

Azimuthal asymmetries of charged hadrons produced muons off longitudinally polarised deuterons at COMPASS.

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Abstract. Azimuthal asymmetries in semi-inclusive production of positive (h^+) and negative hadrons (h^-) have been measured by scattering of 160 GeV muons off longitudinally polarised deuterons at CERN. The asymmetries were decomposed in several terms, according to their expected modulation as a function of the outgoing hadron azimuthal angle ϕ . Each term receives contributions from one or several spin and transverse-momentum-dependent parton distribution and fragmentation functions. The amplitudes of all ϕ -modulation terms of the hadron asymmetries integrated over the kinematic variables are found to be consistent with zero within statistical errors, while the constant terms are nonzero and equal for h^+ and h^- within the statistical errors. The dependencies of the ϕ -modulated terms versus the Bjorken momentum fraction x , the hadron fractional momentum z , and the hadron transverse momentum p_T^h were studied. The x dependence of the constant terms for both positive and negative hadrons is in agreement with the longitudinal double-spin hadron asymmetries, measured in semi-inclusive deep-inelastic scattering. The x dependence of the $\sin\phi$ -modulation term is less pronounced than that in the corresponding HERMES data. All other dependencies of the ϕ -modulation amplitudes are consistent with zero within the statistical errors.

1. Introduction

The quark transverse momentum dependent distributions in nucleons, leading to an appearance of azimuthal asymmetries (AA) of hadrons produced in Semi-Inclusive Deep Inelastic Scattering (SIDIS), have been predicted theoretically (see [1] and references therein). The asymmetries have been seen for the first time by the SMC, HERMES and CLAS experiments [2]. These asymmetries result from a convolution of Parton Distribution Functions (PDF) depending on the transverse or longitudinal component of the quark spin and Parton Fragmentation Functions (PFF). The AAs on the transversely polarised protons and deuterons have been studied by HERMES [3] and COMPASS [4] Collaborations, and on the longitudinally polarised protons and deuterons - by HERMES [5, 6]. The AAs on the deuterons are found to be much smaller than that on protons indicating a different signs of contributions from u- and d-quarks. The search for the AA using the COMPASS spectrometer [7] with the longitudinally polarised deuterons in a wide kinematical range is presented here [8].

The kinematics of the SIDIS is shown in figure 1a with a usual signature of variables in the muon scattering and hadron production planes. In the framework of the parton model of nucleons, the squared modulus of the matrix element of the SIDIS is represented by the diagram of the type shown in figure 1b. The spin dependent transversity PDF, $h_1(x)$, and the Collins PFF, $H_1^\perp(z)$, are given as

examples. More PDFs enter in the total SIDIS cross section. In general, this cross section is a linear function of the muon beam polarisation, P_μ , and of the target polarization components:

$$d\sigma = d\sigma_{00} + P_\mu d\sigma_{L0} + P_L (d\sigma_{0L} + P_\mu d\sigma_{LL}) + |P_T| (d\sigma_{0T} + P_\mu d\sigma_{LT}), \quad (1)$$

where the first (second) subscript of the partial cross section refers to the beam (target) polarisation. The asymmetry, $a(\phi)$, in the hadron production by polarised muons on the target polarised longitudinally (LPT) along or opposite to the muon beam direction, is proportional to the third and fourth terms in Eq. (1) if the beam polarisation remains unchanged:

$$a(\phi) = \frac{d\sigma^{\leftrightarrow} - d\sigma^{\leftarrow\leftarrow}}{|P_L| (d\sigma^{\leftrightarrow} + d\sigma^{\leftarrow\leftarrow})} = - \frac{(d\sigma_{0L} + P_\mu d\sigma_{LL}) - \tan(\theta_\gamma)(d\sigma_{0T} + P_\mu d\sigma_{LT})}{d\sigma_{00} + P_\mu d\sigma_{L0}}. \quad (2)$$

Each partial cross section in Eq. (2) is characterized by terms including a convolution of PDFs and PFFs multiplied by a function of the hadron azimuthal angle.

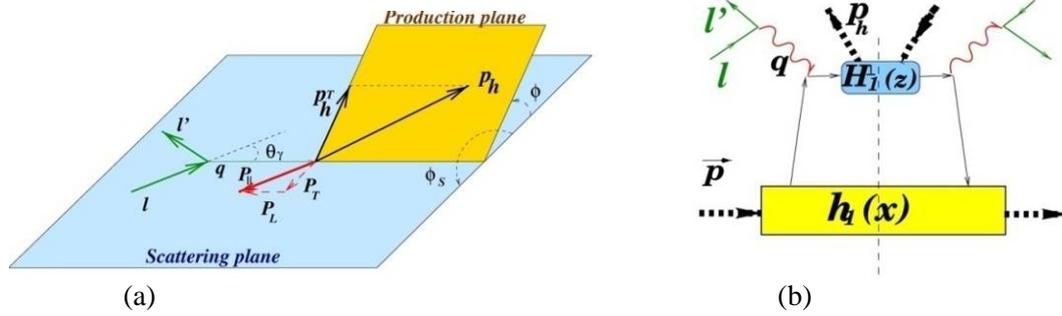


Figure 1: (a) The kinematics of the process. (b) Squared modulus of the matrix element of the SIDIS reaction $\ell + \vec{N} \rightarrow \ell' + h + X$ summed over X states.

Namely, contributions to the numerator of Eq. (2) from each quark and antiquark flavor, up to the order M/Q, have the forms:

$$\begin{aligned} d\sigma_{0L} &\propto \varepsilon x h_{1L}^\perp(x) \otimes H_1^\perp(z) \sin(2\phi) + \sqrt{2\varepsilon(1+\varepsilon)} \frac{M}{Q} x^2 [h_L(x) \otimes H_1^\perp(z) + f_L^\perp(x) \otimes D_1(z)] \sin(\phi), \\ d\sigma_{LL} &\propto \sqrt{1-\varepsilon^2} x g_{1L}(x) \otimes D_1(z) - \sqrt{2\varepsilon(1-\varepsilon)} \frac{M}{Q} x^2 [g_L^\perp(x) \otimes D_1(z) + e_L(x) \otimes H_1^\perp(z)] \cos(\phi), \\ d\sigma_{0T} &\propto \varepsilon \{ x h_1(x) \otimes H_1^\perp(z) \sin(\phi + \phi_S) + x h_{1T}^\perp(x) \otimes H_1^\perp(z) \sin(3\phi - \phi_S) \} \\ &\quad - x f_{1T}^\perp(x) \otimes D_1(z) \sin(\phi - \phi_S), \\ d\sigma_{LT} &\propto \sqrt{1-\varepsilon^2} x g_{1T}(x) \otimes D_1(z) \cos(\phi - \phi_S). \end{aligned} \quad (3)$$

The symbol \otimes represents convolutions with weights in the intrinsic parton transverse momentum on which PDFs and PFFs depend with positive sign if both ingredients are positive, $\varepsilon = 2(1-y)(2-2y+y^2)^{-1}$ and $\phi_S = 0$ or π for LTP. The structure of the partial cross sections and physics interpretations of the PDFs and PFFs in $a(\phi)$ are given in [1].

So, the aim of this study is to see the AA in the hadron production from LPT, as a signal of quark spin dependent PDFs and PFFs, responsible for $\sin\phi$, $\sin 2\phi$, $\sin 3\phi$ and $\cos\phi$ modulations, and to test the x , z and p_T^h dependence of the corresponding amplitudes.

2. Method of analysis and data selection

The experiment is performed in the muon beam M2 at CERN with the COMPASS spectrometer described elsewhere [7]. The muons of the beam originate mainly from the pion and kaon two body decays. They are naturally polarised with the average $P_\mu = -80\%$.

The method of analysis takes advantage of the COMPASS polarised target and data taking procedure. In the years 2002-2004 the target consisted of two cells labeled “U” and “D” (Up- and Down-stream of the setup) placed in the 2.5 T solenoid magnet centered along the beam direction. The target material of the cells (^6LiD) was polarised in opposite directions (positive and negative with respect to the beam) using the Dynamic Nuclear Polarisation. Such a configuration is achieved at a certain orientation (positive or negative) of the solenoid field. The data are taken simultaneously from two cells. There are two sources of systematic effects connected with collection of data, first, due to possible time variation of the spectrometer acceptance, second, due to possible dependence of the acceptance on the orientation of the solenoid field. The first source has been minimised by frequent (three times a day) changing of the cell polarisations adiabatically reversing the solenoid field and, second, – by realising (after few weeks of data taking) the initial configuration of the cell polarisations with the opposite orientation of the solenoid field exchanging the microwave frequency of the cells.

For the AA studies the double ratios of event numbers, R_f , is used in the following form:

$$R_f(\phi) = \left[N_{+,f}^U(\phi) / N_{-,f}^D(\phi) \right] \cdot \left[N_{+,f}^D(\phi) / N_{-,f}^U(\phi) \right]. \quad (4)$$

Here $N_{p,f}^t(\phi)$ is a number of events in each ϕ -bin from the target cell t , $t=U, D$, $p=+$ or $-$ is the sign of the target polarisation, $f=+$ or $-$ is the direction of the target solenoid field. This ratio depends only on physics characteristics of the SIDIS process. It can be expressed via asymmetry $a(\phi)$, Eq. (2) approximate solution of which is:

$$a_f = \left[R_f(\phi) - 1 \right] / (P_{+,f}^U + P_{+,f}^D + P_{-,f}^U + P_{-,f}^D). \quad (5)$$

The $P_{p,f}^t$ is an absolute value of averaged products of the target cell polarisation and dilution factor. Since the asymmetry should not depend on the direction of the solenoid field, one can expect to have $a_+ = a_-$. This expectation has been checked with the data. So, the weighted sum $a(\phi) = a_+(\phi) + a_-(\phi)$, calculated separately for each year of data taking and averaged at the end, is obtained for the final results.

The data selection, aimed at having a set of clean hadrons, has been performed starting from a preselected sample of SIDIS events with $Q^2 > 1$ (GeV/c) 2 and $y > 0.1$, the Q^2 range of which extends up to 100 (GeV/c) 2 . The sample contains all data collected in 2002-2004. Each event includes a reconstructed vertex with incoming and outgoing muons and one or more additional outgoing tracks. Applying cuts on the quality of reconstructed tracks and vertices, vertex positions inside the target cells, energy transfer ($y < 0.9$) and invariant mass of the final states ($5 < W < 18$ GeV), about 96 M of SIDIS events have been selected for further analysis in the incoming muon momentum range 140-180 GeV/c. Tracks originating from the SIDIS events have been identified as hadrons using the information from the two hadron calorimeters available at COMPASS. The total number of the hadrons is about 53 M. Each hadron enters the asymmetry evaluation which has been done in the restricted kinematic region of $x=0.004 - 0.7$, $z=0.2 - 0.9$, $p_T^h = 0.1 - 1$ GeV/c.

3. Results

The weighted sums of the azimuthal asymmetry $a(\phi) = a_+(\phi) + a_-(\phi)$ for negative and positive hadrons have been fitted by a function:

$$a(\phi) = a^{\text{const}} + a^{\sin\phi} \sin\phi + a^{\sin 2\phi} \sin 2\phi + a^{\sin 3\phi} \sin 3\phi + a^{\cos\phi} \cos\phi, \quad (6)$$

where the fit parameters can depend on the variables x , z and p_T^h . The asymmetries, first, have been calculated for hadrons integrated over all kinematic variables, and, second, – as a function of one of variables for hadrons integrated over other two.

For hadrons integrated over kinematic variables, the parameters, characterising ϕ -modulation amplitudes, are compatible with zero while the a^{const} differ from zero and equal to (2.7 ± 1.7) ppm and

(4.0 ± 1.5) ppm for negative and positive hadrons, respectively. As already specified, the a^{const} terms come from the $d\sigma_{LL}$ contribution to the asymmetry, which is proportional to the helicity PDF g_1 convoluted with the PFF D_1 (see Eq. (3)). For the deuteron target these terms are expected to be charge independent. They are related to the hadron asymmetries A_d^h for the negative and positive hadrons. Other amplitudes within the statistical precision of about $1-1.5\sigma$ are compatible with zero but qualitatively (to be confirmed by higher statistics) $a^{\sin\phi}$, $a^{\sin 2\phi}$ and $a^{\sin 3\phi}$ have opposite signs for h^- and h^+ predicted by Wandzura-Wilczek type relation between h_{1T}^\perp and h_1 [9] and by quark models of nucleon [10] due to a non-linear relation $h_{1T}^\perp h_{1L} = -1/2[h_{1L}^\perp]^2$.

Dependence of the AA fit parameters on the kinematic variables is shown in figure 2 with the statistical errors only. Systematic errors are estimated to be much smaller.

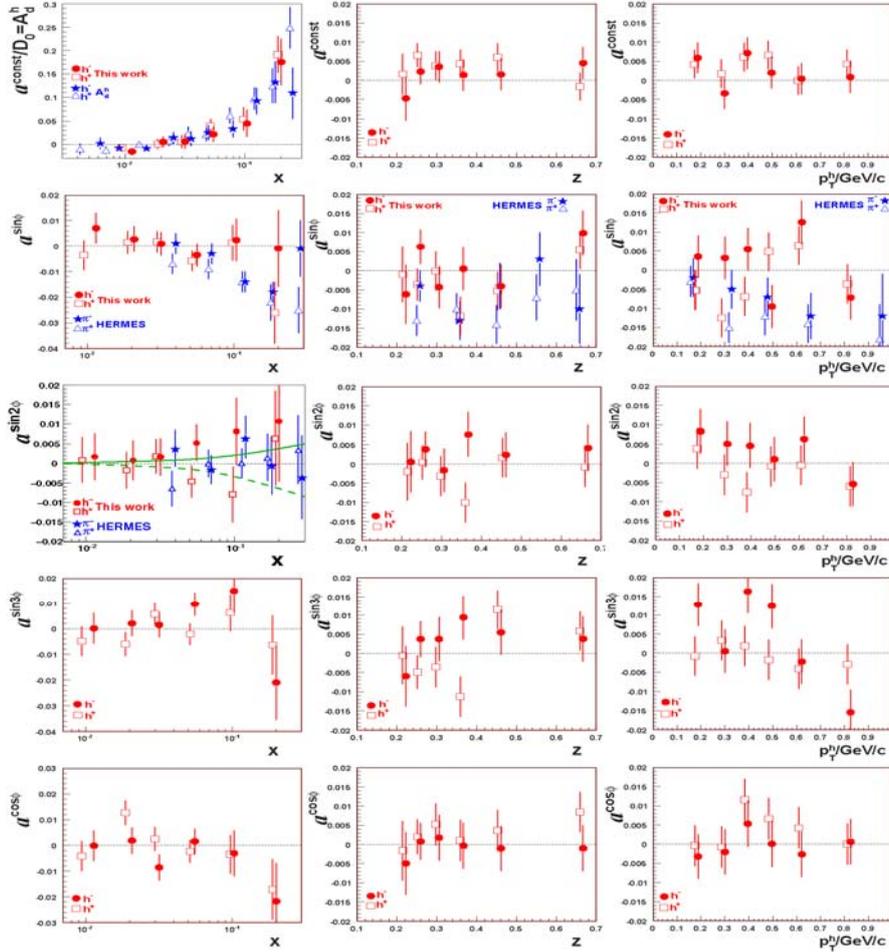


Figure 2. Dependence of the AA fit parameters on the kinematic variables.

The parameters a^{const} (x), being divided by a product of the average muon polarisation and virtual photon depolarisation factor in corresponding x bin, D_0 , by definition, are equal to the asymmetries A_d^h , published by the COMPASS [11]. Agreement of these data with those of the present analysis has demonstrated the internal consistency of the COMPASS results.

The amplitudes $a^{\sin\phi}$ are related to the twist-3 PDFs h_L and f_L entering $d\sigma_{0L}$ as well as to the twist-2 transversity PDF h_1 and Collins PDF f_{1T} entering $d\sigma_{0T}$. All of them contribute to the AA with a factor

$\sim Mx/Q$. The observed x dependence of this modulation is less pronounced in the COMPASS than in the HERMES¹ data [6]. One can note also that the last ones are obtained for leading pions, while our data include all SIDIS hadrons and cover a much wider range in x , Q^2 and W . Restricting our kinematic region to that of the HERMES for the amplitude $a^{\sin\phi}$ we obtain compatible results.

The amplitudes of the $\sin(2\phi)$ modulation are small, consistent with zero within the errors. They could be caused by PDF h_{1L}^\perp in $d\sigma_{0L}$ which is approximately linked [9] with the transversity PDF h_1 by a relation of the Wandzura-Wilczek type. Predictions [9] are shown by dashed (solid) line for h- (h+), respectively.

The amplitudes $a^{\sin 3\phi}$ are compatible with zero as the COMPASS results on the amplitude of the $\sin(3\phi - \phi_S)$ modulation extracted from a transversely polarised target [12] ($\phi_S=0$ for the LPT). This modulation would be due to the pretzelosity PDF h_{1T}^\perp in $d\sigma_{0T}$, suppressed by a factor $\sim xM/Q$.

The $\cos\phi$ modulation of the AA from the LPT is studied here for the first time. The data are consistent with no variations of the modulation amplitudes vs. kinematical variables. This modulation is proportional to the muon beam polarisation and would be due to a pure twist-3 PDF e_L and g_L^\perp in $d\sigma_{LL}$, an analog to the Cahn effect [13] in unpolarised SIDIS [14], and g_{IT} in $d\sigma_{LT}$ suppressed by a factor $\sim xM/Q$.

4. Conclusions

The azimuthal asymmetries in the SIDIS production of negative and positive hadrons by 160 GeV muons on the longitudinally polarised deuterons have been studied. For hadrons integrated over x , z and p_T^h all ϕ -modulation amplitudes of the $a(\phi)$ are consistent with zero, while the ϕ -independent parts differ from zero and are equal for h⁻ and h⁺ within the statistical errors.

The modulation amplitudes as functions of the kinematic variables are studied. The ϕ -independent parts of the $a(\phi)$, $A_d^h \equiv a^{\text{const}}(x)/D_0$ are in agreement with the COMPASS published data [11] on A_d^h . The amplitudes $a^{\sin\phi}(x,z,p_T^h)$ are small and compatible with the HERMES data [6], if one takes into account the difference in x , Q^2 and W between the two experiments. The amplitudes $a^{\sin 2\phi}(x,z,p_T^h)$, $a^{\sin 3\phi}(x,z,p_T^h)$ and $a^{\cos\phi}(x,z,p_T^h)$ are consistent with zero within the statistical errors.

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¹ The sign of HERMES data was inverted in order to match our definition of spin asymmetry by Eq. (2).