ones. The results for $A^{UU}_{cos\phi_h}$ and $A^{UU}_{cos2\phi_h}$, are shown in Fig. 1. For both asymmetries, the values are clearly different from zero and different for positive and negative hadrons. The dependence on all the three kinematical variables is strong, and presently difficult to be explained.[5,6] To give more input to the interpretation of these data a multidimensional analysis has been performed binning the data in a 3-dimensional grid in x (4 bins), z (6 bins) and P_T^h (4 bins). The preliminary results for the first four z bins ($z < 0.55$) have already been released[7] and show interesting effects, e.g. quite different x and P_T^h dependencies in the different z ranges. The complete set of asymmetries will be available soon, very likely in time for the SPIN2012 Symposium, and will hopefully help in the separation of the different contributions. Also, these new results will make easier the comparison with the recent results at lower energy produced by HERMES[8] in somewhat different kinematic ranges.

The final state hadron multiplicities have been measured as functions of both $P_T^{h\,2}$ (Ref. [9]) and z (Ref. [10]). The multiplicities versus $P_T^{h\,2}$ have been extracted in 23 $x - Q^2$ bins in the kinematical region $0.004 < x < 0.12$ and $1 < Q^2 < 10$ GeV^2. In each of these bins the multiplicities have been measured separately for positive and negative hadrons in 8 z bins between 0.2 and 0.8. The slopes of the

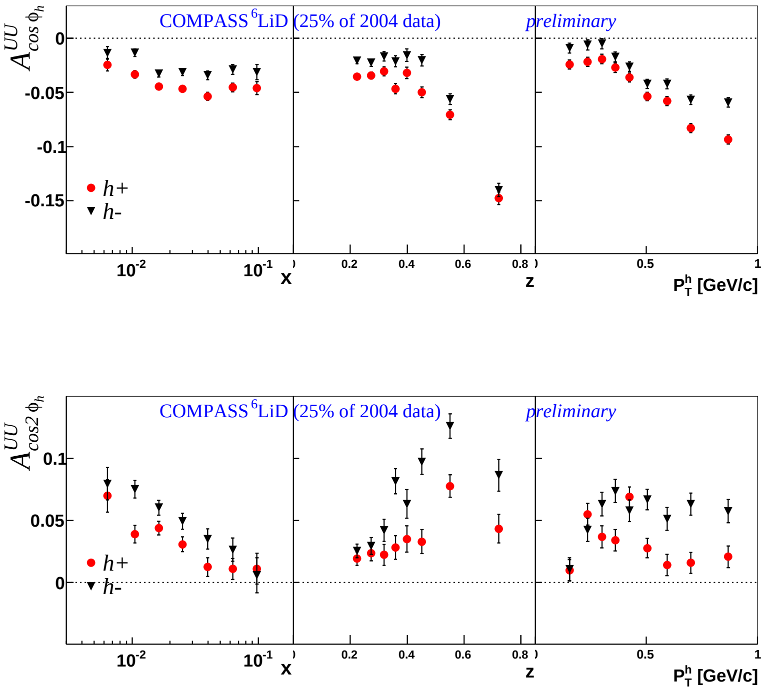

Fig. 1. Top: $A^{UU}_{cos\phi_h}$ for positive (circles, red online) and negative (triangles, black online) hadrons as a function of x, z and P^h_T. The bars give the statistical errors. The systematic uncertainties have been evaluated to be twice the statistical ones. Bottom: same for $A^{UU}_{cos2\phi_h}$.

distributions have been measured in each z bin allowing for a first extraction of the k_T^2 mean values which show a strong Q^2 dependence.

Work is going on also to extract the multiplicities for hadron pairs, a new measurement which is of particular relevance for the extraction of the transversity distribution from the hadron-pair transverse spin asymmetry.

The finalization of these analysis is our short term goal. On a longer time scale, COMPASS plans to perform the same measurements for protons, using a liquid hydrogen target. The SIDIS data will be collected in parallel to the future measurement of the Deeply Virtual Compton Scattering (DVCS) to access the Generalized Parton Distributions which very likely will take place in 2015 and 2016, with a test run already this year.

4. Results from SIDIS Off Transversely Polarised Targets

The data collected with the transversely polarised target allow to extract all the 8 azimuthal asymmetries expected in the cross-section. The asymmetries are measured separately for positive and negative hadrons in 9 x bins, 8 z bins and 9 P_T^h bins using an unbinned maximum likelihood method in which the fitting function includes all the modulations.

The study of systematic effects and the estimation of the systematic uncertainty is done independently for each asymmetry thus the results are not given at the same time for all of them. In so far the COMPASS Collaboration has given higher priority to the measurement of the Collins and Sivers asymmetries, so the results for the other 6 asymmetries are usually produced somewhat later. Till now, we have measured the asymmetries "beyond Collins and Sivers" using all the deuteron data collected between 2002 and 2004, and the proton data collected in 2007.[11] The results for charged hadrons (mostly π's) are all compatible with zero within the accuracy of the present measurements. New input will come from the analysis of the 2010 proton data, which will give results with uncertainties twice smaller than those of the 2007 results.

The Collins and Sivers asymmetries have been measured using all the deuteron data, for positive and negative hadrons as well as for charged pions and for kaons.[12–14] In those data no appreciable asymmetries were observed, a fact which is understood in terms of a cancellation between the u- and d-quark contributions. These data are still today the only SIDIS data even taken on a transversely polarized deuteron target. A measurement with a ^{3}He target has recently been performed at lower energy at Jefferson Lab,[15] with still limited statistics.

The first data with transversely polarised proton target in COMPASS were collected in 2007. The results for the Collins and the Sivers asymmetries for charged hadrons[16] have been obtained with the standard event and hadron selection and are shown as open points in Figs. 2 and 3 respectively.

The Collins asymmetries show a strong x dependence: the asymmetries are compatible with zero at small x and increases up to 0.10 in the valence region ($x > 0.1$) and have opposite sign for positive and negative hadrons. The asymmetries as functions of z and p_T^h have also been extracted in the range $0.032 < x < 0.7$ where the signal is present, both to better investigate the z and P_T^h dependence and to compare them with the measurements performed by HERMES.[17,18] The two sets of data are in good agreement, a quite relevant result, given the higher energy of the lepton beam used in COMPASS which results in Q^2 values about 3 times larger at $x \sim 0.1$.

The Sivers asymmetries from the 2007 data shown in Fig. 3 turned out to be positive for positive hadrons and compatible with zero for negative hadrons. At variance with the Collins asymmetry, the Sivers asymmetry stays positive even for very small x-values, in the previously unmeasured region of the sea. The Sivers asymmetries have also been extracted in the range $0.032 < x < 0.7$, and compared with the HERMES results,[17] finding clear indication for smaller values measured by COMPASS.

The analysis of the 2010 data for the measurement of the Collins and Sivers asymmetries for charged hadrons has been finalized.[19,20] The results are the close

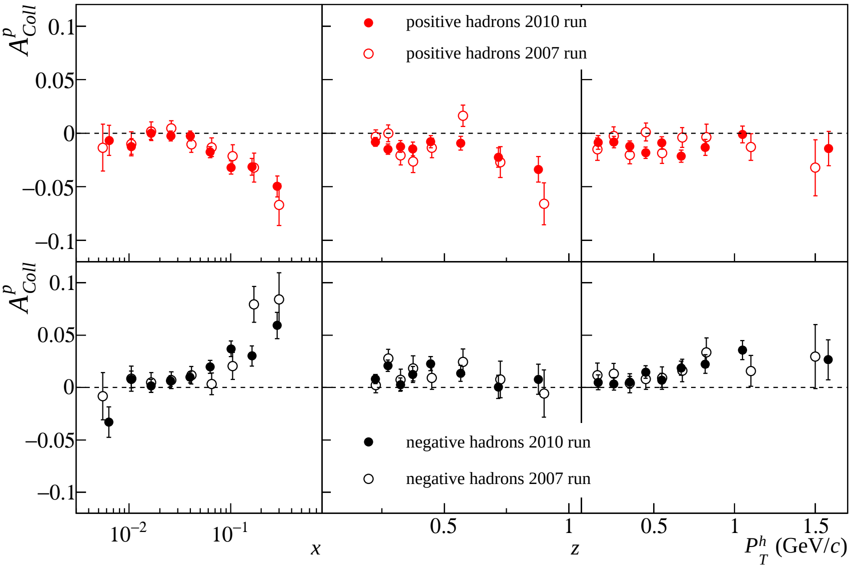

Fig. 2. Collins asymmetry as a function of x, z and P_T^h for positive (top) and negative (bottom) hadrons. The open (closed) points give the results from the 2007 (2010) proton data.

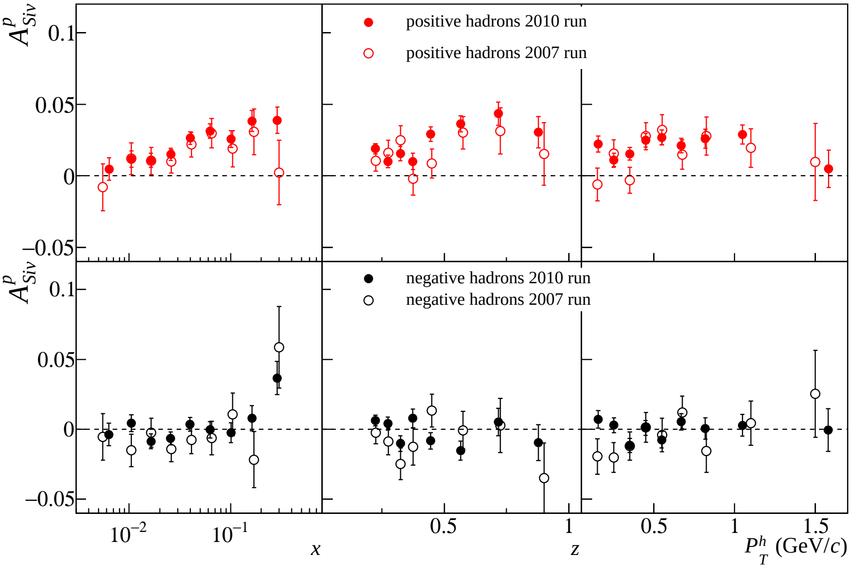

Fig. 3. Sivers asymmetry as function of x, z and P_T^h for positive (top) and negative (bottom) hadrons. The open (closed) points give the results from the 2007 (2010) proton data.

points in Figs. 2 and 3 respectively. The error bars are the statistical uncertainties. The systematic point-to-point uncertainties have been estimated to be half of the statistical ones while the scale uncertainty is 3%.

As can be seen from Fig. 2 the new results for the Collins asymmetries (closed points) confirm the 2007 data results. The uncertainties are about twice smaller, and the dependence on all the three kinematical variables is much better measured. The two sets of data constitute an important new input for the global analysis of the COMPASS, HERMES and BELLE data, and will allow a better extraction of the transversity PDFs and of its first moments.

The Sivers asymmetries for charged hadrons from the 2010 data (closed points in Fig. 3) are also in very good agreement with the results from the 2007 run and the considerable reduction of the uncertainties is evident. The asymmetry is definitely positive for positive hadrons and by now it is very well measured also in the low x region, where it stays positive. The comparison with the HERMES data done selecting the events with $x > 0.032$ shows again smaller values measured at COMPASS. This difference can be explained with the Q^2 evolution of the TMD PDFs which has been calculated very recently.[21] Using it, it is possible to describe simultaneously the COMPASS and the HERMES results.[22,23] Also, as shown in Fig 4, it is possible to describe quite well the z dependence of the Sivers asymmetry for positive hadrons measured at COMPASS for the standard sample and for the $x > 0.032$ sample, which have Q^2 mean values of 3.8 and 8.7 GeV^2 respectively.

Thanks to the high beam momentum and the high statistics of the 2010 data, multidimensional analysis, similar to that done for the unpolarised asymmetries, can also been performed. Presently we have already extracted the Collins and Sivers asymmetries in ranges of z and y different from the standard ones.[19,20] The study of the y dependence of the asymmetries is particularly interesting because of the y

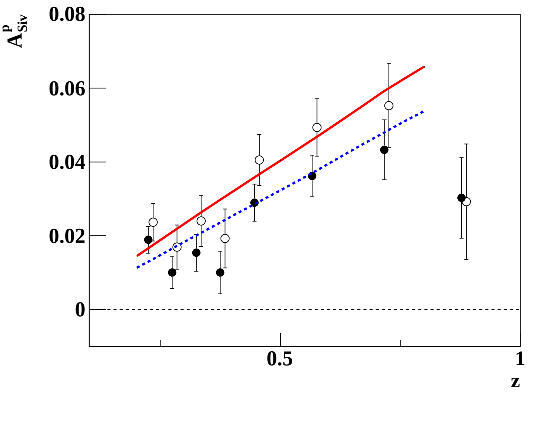

Fig. 4. Sivers asymmetry as function of z for positive hadrons for the ranges $0.004 < x < 0.7$ and $0.032 < x < 0.7$ compared with the calculations of Ref. [22].

correlation with W and in particular with Q^2. The standard range has been divided in two bins ($0.1 < y < 0.2$ and $0.2 < y < 0.9$), and the hadrons produced in events with $0.05 < y < 0.1$ have also been used. The y dependence turned out to be quite clear for the Sivers asymmetry for positive hadrons, which increases going to smaller y values (i.e. to lower Q^2 values), in qualitative agreement with what expected from the TMD PDFs Q^2 evolution and from the HERMES results. Also, there is some indication for a decrease of the Collins asymmetry for negative hadrons at the highest y values.

Finally, the data collected in so far with the transversely polarised targets have been used to measure the two-hadron azimuthal asymmetry. In this case the relevant azimuthal angles are the azimuthal angle of the target spin and an azimuthal angle measured from the hadron production plane. The two-hadron asymmetry is proportional to the products (and not the convolutions) of the transversity PDFs and the so called Di-hadron FFs, which has been measured at BELLE and at BABAR. To assess the spin-averaged FFs, also needed to extract transversity, COMPASS is measuring the multiplicities of hadron pairs produced in unpolarised SIDIS.

The two-hadrons asymmetries measured in COMPASS from the deuteron data[24] are compatible with zero, as expected. The results from the 2007 proton data,[24] again confirmed with higher precision by the 2010 data results,[25] show a clear signal, very similar in size and x dependence to the one measured for the Collins asymmetry. With the new results the interesting and somehow unexpected dependence on the two hadron invariant mass M is also very clear. The two-hadron proton data alone allow for the extraction, with some assumption, of a linear combination of the u and d quark transversity function.[26] When the same procedure is applied to the deuteron data, a different linear combination can be extracted, so that using both sets of data the u and d quark transversity PDFs are separately obtained.[27,28] In particular such calculations have shown again that the statistics of the deuteron measurements is marginal.

Results for the Collins, Sivers and two-hadron asymmetries for identified hadrons from the 2010 proton data are expected to come soon, as well as a more complete multidimensional analysis for the Collins ans Sivers asymmetries.

5. Conclusions and Outlook

In the last ten years COMPASS has given important contributions to the study of the transverse spin and transverse momentum structure of the nucleon measuring SIDIS off proton and deuteron targets. A major point has been the measurement of the Collins and Sivers asymmetries for the proton, which turned out to be similar to those measured, at lower energy, by HERMES, giving important information on the real nature of these effects. The analysis of the COMPASS SIDIS data collected in so far is not yet over, and several new results are expected to come in the near future.

In the next three years, SIDIS data with unpolarised proton targets will be collected in parallel to the DVCS measurements, and a more detailed investigation of the azimuthal asymmetries as well as of the hadron multiplicities will be possible. New information on transverse momentum and transverse spin effects will come from the measurements of DY processes in pion - transversely polarised proton interactions. On a longer time scale, given the relevance of SIDIS in the study of the transverse structure of the nucleon, further measurements with the transversely polarised deuteron and proton targets are also possible.

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