AZIMUTHAL ASYMMETRIES IN PRODUCTION OF CHARGED HADRONS BY HIGH ENERGY MUONS ON POLARIZED DEUTERIUM TARGETS[1]

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Abstract

Search for azimuthal asymmetries in semi-inclusive production of charged hadrons by 160 GeV muons on the longitudinally polarized deuterium target, has been performed using the 2002- 2004 COMPASS data. The observed asymmetries integrated over the kinematical variables do not depend on the azimuthal angle of produced hadrons and are consistent with the ratio $g_1^d(x)/f_1^d(x)$. The asymmetries are parameterized taking into account possible contributions from different parton distribution functions and parton fragmentation functions depending on the transverse spin of quarks.They can be modulated (either/or/and) with $\sin(\phi)$, $\sin(2\phi)$, $\sin(3\phi)$ and $\cos(\phi)$. The x-, z- and p_h^T-dependencies of these amplitudes are studied.

1. Introduction. Although the longitudinal spin structure of nucleons has been investigated for more than 20 years and results are very well known, the studies of the transverse spin structure of nucleons have been started recently. Since the pioneering HERMES [1] and CLAS [2] experiments it is known that the signature of the transverse spin effects is an appearance of azimuthal asymmetries (AA) of the hadrons produced in Semi-Inclusive Deep Inelastic Scattering (SIDIS) of leptons on polarized targets.

These asymmetries are related with new Parton Distribution Functions (PDF) and new polarized Parton Fragmentation Functions (PFF), depending on the transverse spin of quarks [3]. AAs on the transversally polarized targets have been already reported by HERMES [4] and COMPASS [5, 6], and on the longitudinally polarized targets - by HERMES [7, 8]. The search for the AA using the COMPASS spectrometer [9] with the longitudinally polarized deuterium target is described below.

In the framework of the parton model of nucleons, the squared modulus of the matrix element of the SIDIS is represented by the type of the diagram in Fig.1a, where an example of one of the new PDF, transversity, $h_1(x)$ and new Collins PFF, $H_1^\perp(z)$, is shown. New PDFs and PFFs, due to their chiral odd structure, always appear in pairs.

The kinematics of the SIDIS is shown in Fig.1b, where $\ell\,(\ell')$ is the 4-momentum of incident (scattered) lepton, $q = \ell - \ell'$, $Q^2 = -q^2$, θ_γ is the angle of the virtual photon momentum $\vec{q}$ with respect to the beam, $P_L(P_T)$ is a longitudinal (transversal) component of the target polarization, P_{II}, with respect to the virtual photon momentum in the laboratory frame, p_h is the hadron momentum with the transverse component p_h^T, ϕ is the azimuthal angle between the scattering plane and hadron production plane, ϕ_S is the angle of the target polarization vector with respect to the lepton scattering
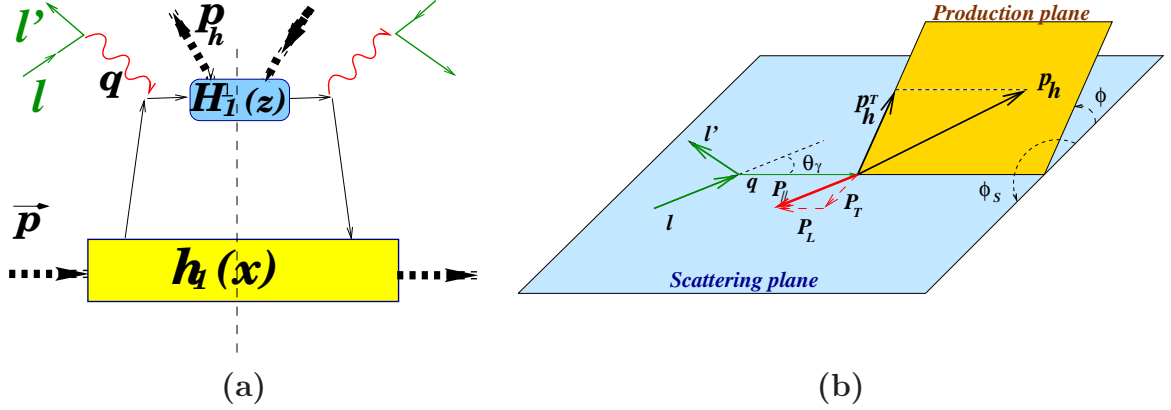

Figure 1: The squared modulus of the matrix element of the SIDIS reaction $\ell + \vec{N} \to \ell' + h + X$ summed over X states **(a)** and kinematics of the process **(b)**.

plane (for the longitudinal target polarization $\phi_S = 0$ or π. For the target polarization P_{II}, which is longitudinal with respect to the lepton beam, the transverse component is equal to $|P_T| = P_{II} \sin(\theta_\gamma)$, where $\sin(\theta_\gamma) \approx 2\frac{M}{Q}x\sqrt{1-y}$, $y = \frac{q \cdot p}{p \cdot \ell}$ and M is the nucleon mass. The Bjorken variable x and the hadron fractional momentum z are defined as $x = Q^2/2p \cdot q$, $z = p \cdot p_h/p \cdot q$, where p is the 4-momentum of the incident nucleon.

In general, the total cross section of the SIDIS reaction is a linear function of the lepton beam polarization,P_μ, and of the target polarization P_{II} or its components:

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

where the first (second) subscript of the partial cross sections means the beam (target) polarization.

The asymmetry, a(ϕ), in the hadron production from the longitudinally polarized target (LPT), is defined by the expression:

$$a(\phi) = \frac{d\sigma^{\to\Rightarrow} - d\sigma^{\to\Leftarrow}}{d\sigma^{\to\Rightarrow} + d\sigma^{\to\Leftarrow}} \propto P_L \left(d\sigma_{0L} + P_\mu d\sigma_{LL}\right) + |P_L| \sin(\theta_\gamma) \left(d\sigma_{0T} + P_\mu d\sigma_{LT}\right). \tag{2}$$

Each of the partial cross sections is characterized by the specific dependence of the definite convolution of PDF and PFF times a function the azimuthal angle of the outgoing hadron. Namely, contributions to Eq. (2) from each quark and antiquark flavor, up to the order (M/Q), have the forms:

$$d\sigma_{0L} \propto \epsilon x h_{1L}^\perp(x) \otimes H_1^\perp(z) \sin(2\phi) + \sqrt{2\epsilon(1-\epsilon)}\frac{M}{Q}x^2 \left(h_L(x) \otimes H_1^\perp(z) + f_L^\perp(x) \otimes D_1(z)\right) \sin(\phi),$$

$$d\sigma_{LL} \propto \sqrt{1-\epsilon^2}x g_{1L}(x) \otimes D_1(z) + \sqrt{2\epsilon(1-\epsilon)}\frac{M}{Q}x^2 \left(g_L^\perp(x) \otimes D_1(z) + e_L(x) \otimes H_1^\perp(z)\right) \cos(\phi),$$

$$d\sigma_{0T} \propto \epsilon \{x h_1(x) \otimes H_1^\perp(z) \sin(\phi+\phi_S) + x h_{1T}^\perp(x) \otimes H_1^\perp(z) \sin(3\phi-\phi_S) - x f_{1T}^\perp(x) \otimes D_1(z) \sin(\phi-\phi_S)\},$$

$$d\sigma_{LT} \propto \sqrt{1-\epsilon^2}x g_{1T}(x) \otimes D_1(z) \cos(\phi - \phi_S), \tag{3}$$

where $\otimes$ is a convolution in parton's internal transversal momentum, k_T, on which PDF and PFF depend, $\phi_s=0$ for the LPT and $\epsilon \approx \frac{2(1-y)}{2-2y+y^2}$. The structure of the partial cross sections and physics interpretations of the new PDFs and PFFs, entering in a(ϕ), are given in [10–12].

So, the aim of this study is to see the AA in the hadron production from LTP, as a manifestation of new PDFs and PFFs and the x, z and p_h^T- dependence of the corresponding amplitudes.

2. Method of analysis. The COMPASS polarized target [9] in 2002-2004 years had two cells, Up- and Down-stream of the beam, placed in the 2.5 T solenoid magnetic field. The target material of the cells (^{6}LiD or NH$_3$) can be polarized in opposite directions with respect to the beam, for example in the U-cell along to the beam (positive polarization) and in D-cell – opposite to the beam (negative polarization) and vice versa. Such a configuration can be achieved by means of the microwave field at low temperatures at any direction of the solenoid magnetic field holding the polarization. Suppose that the above configuration of the cell polarizations is realized with the positive (along to the beam) solenoid field, then, to avoid possible systematic effects in acceptance connected with this field, after some time the same configuration of polarizations is realized by means of the microwave field with the negative (opposite to the beam) solenoid field. Microwave polarization reversals are repeated several times while data taking. In order to minimize systematics caused by the time dependent variation of the acceptance between the microwave reversals, the polarizations are frequently reversed by inverting of the solenoid field.

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

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

where $N_{p,f}^t(\phi)$ 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 polarization, $f = +$ or $-$ is the direction of the target solenoid field. Using Eqs. (1,2,3) with $P_\pm$ as an absolute value of averaged products of the positive or negative target polarization and dilution factor, the number of events can be expressed as

$$N_{p,f}^t = C_f^t(\phi)L_{p,f}^t\left[(B_0 + B_1\cos(\phi) + B_2\sin(\phi) + \ldots) \pm P_p(A_0 + A_1\sin(\phi) + A_2\sin(2\phi) + \ldots)\right],\quad(5)$$

where $C_f^t(\phi)$ is the acceptance factor (source of false asymmetries), $L_{p,f}^t$ is a luminosity depending on the beam flux and target densities. The coefficients B$_0$, B$_1$, ... and A_0, A_1, ... characterize contributions of partial cross sections. Substituting Eq.(5) in Eq. (4) one can see that the acceptance factors are canceled, as well as the luminosity factors if the beam muons cross the both cells. So, the ratio $R_f(\phi)$ depends only on physics characteristics of the SIDIS process and it is expressed via asymmetry $a(\phi)$, Eq. (2), in the quadratic equation, approximate solution of which is:

$$a_f = \left[R_f(\phi) - 1\right]/\left(P_{+,f}^U + P_{+,f}^D + P_{-,f}^U + P_{-,f}^D\right).\qquad(6)$$

Since asymmetry should not depend on the direction of the solenoid field, one can expect to have $a_+ = a_-$. Small difference between a_+ and a_- could appear due to the solenoid field dependent contributions non-factorizable in Eq. (5). But these contributions have different signs and canceled in the sum $a(\phi) = a_+(\phi) + a_-(\phi)$. 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.

3. Data selection. The data selection, aimed at having a clean sample of hadrons, has been performed in three steps, using a preselected sample. This sample contained about 167.5M of SIDIS events with $Q^2 > 1$ GeV^2 and $y > 0.1$ in a form of reconstructed vertices with incoming and outgoing muons and one or more additional outgoing tracks.

1. "GOOD SIDIS EVENTS" have been selected out of the preselected ones applying more stringent cuts on the quality of reconstructed tracks and vertices, vertex positions inside the target cells, momentum of the incoming muon (140-180 GeV/c), energy transfer ($y < 0.9$) and invariant mass of the final states ($W > 5$ GeV). About 58% of events of the initial sample have survived after these cuts.

2. "GOOD TRACKS" (about 157 M) have been selected out of the total tracks (about 290 M) from GOOD SIDIS EVENTS excluding the tracks identified as muons and tracks with $z > 1$ and $p_h^T < 0.1$ GeV/c.

3. "GOOD HADRONS" from GOOD TRACKS have been identified using the information from the hadron calorimeters HCAL1 and HCAL2. Each of the GOOD TRACKS is considered as the GOOD HADRON if: this track hits one of the calorimeter, the calorimeter has the energy cluster associated with this hit with $E_{HCAL1} > 5$ GeV, or $E_{HCAL2} > 7$ GeV, coordinates of the cluster are compatible with coordinates of the track and the energy of the cluster is compatible with the momentum of the track.

The total number of GOOD HADRONS was about 53 M. Each of the GOOD HADRONS is included to the asymmetry evaluations.

4. Results. The weighted sum of azimuthal asymmetries a(ϕ)=a$_+$(ϕ)+a$_-$(ϕ), averaged over all kinematical variables, are shown in Fig. 2 for negative and positive hadrons. They have been fitted by functions

$$a(\phi) = a^{\mathrm{const}} + a^{\sin\phi} \sin(\phi) + a^{\sin 2\phi} \sin(2\phi) + a^{\sin 3\phi} \sin(3\phi) + a^{\cos\phi} \cos(\phi). \qquad (7)$$

The fit parameters, characterizing ϕ-modulation amplitudes, are compatible with zero. The ϕ-independent parts of a(ϕ) differ from zero and are almost equal for h^- and h^+. The fits of $a(\phi)$ by constants are also shown is Fig. 2.
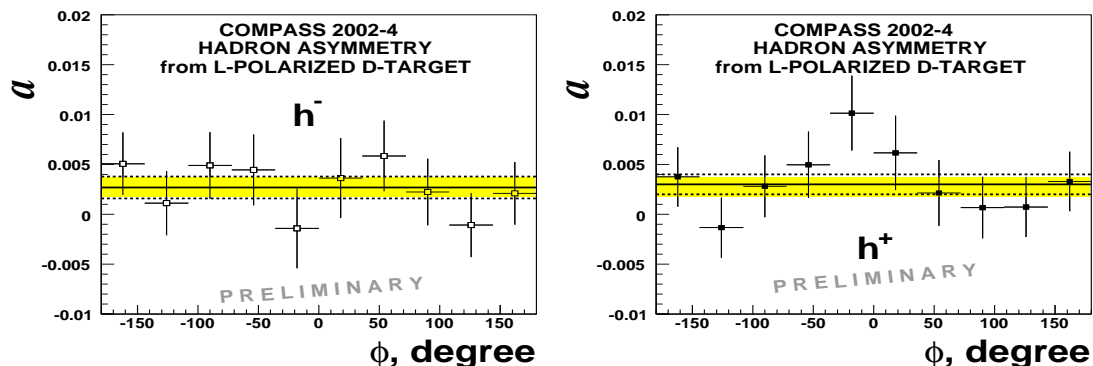

Figure 2: Azimuthal asymmetries a(ϕ) for negative (left) and positive (right) hadrons and results of fits by the constants with $\chi^2/d.f.$ equal to 3.4/5 (5.2/5), respectively.

As already specified, the ϕ-independent parts of asymmetries come from the $d\sigma_{LL}$ contributions to the cross sections, which are proportional to helicity PDF times PFF (see Eq. (3)) of non-polarized quarks in the non-polarized hadron. For the deuteron target this contribution is expected to be charge independent.

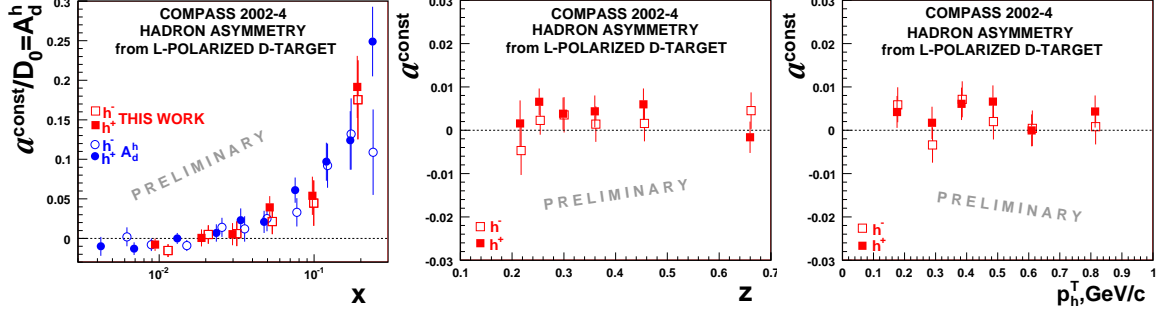Dependence of the AA fit parameters on the kinematical variables are shown in Figs. 3-7.

Figure 3: Dependence of the AA fit parameters a^{const} on kinematical variables.

The parameters $a^{\mathrm{const}}(x)$, being divided by the virtual photon depolarization factor D_0, are equal (by definition) to the asymmetry $A_d^h(x)$, already published by COMPASS [13]. Agreement of these data and data of the present analysis has demonstrated internal consistency of the results.
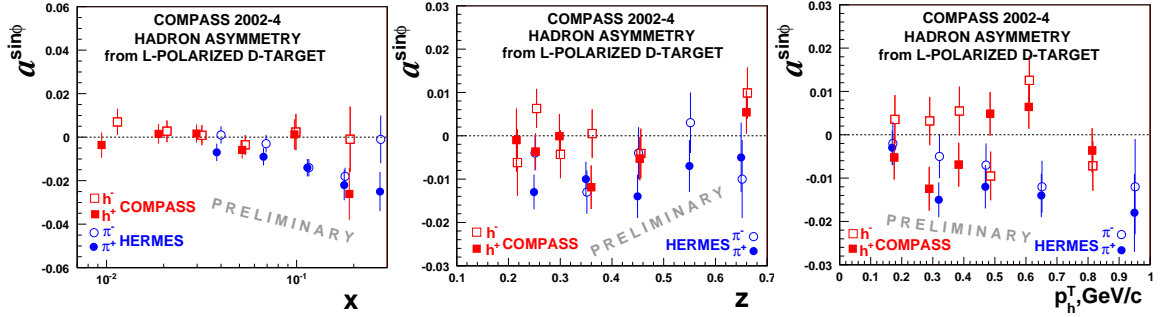

Figure 4: Dependence of the AA fit parameters $a^{\sin\phi}$ on kinematical variables and similar data of HERMES [8] for identified leading pions.

The x-dependence of the $\sin(\phi)$ modulations of the AA, observed by HERMES, is less pronounced at COMPASS. This modulation is due to pure twist-3 PDF's entering from the $d\sigma_{0L}$ contribution to the AA with a factor Mx/Q.
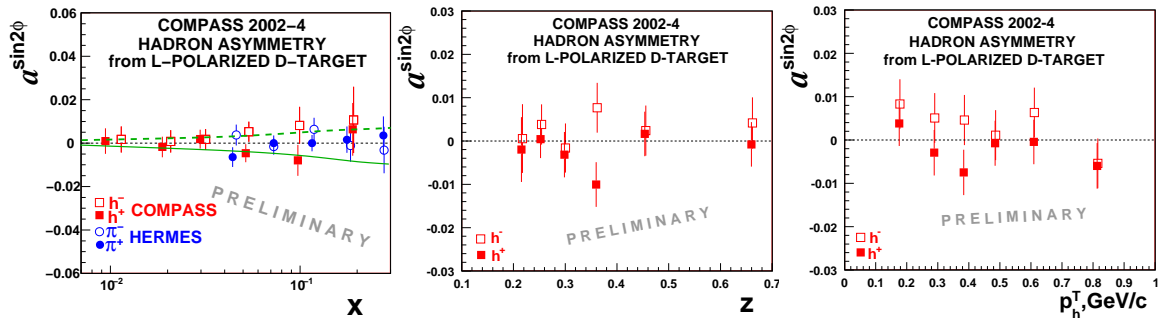

Figure 5: Dependence of the AA fit parameters $a^{\sin 2\phi}$ on kinematical variables compared to the data of HERMES and calculations by H.Avakian et al. [14]: dashed line $- h^-$, solid line $- h^+$.

The amplitudes of the $\sin(2\phi)$ modulations are small, consistent with zero within the errors. They could be caused by PDF $h_{1L}^\perp$ in $d\sigma_{0L}$.
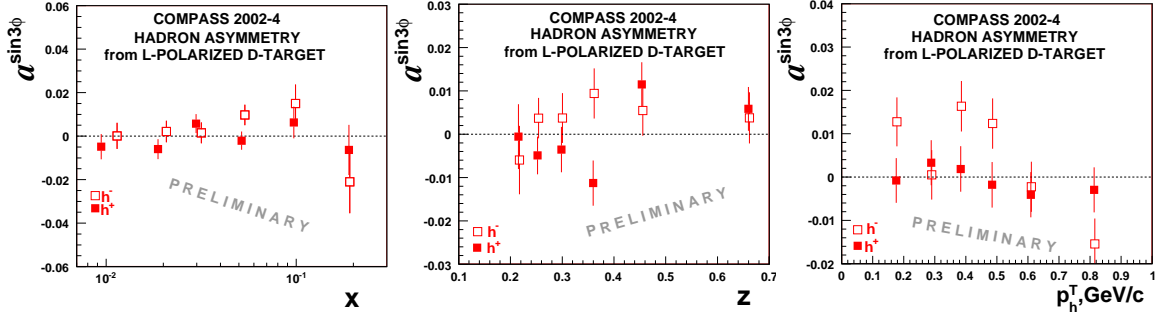
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Figure 6: Dependence of the AA fit parameters $a^{\sin 3\phi}$ on kinematical variables.

Some peculiarities of the data on the $a^{\sin 3\phi}$ are seen from Fig. 6, for instance, the points for h^- are mostly positive while for h^+ they are mostly negative like for the COMPASS results from the transversally polarized target [15]. Remind that this modulation could come from the pretzelosity PDF $h_{1T}^{\perp}$ in $d\sigma_{0T}$, additionally suppressed by $\sin(\theta_\gamma) \sim xM/Q$.
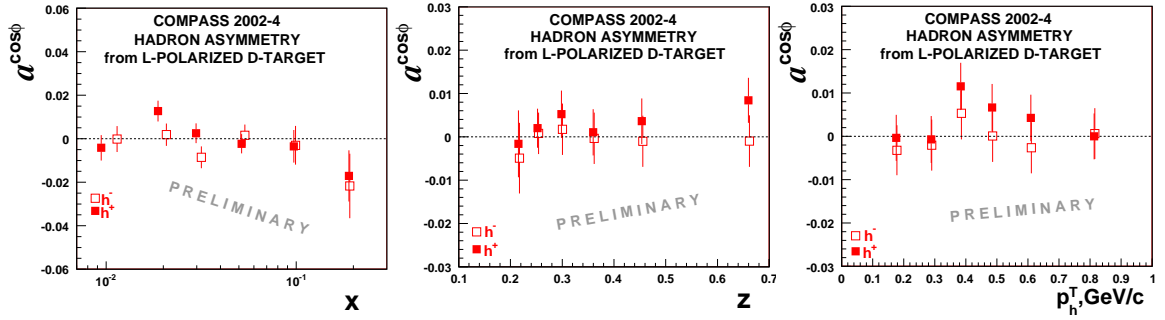

Figure 7: Dependence of the AA fit parameters $a^{\cos\phi}$ on kinematical variables.

The $\cos(\phi)$ modulation of the AA is studied for the first time. It is mainly due to a pure twist-3 PDF $g_L^{\perp}$ in $d\sigma_{LL}$, an analog to the Cahn effect [16] in unpolarized SIDIS.

5. Conclusions and prospects.

1. The azimuthal asymmetries $(a(\phi))$ in the SIDIS $(Q^2 > 1 \text{ GeV}^2, y > 0.1)$ production of negative (h^-) and positive (h^+) hadrons by 160 GeV muons on the longitudinally polarized deuterium target, have been studied with the COMPASS data collected in $2002 - 2004$.

2. For the integrated over x, z and p_h^T variables all ϕ-modulation amplitudes of $a(\phi)$ are consistent with zero within errors, while the ϕ-independent parts of the $a(\phi)$ differ from zero and are almost equal for h^- and h^+.

3. The amplitudes as functions of kinematical variables are studied in the region of $x = 0.004 - 0.7$, $z = 0.2 - 0.9$, $p_h^T = 0.1 - 1$ GeV/c. It was found that:

   - ϕ-independent parts of the $a(\phi)$, $a^{\text{const}}(x)/D_0 = A_d^h$, where D_0 is a virtual photon depolarization factor, are in agreement with the COMPASS published data [13] on A_d^h, calculated by another method and using different cuts;

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- the amplitudes $a^{\sin\phi}(x, z, p_h^T)$ are small and in general do not contradict to the HERMES data [8], if one takes into account the difference in x, Q^2 and W between the two experiments. One can also note, that in the HERMES experiment the asymmetries are calculated for identified leading pions, while in this analysis every hadron is included in the asymmetry evaluations;
- the amplitudes $a^{\sin 2\phi}$, $a^{\sin 3\phi}$ and $a^{\cos\phi}$ are consistent with zero within statistical errors of about 0.5% (only statistical errors are shown in the plots while systematic errors are estimated to be much smaller).

4. The results of this analysis are obtained with restriction $z > 0.2$ of the energy fraction of the hadron in order to assure that it comes from the current fragmentation region. This request removes almost one half of statistics. The tests have shown that with a lower cut, $z > 0.05$, the results are identical.

5. The reported data are preliminary. New data of 2006 from the deuterium target will be added. These data will increase the statistics by about a factor of 2. New data of 2007 from the hydrogen target will be very interesting in comparison with the effects already observed by the COMPASS and HERMES on the transversally polarized targets.

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