

TRANSVERSE SPIN AND TRANSVERSE MOMENTUM STRUCTURE OF THE NUCLEON FROM THE COMPASS EXPERIMENT

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Abstract

A selection is presented of recent results from the COMPASS Collaboration on transverse spin and transverse momentum effects in semi-inclusive deeply inelastic scattering (SIDIS) of 160 GeV/c muons off proton and deuteron targets.

1 Introduction

The description of the partonic structure of the nucleon is one of the central problems of hadronic physics. In recent years considerable theoretical and experimental progress has been made and the relevance of the quark transverse spin and transverse momentum has been clearly assessed. In the present theoretical framework, eight transverse momentum dependent parton distribution functions (TMD PDFs) are required at leading twist for each quark flavour. They describe all possible correlations between the transverse momentum and spin of the quarks and the spin of the nucleon. When integrating over the quark transverse momentum five of these functions vanish, while three of them give the well known number, helicity and transversity distribution functions. Among these last three functions, the transversity distribution, which is the analogous of the helicity PDFs in the case of transversely polarized nucleons, was thoroughly studied only in the 90s and experimentally it is the least known one. On the experimental side, semi-inclusive deeply inelastic lepton scattering (SIDIS) is today the major source of information to access the TMD PDFs. It allows to access easily convolutions of the different TMD PDFs and fragmentation functions via high statistic measurements of asymmetries in the azimuthal distributions of the final-state hadrons. Also, using different (p , d , or n) targets and identifying the final state hadrons, one can separate the contributions of the quarks of different flavour. The clear non-zero spin asymmetries recently measured in SIDIS off transversely polarized targets by both HERMES at DESY and COMPASS at CERN at different beam energies, can be described quite well with the present formalism, and thus give much confidence in the overall picture [1].

COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy) is a fixed-target experiment at the CERN SPS taking data since 2002. The COMPASS spectrometer is by now very well known in the scientific community and I will not spend any time in describing it, but only refer to the NIM paper of Ref. [2] and to the previous speaker [3]. An important part of the experimental programme consists in the study of the nucleon structure and SIDIS data have been collected using a 160 GeV longitudinally

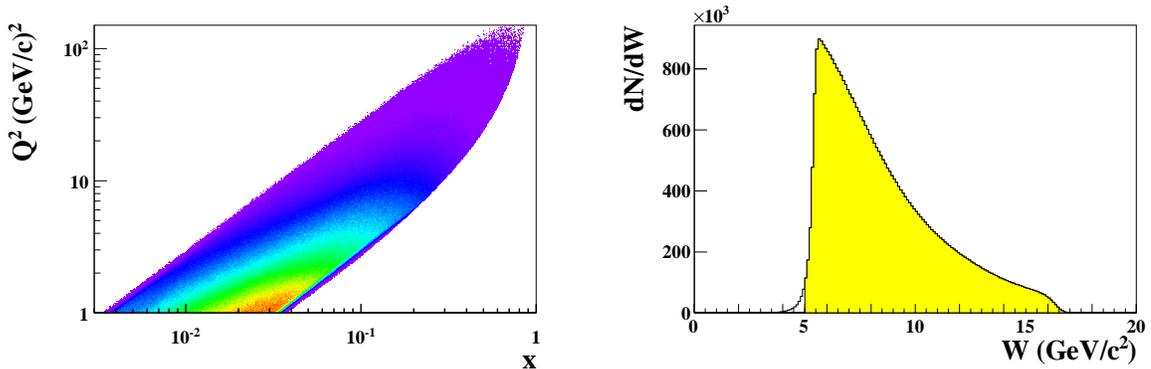


Figure 1: Left: $x - Q^2$ correlation for charged hadrons. Right: W distribution.

polarized muon beam and either longitudinally or transversely polarized proton (NH_3) and deuteron (${}^6\text{LiD}$) targets. A selection of the results on the azimuthal asymmetries in $\mu N \rightarrow \mu' h^\pm X$ extracted from the data collected with transversely polarized targets is presented, with particular focus on the most recent measurements from the data collected in 2007 and 2010 with the proton target. These results exhibit clear signals for the Collins asymmetry, interpreted as a convolution of a non-zero transversity PDF and the Collins fragmentation function (FF), and for the Sivers asymmetry which is related to the Sivers function, the most famous and discussed of the TMD PDFs. At the same time six more transverse spin dependent azimuthal asymmetries have been obtained from the proton and the deuteron data. They have all their own interpretation in terms of the QCD parton model, preliminary results have already been presented at several conferences, but I have not enough space to include them in this written report. Large asymmetries have been measured in the production of oppositely charged hadron pairs (2-h) and the comparison between the Collins asymmetry and the 2-h asymmetry has led to interesting observations on the hadronisation mechanism of transversely polarised quarks. The data collected with the ${}^6\text{LiD}$ target, suitably averaged up to cancel possible target polarization effects, have also been analysed to search for the azimuthal modulations in the production of hadrons which are expected to be present in the unpolarised SIDIS cross-section. The azimuthal hadron asymmetries, which are related to the Boer-Mulders TMD PDF, show strong and somewhat puzzling kinematical dependences.

2 Collins and Sivers asymmetries

SIDIS data with a 160 GeV μ^+ beam and with the transversely polarised deuteron target (${}^6\text{LiD}$) were taken in the years 2002 to 2004. In 2007 and 2010 the transversely polarised proton target (NH_3) was used, again with the 160 GeV μ^+ beam.

The data analysis is very similar for all the years of data taking and the relevant cuts applied to select the “good events” are also the same. Only events with photon virtuality $Q^2 > 1$ $(\text{GeV}/c)^2$, fractional energy of the virtual photon $0.1 < y < 0.9$, and mass of the hadronic final state system $W > 5$ GeV/c^2 are considered. The charged hadrons are required to have at least 0.1 GeV/c transverse momentum p_T^h with respect to the virtual photon direction and a fraction of the available energy $z > 0.2$. The $x - Q^2$ correlation

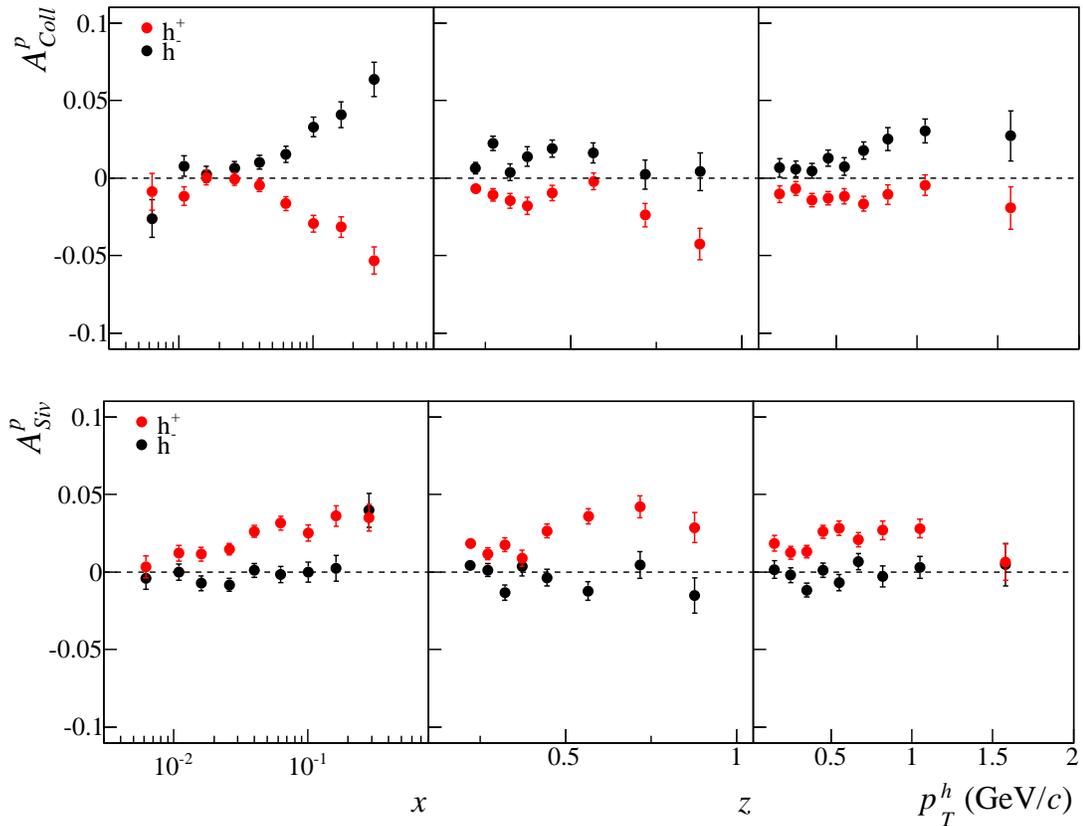


Figure 2: Collins (upper panel) and Sivers (lower panel) asymmetries for positive (red points) and negative (black points) hadrons as functions of x , z and p_T^h from the combined 2007 and 2010 proton data.

for charged hadrons from 2010 data is shown in Fig. 1 (left). As can be seen, the x range goes from $x \simeq 3 \cdot 10^{-3}$ to $x \simeq 0.7$ with relatively large Q^2 values in the valence region. Figure 1 (right) gives the corresponding W distribution. In the standard analysis, the transverse-spin asymmetries are measured separately for positive and negative hadrons (or pions or kaons) as functions of x , z or p_T^h . The complete definition (namely sign and kinematic factors) of the asymmetries can be found in the published papers [4].

The Collins and Sivers asymmetries for positive and negative hadrons from the 2004 deuteron data [5] turned out to be compatible with zero within the few percent uncertainties, at variance with the non-zero results obtained by the HERMES experiment on proton [6]. These data could be understood in terms of cancellation between the u and d quark contributions in the deuteron target, and together with the Belle data of the $e + e- \rightarrow hadrons$ process were used in global fits to extract the transversity and Sivers functions. Still today these COMPASS data are the only SIDIS data collected with a transversely polarised deuteron target.

The first results for the charged hadrons Collins and Sivers asymmetries on proton from COMPASS [7] came from the analysis of the 2007 data, while higher precision results have been obtained from the 2010 data [4]. Very recently, results for charged pions and kaons have also been produced [8].

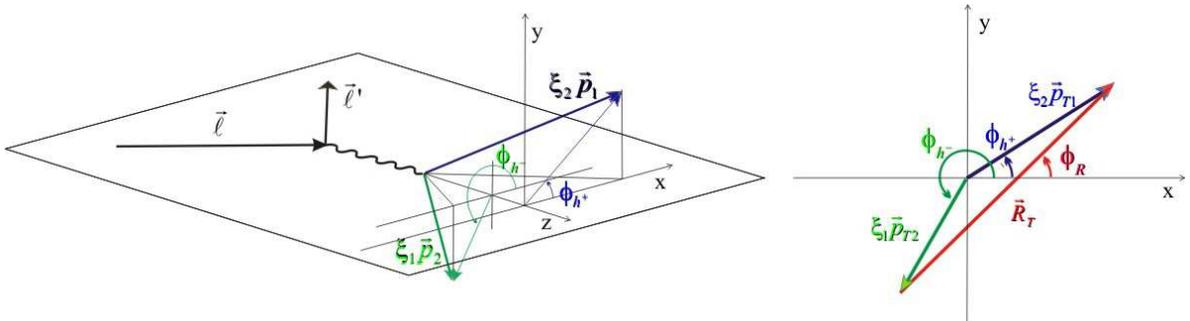


Figure 3: Kinematics of hadron pair production process in SIDIS. The 3-momenta \vec{l} and \vec{l}' of the incoming and scattered lepton define the scattering plane, the z axis (the direction of the virtual photon direction) and the x axis. The vectors \vec{p}_1 and \vec{p}_2 are the 3-momenta of the positive and negative hadron respectively. The vector \vec{R} is defined as $\vec{R} = (z_2 \vec{p}_1 - z_1 \vec{p}_2)/(z_1 + z_2) = \xi_2 \vec{p}_1 - \xi_1 \vec{p}_2$. The subscript T indicates the transverse component with respect to the virtual photon direction.

The combined results for non-identified hadrons from 2007 and 2010 are shown in Fig. 2. The Collins asymmetries (upper plots) are compatible with zero in the previously unmeasured $x < 0.03$ region while at larger x they are clearly different from zero, with opposite sign for positive and negative hadrons and in nice agreement, both in sign and in magnitude, with the HERMES results [6]. There is no indication for lower values of the Collins asymmetry at the higher COMPASS Q^2 values as compared to the HERMES measurement.

The Sivers asymmetries for charged hadrons are given in the lower plots of Fig. 2. For h^- they are compatible with zero with some indication for small negative values over the entire x range but in the last bin. In the case of h^+ , the Sivers asymmetry is positive down to very small x values and in the $x > 0.03$ region it is smaller than the same asymmetry measured by HERMES [6], a fact which can be understood in terms of the recent calculations on TMDs evolution.

3 Two-hadron asymmetry

An alternative approach to the transversity PDF in SIDIS utilises the transverse spin asymmetry in the production of pairs of oppositely charged hadrons, in the process $lN \rightarrow lh^+h^-X$ [9]. In the SIDIS cross-section an azimuthal modulation is expected as a function of $\phi_{RS} = \phi_R + \phi_S - \pi$, whose amplitude is proportional to the product of the transversity PDF and a new chiral-odd FF, the Dihadron Fragmentation Function (DiFF) $H^\angle(z, M_{h^+h^-}, \cos \theta)$ [10]. The angle ϕ_R is the azimuthal angle of the relative momentum R of the two hadrons as depicted in Fig. 3, $\pi - \phi_S$ is the azimuthal angle of the spin vector of the struck quark, z is the sum of the fractional energy of the two hadrons, $M_{h^+h^-}$ is the invariant mass of the two hadrons, and θ is the polar angle of h^+ . First evidence for azimuthal asymmetries in lepton production of $\pi^+\pi^-$ pairs on transversely polarized protons was published by HERMES [11], while results on both proton and deuteron targets for unidentified charged hadrons pairs h^+h^- have been published by COMPASS [12].

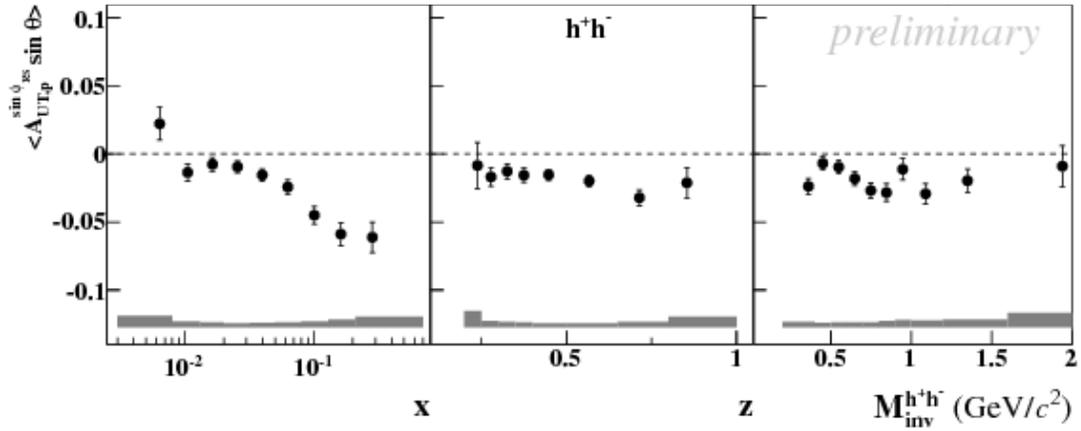


Figure 4: Unidentified 2-h asymmetries as functions of x , z and M_{h+h^-} from the 2007 and the 2010 proton data.

Using these data and the Belle data on e^+e^- annihilation into two pairs of hadrons [13] a first extraction of the u and d quark transversity could be performed [14], which was in good agreement with the extraction of Ref. [15], based on the Collins asymmetry of single hadrons. The same procedure was applied to directly extract u and d quark transversities in the different x bins using COMPASS proton and deuteron results [16]. The data collected by COMPASS in 2010 on the transversely polarized proton target provided a sample of hadron pairs larger than the published one by a factor of three. Preliminary results were first shown at Transversity 2011 [17]. The selection of the two hadron events follows the same track than the single-hadron analysis, but more requirements are imposed. All possible combinations of oppositely charged hadron pairs originating from the vertex are taken into account in the analysis. At least three outgoing tracks are demanded for an interaction vertex, and each hadron has to have a fractional energy $z > 0.1$ and $x_F > 0.1$, to ensure that the hadrons are not produced in the target fragmentation. A cut of $R_T > 0.07$ GeV/c ensures a good definition of ϕ_{RS} . Within measurement errors, the 2-h asymmetry of the COMPASS deuteron data from the 2002-2004 runs are compatible with zero. On the other hand, the data on the proton target definitively show a non-zero signal, in particular in the x -valence region, as clear from Fig. 4, where the combined results from the 2007 and the 2010 runs are shown as a function of x , z and M_{h+h^-} . These data are in good agreement with the only other existing measurement from the HERMES Collaboration, but the statistics of the COMPASS sample is considerably higher thanks to the larger phase space available. A remarkable similarity can thus be noted between the 2-h asymmetry and the Collins asymmetry for h^+ , which will be further discussed in Section 5.

4 Azimuthal modulations in unpolarised SIDIS

Since the early times of the quark-parton model it was realised that a possible intrinsic transverse momentum of the target quark would cause measurable effects in the SIDIS cross-section, namely a $\cos \phi_h$ and a $\cos 2\phi_h$ modulation. Recently the study of these modulations has become particularly interesting within the framework of the new TMD

approach to the PDFs and FFs. The amplitudes of these modulations, $A_{\cos \phi_h}^{UU}$ and $A_{\cos 2\phi_h}^{UU}$ are not only due to the kinematic of the scattering process (Cahn effect) but depend also on a new TMD PDF, the so-called Boer-Mulders function, which describes the correlation between the quark transverse spin and its transverse momentum in an unpolarised nucleon. In the amplitudes the Boer-Mulders function is convoluted with the Collins function, and its extraction from the unpolarised SIDIS cross section data is an important goal of the HERMES, CLAS and COMPASS Collaborations. COMPASS has extracted [18] the amplitudes $A_{\cos \phi_h}^{UU}$ and $A_{\cos 2\phi_h}^{UU}$ from a sample of data collected in 2004 on a ${}^6\text{LiD}$ target (to a good approximation, an isoscalar deuteron target). An $A_{\sin \phi_h}^{LU}$ asymmetry is also expected to be present due to higher twist effects and has been measured. It has no clear interpretation in terms of the parton model, it turns out to be small, and will be neglected in the following. To extract the azimuthal asymmetries one has to correct the measured azimuthal distributions by the ϕ_h dependent part of the apparatus acceptance and to fit the corrected distribution with the appropriate ϕ_h function. To reduce as much as possible the acceptance corrections, some tighter cuts have been applied to the SIDIS event selection as compared to the standard analysis. The final event and hadron selection is in this case: $Q^2 > 1 \text{ GeV}^2/c^2$, $W > 5 \text{ GeV}/c^2$, $0.003 < x < 0.13$, $0.2 < y < 0.9$, $\theta_{\gamma^*}^{lab} < 60 \text{ mrad}$, $0.2 < z < 0.85$ and $0.1 < p_T^h < 1.0 \text{ GeV}/c$.

The amplitudes of the azimuthal modulations have been obtained binning the data both separately in each of the relevant kinematic variables x , z or p_T^h and in a three-dimensional grid of these three variables. The amplitudes of the $\cos \phi_h$ and $\cos 2\phi_h$ modulations show strong kinematic dependences both for positive and negative hadrons. As an example, the preliminary results for $\cos \phi_h$ are shown in Fig. 5. Also $A_{\cos 2\phi_h}^{UU}$ shows a similarly strong dependence on the x , z and p_T^h variables, which up to now has not been reproduced with theoretical models.

5 Interplay between Collins and dihadron asymmetries

There is a striking similarity between the Collins asymmetries in Fig. 2 and the 2-h asymmetries as functions of x shown in Fig. 4. First of all there is a mirror-symmetry between the Collins asymmetry for positive and for negative hadrons, the magnitude of the asymmetries being essentially identical and the sign being opposite in each x -bin. This symmetry has been phenomenologically described in terms of u quark dominance and almost opposite favoured and unflavoured Collins FFs [15].

The observation that the new COMPASS results on the 2-h asymmetries allow is that the values of the 2-h asymmetries are slightly higher but very close to the values of the Collins asymmetries for positive hadrons and to the mean of the values of the Collins asymmetry for positive and for negative hadrons, after changing the sign of the asymmetry of the negative hadrons. The hadron samples on which these asymmetries are evaluated are different, since at least one hadron with $z > 0.2$ is required to evaluate the Collins asymmetry while all the combinations of positive and negative hadrons with $z > 0.1$ are used in the case of the 2-h asymmetry. It has been checked however that the similarity between the two different asymmetries stays the same when measuring the asymmetries on the common hadron sample. This gives a strong indication that the

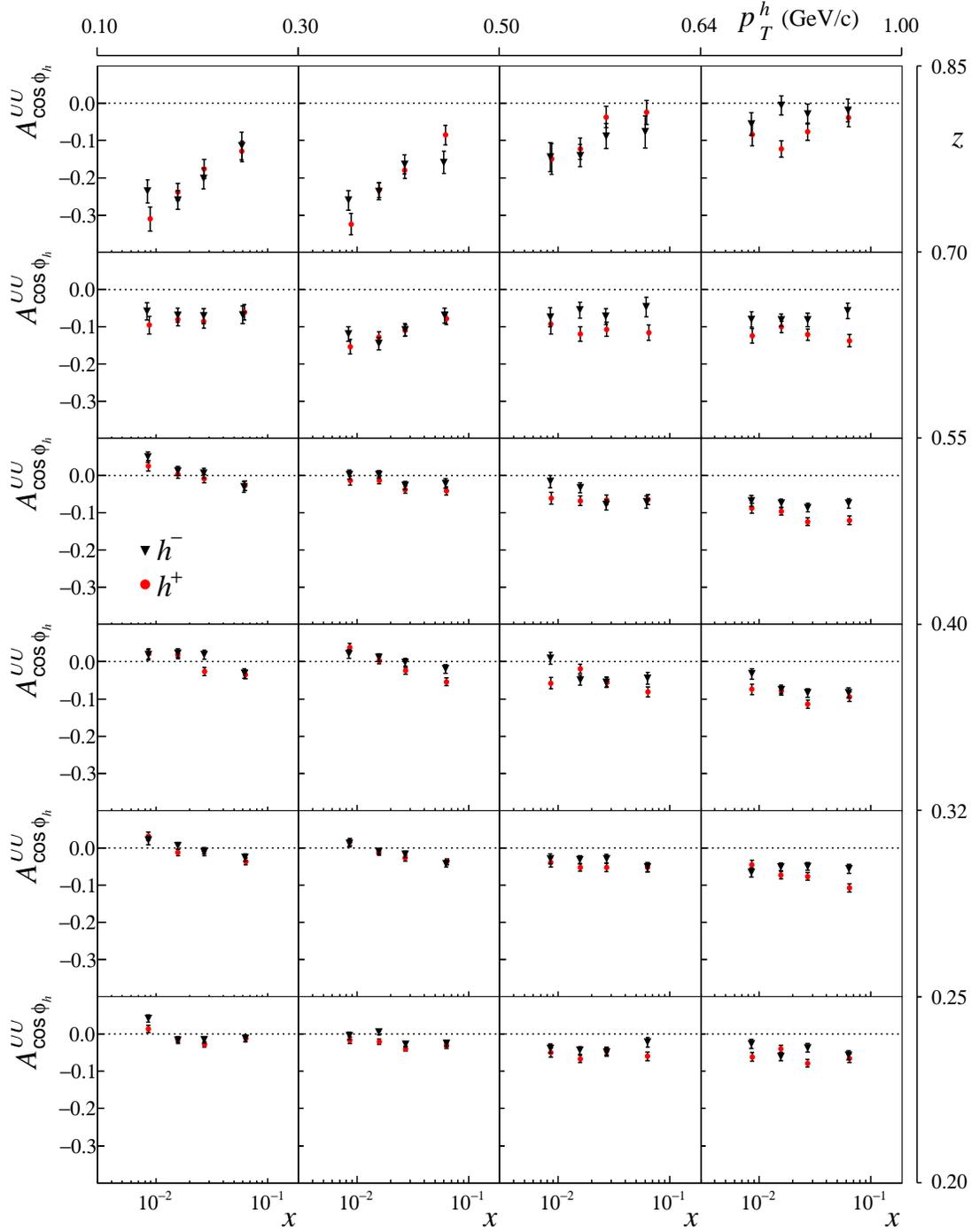


Figure 5: The preliminary results for the $\cos \phi_h$ asymmetries $A_{\cos \phi_h}^{UU}$ for positive and negative hadrons as functions of x in the different z and p_T^h bins from 2004 unpolarised ${}^6\text{LiD}$ data.

analysing powers of the 1- and 2-h channels are almost the same, and their comparison will allow to access the contribution of the convolution over the transverse momenta in the Collins asymmetry.

More work has been done to understand the similarities between the Collins and the

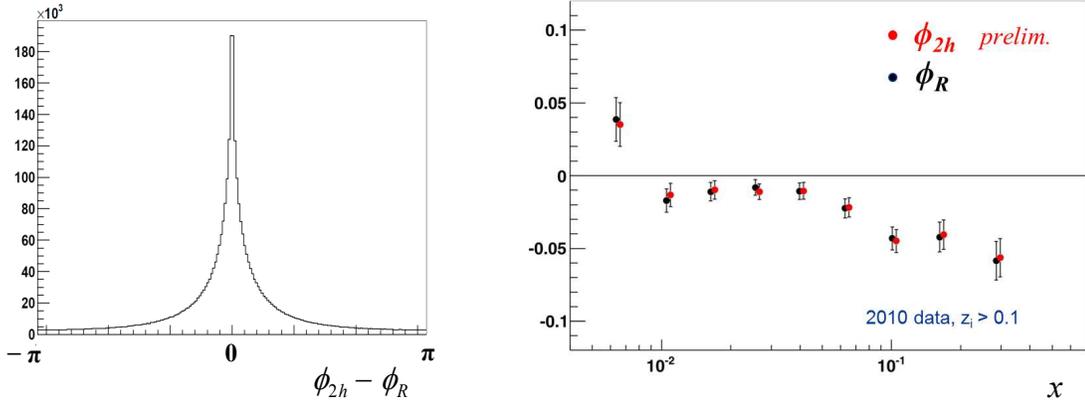


Figure 6: Left: difference between ϕ_{2h} and ϕ_R . Right: comparison between the 2-h asymmetries evaluated (see text) using ϕ_R (black points) and ϕ_{2h} (red points) from the 2010 data.

2-h asymmetries [19]. The mirror symmetry of the Collins asymmetry for positive and negative hadrons suggests that when a transversely polarized quark fragments oppositely charged hadrons have azimuthal angles ϕ_{h+} and ϕ_{h-} differing by π . An anti-correlation between ϕ_{h+} and ϕ_{h-} is expected as a consequence of the local transverse momentum conservation in the fragmentation. The new and relevant point is that this correlation shows up also in the Collins asymmetry, so that the asymmetry exhibited by the hadron pair can be obtained in a way which is different from the one described in Sect. 3. For each pair of oppositely charged hadrons, using the unit vectors of their transverse momenta we have evaluated the angle ϕ_{2h} which is the arithmetic mean (modulus π) of the azimuthal angles of the two hadrons after correcting ϕ_{h-} for the already mentioned π difference.

This azimuthal angle of the hadron pair is strongly correlated with ϕ_R , as can be seen in Fig. 6 (left) where the difference of the two angles is shown. By subtracting from ϕ_{2h} the azimuthal angle $\pi - \phi_S$ as done in the standard analysis described in Sect. 3, one obtains the angle ϕ_{2hS} which is simply the mean of the Collins angle of the positive and negative hadrons, namely a Collins angle for the hadron pair. The amplitude of the $\sin \phi_{2hS}$ modulation, which can be called the Collins asymmetries for the hadron pair, is shown as a function of x in Fig. 6 (right) for all the h^+h pairs with $z > 0.1$ in the 2010 data, and compared with the 2-h asymmetries extracted from the same data sample. It is clear that the asymmetries are very close, hinting at a common physical origin for the Collins mechanism and the dihadron fragmentation, as originally suggested in the original 3P_0 Lund model and in the recursive string fragmentation model [20].

6 Acknowledgements

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