

TRANSVERSITY PHYSICS AT COMPASS

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Abstract

Transverse spin physics is an important part of the scientific programme of the COMPASS experiment at CERN, which started taking data in 2002, scattering 160 GeV/c muon beam on a polarized ⁶LiD target. The analysis of the data taken with the target polarized orthogonally to the muon beam direction has allowed to measure for the first time the Collins and Sivers asymmetries of the deuteron. Both for the positive and the negative hadrons produced in semi-inclusive DIS the measured asymmetries are small and, within errors, compatible with zero: results on part of the accumulated statistics have already been published. Two-hadron asymmetries and Λ polarization transferred from the struck quark are also being investigated, and preliminary results on the data collected in the years 2002 and 2003 are given.

1 Introduction

The importance of transverse spin effects at high energy in hadronic physics has grown up steadily since the discovery in 1976 that Λ hyperons produced in pN interactions exhibit an anomalously large transverse polarization [1]. Nowadays transversity is the subject of intense theoretical activity [2], an important part of the scientific programme of the HERMES experiment at DESY, of the COMPASS experiment at CERN, and of the RHIC experiments at BNL, and the topical content of important international workshops [3].

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To completely specify the quark structure of the nucleon at the twist-two level, the transverse spin distributions $\Delta_T q(x)$ must be added to the momentum distribution $q(x)$ and to the helicity distribution $\Delta q(x)$ [4]. If the quarks are collinear with the parent nucleon (no intrinsic k_T), or after integration over k_T , these three distributions exhaust the information on the internal dynamics of the nucleon.

The transversity distributions $\Delta_T q(x)$ have never been measured, since they are chirally-odd and therefore absent in inclusive DIS, the usual source of information on the nucleon partonic structure. As suggested in Ref. [5], they may instead be extracted from measurements of the spin asymmetries in cross-sections for semi-inclusive DIS (SIDIS) between leptons and transversely polarized nucleons, in which a hadron is also detected in the final state. In such processes the measurable asymmetry A_{Coll} (“Collins asymmetry”) is due to the combined effect of $\Delta_T q(x)$ and another chirally-odd function, $\Delta_T^0 D_q^h$, which describes the spin dependent part of the hadronization of a transversely polarized quark q in a hadron h .

A different mechanism has also been suggested in the past [6] as a possible cause of a spin asymmetry in the cross-section of SIDIS between leptons and transversely polarized nucleons. Allowing for an intrinsic k_T dependence of the quark distribution in a nucleon, a left-right asymmetry could be induced in such a distribution by a transverse nucleon polarization, thus causing an asymmetry A_{Siv} (the “Sivers asymmetry”) in the quark fragmentation hadron with respect to the nucleon polarization. These two mechanisms can be measured separately in SIDIS on a transversely polarized nucleon [7].

According to Collins, the fragmentation function of a quark of flavour q into a hadron h can be written as

$$D_q^h(z, \vec{p}_T) = D_q^h(z, p_T) + \Delta_T^0 D_q^h(z, p_T) \cdot \sin \Phi_C \quad (1)$$

where \vec{p}_T is the final hadron transverse momentum with respect to the quark direction (e.g. the virtual photon direction), $z = E_h/(E_l - E_{l'})$ is the fraction of available energy carried by the hadron (E_h is the hadron energy, E_l is the incoming lepton energy and $E_{l'}$ is the scattered lepton energy). The “Collins angle” Φ_C is conveniently defined in a system in which the z -axis is the virtual photon direction and the x - z plane is the muon scattering plane (see Fig. 1). In this reference system $\Phi_C = \phi_h - \phi_{s'}$, where ϕ_h is the hadron azimuthal angle, and $\phi_{s'}$ is the azimuthal angle of the transverse spin of the struck quark, as illustrated in Fig. 1. Since $\phi_{s'} = \pi - \phi_s$, with ϕ_s the

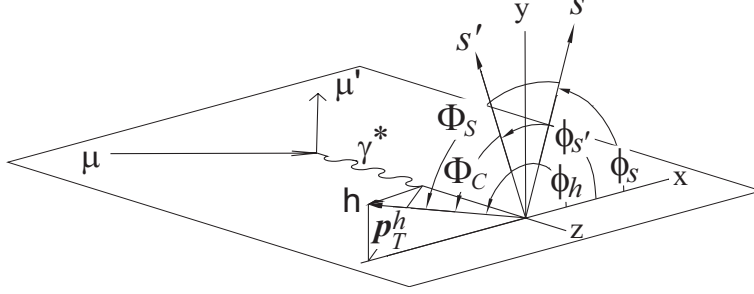


Figure 1. Definition of the Collins and Sivers angles.

transverse spin of the initial quark (nucleon), it is also $\Phi_C = \phi_h + \phi_s - \pi$, i.e. $\sin \Phi_C = -\sin(\phi_h + \phi_s)$. At leading order in the collinear case A_{Coll} can be written as

$$A_{Coll} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h} \quad (2)$$

where e_q is the quark charge. The quantity $\Delta_T^0 D_q^h$ can be obtained by investigating the fragmentation of a polarized quark q into a hadron h .

In the approach of Sivers, allowing for an intrinsic \vec{k}_T dependence of the quark distribution in a nucleon, a left-right asymmetry could be induced in such a distribution by a transverse nucleon polarization, $q_T(x, \vec{k}_T) = q(x, |\vec{k}_T|^2) + \Delta_0^T q(x, |\vec{k}_T|^2) \cdot \sin \Phi_S$, where $\Phi_S = \phi_h - \phi_s \neq \Phi_C$ is the ‘‘Sivers angle’’. Neglecting the hadron transverse momentum with respect to the fragmenting quark, this \vec{k}_T dependence could cause the ‘‘Sivers asymmetry’’

$$A_{Siv} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h} \quad (3)$$

in the distribution of the hadrons resulting from the quark fragmentation with respect to the nucleon polarization which could be revealed as a $\sin \Phi_S$ modulation in the distribution of produced hadrons.

2 Single hadron asymmetries

The COMPASS experiment is described in these Proceedings [8] and in more detail in Ref. [9]. Up to now, data have been taken on polarized deuterons,

using a polarized ${}^6\text{LiD}$ target. The polarized target consists of two cells, each 60 cm long, located along the beam line, one after the other, in two separate RF cavities. Data are taken simultaneously on the two target cells, which are oppositely polarized. The target magnet can provide both a solenoid field (2.5 T), for longitudinal polarization measurements, and a dipole field (0.5 T) used for adiabatic spin rotation and for the transversity measurements. Correspondingly, the target polarization can be oriented either longitudinally or transversely to the beam direction. Polarizations of 50% have been reached routinely with the ${}^6\text{LiD}$ target, which has a favourable dilution factor $f \simeq 0.4$, since ${}^6\text{LiD}$ basically consists of a deuteron plus an ${}^4\text{He}$ core. When operating in the transverse polarization mode the polarization is reversed after 4-5 days by changing the RF frequencies in the two target cells. Typical polarization values for the transverse running are 50% in the first period of data taking, and 40% in the subsequent periods, after polarization reversal.

About 20% of the total beam-time in 2002, 2003 and 2004 was devoted to the run with the transversely polarized deuteron target. The accumulated sample of 2002 data with transverse polarization of the target comprises $6 \cdot 10^9$ events. The amount of data collected in 2003 is a factor of two larger than in 2002, and that collected in 2004 is a factor of two larger than in 2003. The single hadron analysis of the 2003 and 2004 data is not yet finalized, and I will report only on the 2002 results.

In 2002 the data were taken during two separate periods, and in each period data were taken with two different orientations of the target cells.

To select semi-inclusive events, an incoming and scattered muon (primary vertex) plus at least one charged hadron from this vertex were required. Muon identification was performed with muon filters, consisting of a large amount of material to be traversed and a suitable tracking system. To select DIS events, the kinematic cuts $Q^2 > 1$ (GeV/c) 2 , $W > 5$ GeV/c 2 and $0.1 < y < 0.9$ were applied to the data. The upper limit on y was applied to keep radiative corrections small. In addition the transverse momentum cut $p_T > 0.1$ GeV/c was applied to unambiguously calculate angles. Asymmetries have been extracted for the charged hadron with the highest energy (leading, $z > 0.25$) as well as for all detected charged hadrons with $z > 0.2$. The identification provided by the RICH was not used in this analysis.

Collins and Sivers asymmetries were fitted separately. The number of events for each cell and for each orientation of the target polarization can be

written as

$$N_h^{\uparrow(\downarrow)}(\Phi_{C/S}) \propto (1 \pm \epsilon_{C/S} \cdot \sin \Phi_{C/S}), \quad (4)$$

where $\epsilon_{C/S}$ is the amplitude of the experimental asymmetry, the arrows refer to the two orientations of the target polarization, and $\Phi_{C/S}$ is evaluated as if the spin of the target always pointed upward, along the vertical direction.

The quantities ϵ_C and ϵ_S can be written as a function of the Collins and Sivers asymmetries:

$$\begin{aligned} \epsilon_C &= A_{Coll} \cdot P_T \cdot f \cdot D_{NN}, \\ \epsilon_S &= A_{Siv} \cdot P_T \cdot f, \end{aligned} \quad (5)$$

where P_T is the target polarization, $D_{NN} = (1 - y)/(1 - y + y^2/2)$ is the transverse spin transfer coefficient from the initial to the struck quark, and f is the target dilution factor. The asymmetry $\epsilon_{C/S}$ is fitted separately for the two target cells with two opposite spin orientations from the expression:

$$\epsilon_{C/S} \cdot \sin \Phi_{C/S} = \frac{N_h^{\uparrow}(\Phi_{C/S}) - r \cdot N_h^{\downarrow}(\Phi_{C/S})}{N_h^{\uparrow}(\Phi_{C/S}) + r \cdot N_h^{\downarrow}(\Phi_{C/S})} \quad (6)$$

where $r = N_{h,tot}^{\uparrow}/N_{h,tot}^{\downarrow}$ is a normalization factor and corresponds to the ratio of the total number of events with two target polarization orientations. The results from the two target cells and for the two data-taking periods have been averaged, after checking their statistical compatibility.

The resulting asymmetries are plotted against the kinematic variables x , z and p_T in Fig. 2 for all hadrons. These results, which refer to the 2002 run, have already been published [10]. Similar results have been obtained in the case of leading hadrons. Only statistical errors are shown in Fig. 2: systematic errors have been shown to be smaller than statistical ones. Full points correspond to the positively charged hadrons and open points correspond to the negatively charged hadrons. As apparent from Fig. 2 both the Collins and Sivers asymmetries are small and compatible with zero. This might either hint to a cancellation between proton and neutron or to a too small Collins mechanism. However, if the Collins function $\Delta_T^0 D_q^h(z, p_T)$ is not zero and as large as indicated from the preliminary results by the BELLE Collaboration [11], then our data provide evidence for cancellation in the isoscalar target.

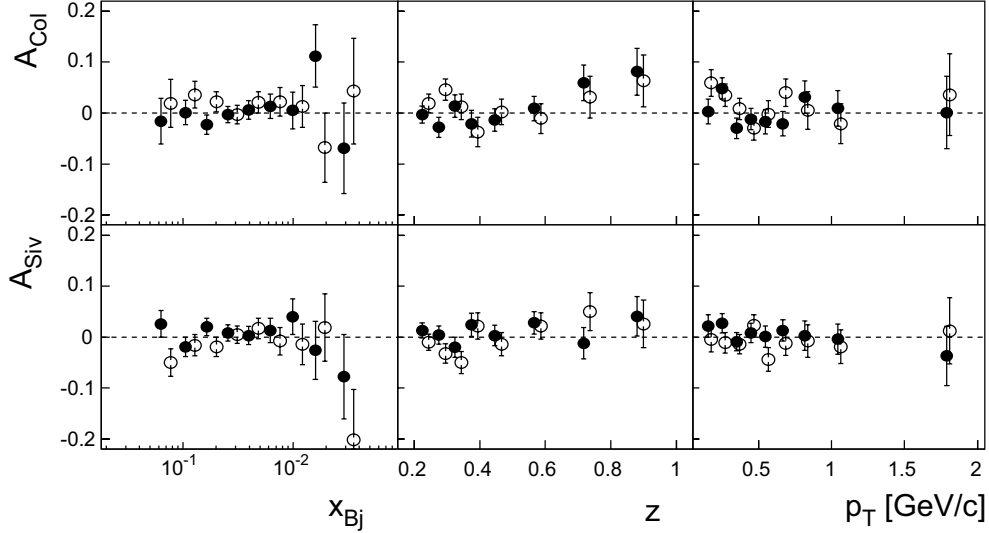


Figure 2. Collins and Sivers asymmetry for positive (full points) and negative (open points) hadrons as a function of x , z and p_T .

The HERMES transversity data on protons and our transversity data on deuterons already allow for a combined analysis aiming at the extraction of the Sivers functions and of the transversity distributions. Within the limited statistical accuracy of the published data, a few global analysis have already been performed, and the observed phenomena can be described in a unified scheme [12, 13].

3 Two-hadron asymmetries

Another process has been suggested to address transversity, namely semi-inclusive DIS where at least two-hadrons are observed in the final state. Here the cross-section at leading twist can be parametrized in terms of the convolution of transversity with an interference fragmentation function $H_1^{\chi}(Z, M_{inv}^2)$, which is also chirally-odd. If a pair of hadrons is the result of the fragmentation of a transversely polarised quark, an asymmetry $A_{\phi_{RS}}$ depending on the angle between the scattering plane and the 2 hadron plane is expected:

$$A_{\phi_{RS}} = \frac{\Sigma_q e_q^2 \Delta_T q(x) \cdot H_1^{\chi}(Z, M_{inv}^2)}{\Sigma_q e_q^2 q(x) D_q^h(Z, M_{inv}^2)}. \quad (7)$$

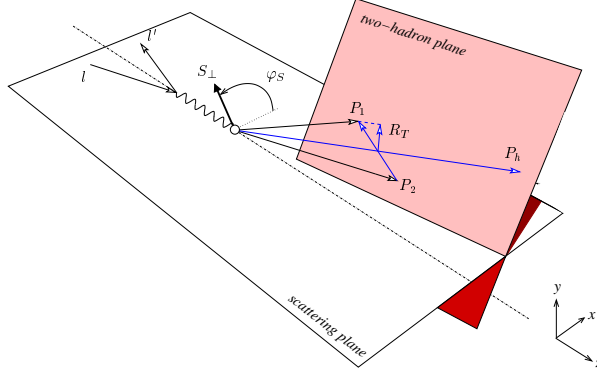


Figure 3. Reference system and angles definitions for the two-hadron analysis [18]. \vec{S}_\perp is the vector component of the target quark spin perpendicular to the virtual photon direction.

Here Z is the sum of scaled hadron energies ($Z = z_{h1} + z_{h2}$) and M_{inv} is the invariant mass of two-hadrons. The sum is over the quark flavours q . The expected properties of the interference fragmentation function and suggestions on how to access it experimentally can be found in several publications [14, 15, 16, 17].

The asymmetry (7) is related to the experimentally measured counting rate asymmetry, which is defined in the following way:

$$\begin{aligned}
 A_m(\phi_{RS}) &= \frac{N^\uparrow(\phi_{RS}) - rN^\downarrow(\phi_{RS})}{N^\uparrow(\phi_{RS}) + rN^\downarrow(\phi_{RS})} \\
 &= A_{UT}^{\sin\phi_{RS}} \sin\phi_{RS} = D_{NN} P_T f A_{\phi_{RS}} \sin\phi_{RS}, \quad (8)
 \end{aligned}$$

where $N^{\uparrow(\downarrow)}$ is the number of events for the target with the up (down) polarization orientation in the laboratory system, $r = N_{tot}^\uparrow/N_{tot}^\downarrow$ is the ratio of the total number of events (i.e. integrated over the angle ϕ_{RS}) for the two-polarization orientations, and D_{NN} , P_T and f have the same meaning as in formula (5). The angle ϕ_{RS} is defined as $\phi_{RS} = \phi_R - \phi_{S'}$, where ϕ_R is the azimuthal angle of \vec{R}_T , which is the vector component of the difference of the two-hadron momenta $\vec{R}_h = (\vec{P}_1 - \vec{P}_2)/2$ perpendicular to their sum $\vec{P}_h = (\vec{P}_1 + \vec{P}_2)$; $\phi_{S'}$ is still the azimuthal angle of the struck quark spin. The reference system for the measurement is again defined by the scattering plane of the lepton and the direction of the virtual photon, as shown in Fig. 3.

The asymmetries $A_{UT}^{\sin\phi_{RS}}$ are obtained from the fit to the $A_m(\phi_{RS})$ dis-

tributions. Here we give preliminary results from the data collected during the years 2002 and 2003.

The event selection is basically the same as for the single hadron analysis, plus the requirement that the events contain at least one reconstructed hadron pair with oppositely charged hadrons. In the calculation of \vec{R}_T , we always take as hadron 1 the positively charged hadron. If more hadrons are present in an event, ϕ_{RS} is evaluated for all pairs of positive and negative hadrons. Current fragmentation region is guaranteed by cuts on $z_{h1,2} > 0.1$ and $x_F > 0.1$ for each hadron. In order to remove exclusive mesons a cut on $Z < 0.9$ is applied. An additional cut on R_T ($R_T > 50$ MeV/c) is performed in order to have well defined angles.

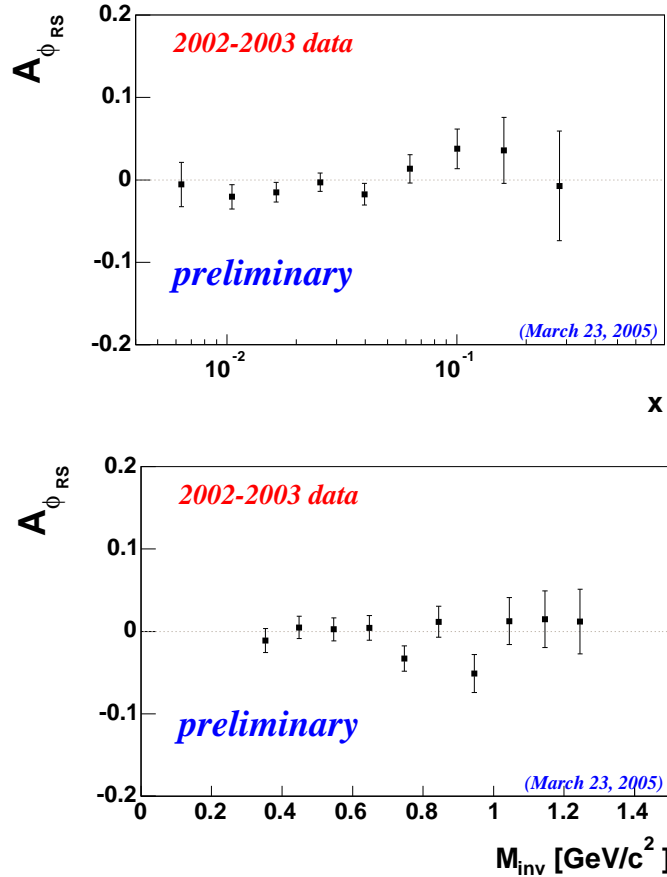


Figure 4. Two-hadron asymmetry $A_{\phi_{RS}}$ as a function of x (top), of the two-hadron invariant mass M_{inv} (bottom).

The resulting asymmetries have been shown for the first time at DIS05 [19], and are given in Fig. 4 as functions of the variables x and M_{inv} . For the invariant mass calculation, all hadrons are assumed to be pions. The results are compatible with zero. The indicated errors are statistical. The size of the systematics errors were estimated by evaluating “false asymmetries” of the data. The extracted false asymmetries are compatible with zero and their statistical errors are of the same size as the statistical uncertainties of the physics result.

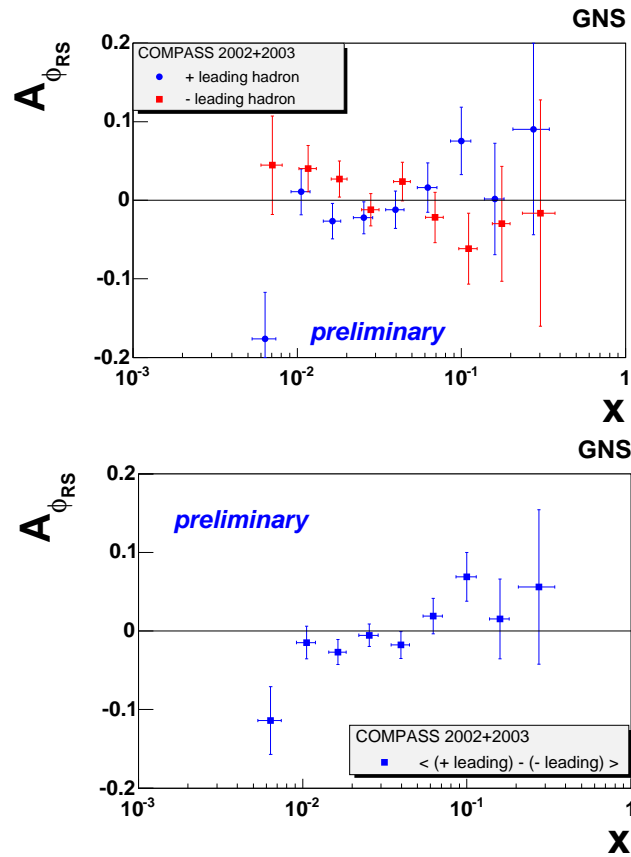


Figure 5. Two-hadron asymmetry $A_{\phi_{RS}}$ as a function of x for the two-oppositely charged hadrons with the largest p_T in the event. In the upper plot the asymmetry is shown separately for the case in which the leading hadron (hadron 1 in the calculation of \vec{R}_T) is positive and negative. The lower plot shows the asymmetry $A_{\phi_{RS}}$ for the same events, but taking as hadron 1 always the positive one.

To search for an effect, we have tried also different selection of the hadron pairs, in particular we have evaluated the asymmetries for the two-oppositely charged hadrons with the largest p_T in the event. The asymmetry $A_{\phi_{RS}}$ is shown separately for the case of positive leading hadrons and of negative leading hadrons in Fig. 5 (top). At large x a hint for a mirror symmetry of the two-sets of data could be seen, suggesting that the possible asymmetry (if any) could be associated with the hadron charge. We have weighted averaged the two-sets of data, evaluating ϕ_{RS} starting always with the positive hadron, and the resulting asymmetry is shown in Fig. 5 (bottom). Some effects could be seen at large x , but clearly more statistics is mandatory before drawing any conclusion.

For all these analyses, particle identification as provided by the RICH detector has not been used. Work is ongoing to evaluate the two-hadron asymmetries for identified charged hadrons. The effect of the RICH identification of hadrons is illustrated in Fig. 6, which refers to the data collected in the year 2003, when the RICH was fully operational. The left plot compares

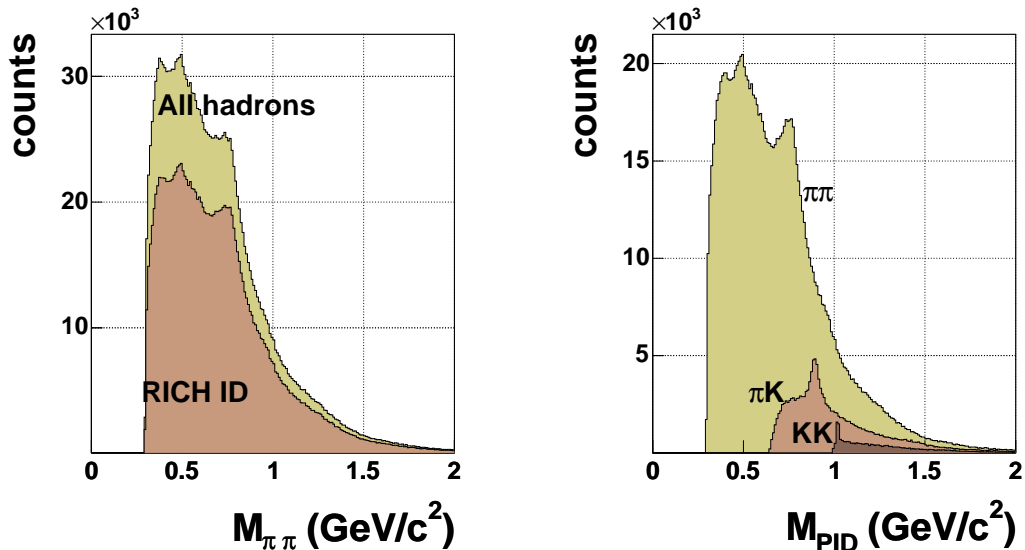


Figure 6. Left plot: invariant mass distribution of two-hadrons for all reconstructed hadron pairs and for the hadrons identified by RICH (the π mass is assumed). Right plot: histograms of the invariant masses of hadron pairs with the mass hypothesis for each hadron as given by the RICH.

the invariant mass distribution for all reconstructed hadron combinations and for the combinations where for both particles the RICH has provided an identification. The fraction of the combinations with the RICH identification is $\sim 75\%$ of all reconstructed pairs. In the plot to the right one can see the effect of hadron identification in the invariant mass spectrum: in the three histograms the invariant mass is evaluated following the mass assignments as given by the RICH.

4 Λ asymmetries

Still another approach to transversity is based on the measurement of the spin transfer to the Λ hyperons produced in the DIS on transversely polarized targets, as originally suggested in [20, 21, 22], and more recently by Anselmino [23].

If in the fragmentation process at least part of the struck quark polarization is transferred to the Λ , than the angular distribution in the weak $\Lambda \rightarrow p\pi^-$ decay can provide information on the initial polarization state of the quark in the nucleon. The Λ polarization measured experimentally is therefore given by:

$$\begin{aligned} P_{\Lambda}^T &= \frac{d\sigma^{\mu N^{\uparrow} \rightarrow \mu' \Lambda^{\uparrow} X} - d\sigma^{\mu N^{\downarrow} \rightarrow \mu' \Lambda^{\uparrow} X}}{d\sigma^{\mu N^{\uparrow} \rightarrow \mu' \Lambda^{\uparrow} X} + d\sigma^{\mu N^{\downarrow} \rightarrow \mu' \Lambda^{\uparrow} X}} = \\ &= f P_T D_{NN} \cdot \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T D_q^{\Lambda}(z)}{\sum_q e_q^2 q(x) D_q^{\Lambda}(z)}, \end{aligned} \quad (9)$$

where the T -axis points along the polarization vector of the struck quark, and $\Delta_T D_q^{\Lambda}(z)$ is the polarized fragmentation function (chirally-odd) that describes the spin transfer from the quark to the final state hyperon. The quantities f , P_T , and D_{NN} are the same as in equation 5.

The event selection is based on the requirement to have a scattering $\mu \rightarrow \mu'$ primary vertex reconstructed within the geometrical volume of the target, together with a two-body charged decay of a neutral particle downstream of the target. The Λ hyperons undergo the decay $\Lambda \rightarrow p\pi^-$ in about 63% of the cases. The decay is detected as a V-shaped vertex in the reconstructed events.

The main sources of background in the Λ sample come from K^0 decays, photon conversion and fake vertices from accidental track associations. To

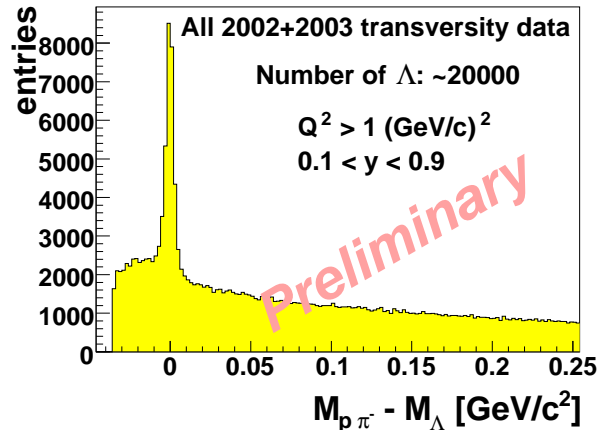


Figure 7. Invariant mass spectrum of the data sample used in this analysis, after all the event selection cuts. The overall number of detected Λ decays is about 20000.

reduce the background, the longitudinal position of the decay vertex is restricted to a region between the target exit window and the first tracking station. A minimal transverse momentum $p_T > 23$ MeV/ c of the decay proton with respect to the decaying hyperon is required. The invariant mass spectrum is shown in Fig. 7: only events with a reconstructed Λ invariant mass in a window of 0.70 GeV/ c^2 centered on the PDG value of the Λ mass, are kept in the final event sample used for the polarization calculation. This analysis has used all the data collected with the transversely polarized deuteron target in 2002 and 2003. The overall number of detected Λ decays in this sample is about 20000.

The angular distribution of the decay proton in the Λ rest frame, measured in the experiment, is given by

$$\frac{dN}{d\theta_T^*} = N_0 \cdot \left(1 + \alpha P_\Lambda^T \cos(\theta_T^*)\right) \cdot Acc(\theta_T^*) \quad (10)$$

where θ_T^* is the angle of the proton with respect to the T -axis. The $Acc(\theta_T^*)$ function represents the distortion of the theoretical angular distribution introduced by the experimental apparatus. This distortion is usually corrected by combining real data and MonteCarlo (MC) simulations. This approach is however quite sensitive to the accuracy of the MC description of the experiment, and requires large MC data samples to get a good statistical accuracy.

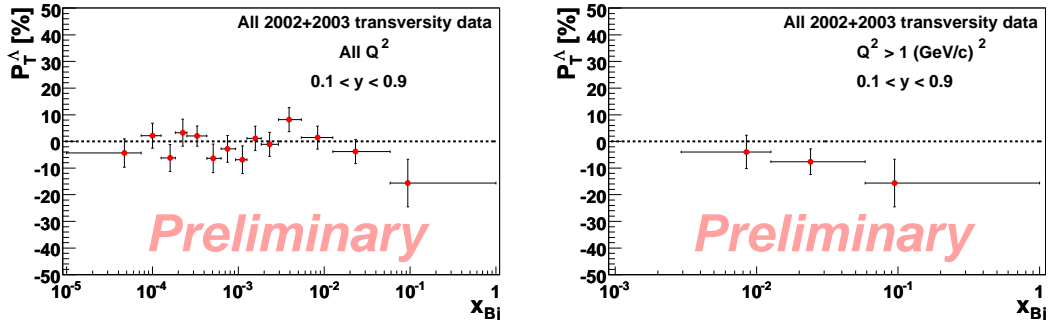


Figure 8. Measured Λ polarization as a function of x , without (left) and with (right) the cut $Q^2 > 1(\text{GeV}/c)^2$.

In this analysis we used a technique based only on real data samples, exploiting some of the symmetries of the experimental apparatus. The technique is based on the combination of two-data taking periods, in the same experimental conditions but with opposite target cell orientations. Under general assumptions on the existing symmetries, the acceptance functions are cancelled and only the terms proportional to the true Λ polarization remain. The method is described in detail in Ref. [24], and will not be repeated here.

The measured P_{Λ}^T as a function of x is shown in Fig. 8 (left) for the full data sample and in Fig. 8 (right) for the DIS region ($Q^2 > 1 (\text{GeV}/c)^2$). The measured values are compatible with zero in all the accessible x range. The data points at $x \sim 0.1$, where the transversity distribution function is expected to be peaked, still have a poor statistical accuracy, therefore no conclusion can be drawn yet on the spin transfer from the target quark to the final state Λ .

5 Conclusion and outlook

It has been a pleasure to be again in Dubna and attend this most interesting workshop, and I'd like to thank Anatoly and the Organizing Committee for the invitation.

I have tried to summarize the physics motivations we have in COMPASS to pursue the physics case for transversity. The case for transversity has been in COMPASS from its very beginning, and has gained momentum as time has passed. Due to the variety of physics issues the Collaboration wants

to address, we could dedicate only part of the running time to transverse polarization, and given the importance of measuring $\Delta G/G$ data have been taken in so far with the deuteron target, whose figure of merit is particularly good for that measurement. Still, we have produced the first ever results of Collins and Sivers single spin asymmetries on a transversely polarized deuteron target.

I have reported on transversity data collected over three years, 2002, 2003, and 2004 (this year the experiment is on pause, all machines at CERN being switched off), and described the three approaches we have to transversity: single hadron asymmetries, two-hadron asymmetries, and Λ polarization. Within statistics, the present evidence from 2002 and 2003 data is that all the measured asymmetries on the deuteron are compatible with zero. Taking into account the HERMES results on a proton target (non-zero effects by many standard deviations) and the BELLE result on $e + e^- \rightarrow$ hadrons (convincing evidence for non-zero Collins effect) we can only conclude that there are cancellation effects between protons and neutrons.

At this point it is of the greatest importance to reduce as much as possible the errors of our measurements on deuterons, and we are finalizing the analysis of the collected data. The next step is to measure transversity with the transversely polarized proton target, which is in the plans of our Collaboration for 2006. This measurement will take advantage of the new COMPASS polarized target magnet, which will allow to increase the acceptance particularly at large x , where transversity is expected to be larger.

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