AZIMUTHAL ASYMMETRIES IN SEMI-INCLUSIVE PRODUCTION OF CHARGED HADRONS BY HIGH ENERGY MUONS ON THE LONGITUDINALLY POLARIZED DEUTERATED TARGETS[1]

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Abstract

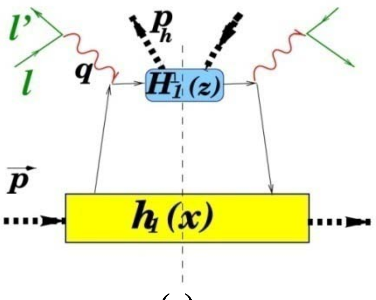
Studies of the azimuthal asymmetries in semi-inclusive production of charged hadrons by 160 GeV muons on the longitudinally polarized deuterated target have been performed using the 2002-2004 COMPASS data. The observed asymmetries integrated over the kinematical variables do not depend on the azimuthal angle of produced hadrons and are consistent with the contributions from 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 which are modulated (either/or/and) with *sin* (ϕ), *sin* (2ϕ), *sin* (3ϕ) and *cos* (ϕ).
The *x*-, *z*- and p_h^T- dependencies of amplitudes of these modulations are studied also.

1. Introduction

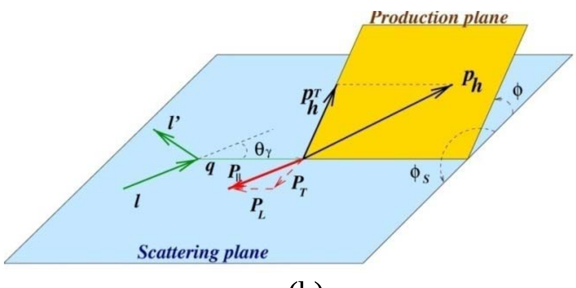
Although the longitudinal spin structure of the nucleons has been investigated for more then 20 years and results are very well known, studies of the transverse spin structure of nucleons started relatively recently. Since the pioneering HERMES [1] and CLAS [2] experiments, it is known that the signature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

These asymmetries are connected with the new Parton Distribution Functions (PDF) and new polarized Parton Fragmentation Functions (PFF), depending on the transverse spin of quarks [3]. The AA's on the transversally polarized targets have been already reported by HERMES [4] and COMPASS [5] and on the longitudinally polarized targets by HERMES [6], [7]. The search for the AA using the COMPASS spectrometer [8] 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 PDF and PFF, due to their chiral odd structure, appear always in pairs.



(a)



(b)

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

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

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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 lab. 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 plane (for the longitudinal target polarization ϕ_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 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 incident nucleon.

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

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

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

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

$$a(\phi) = \frac{d\sigma^{\rightarrow\Rightarrow} - d\sigma^{\rightarrow\Leftarrow}}{d\sigma^{\rightarrow\Rightarrow} + d\sigma^{\rightarrow\Leftarrow}} \sim P_L(d\sigma_{0L} + Pd\sigma_{LL}) + P_L\sin(\theta_\gamma)(d\sigma_{0T} + Pd\sigma_{LT}), \qquad (2)$$

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

$$d\sigma_{0L} \propto x h_{1L}^{\perp}(x)\oplus H_1^{\perp}(z)\sin(2\phi) + \frac{M}{Q}x^2\left[h_L(x)\oplus H_1^{\perp}(z) + f_L^{\perp}(x)\oplus D_1(z)\right]\sin(\phi), \qquad (3)$$

$$d\sigma_{LL} \propto x g_{1L}(x)\oplus D_1(z)\sin(2\phi) + \frac{M}{Q}x^2\left[g_1^{\perp}(x)\oplus D_1(z) + e_L(x)\oplus H_1^{\perp}(z)\right],$$

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

$$-x f_{1T}^{\perp}(x)\oplus D_1(z)\sin(\phi-\phi_S),$$

$$d\sigma_{LT} \propto \quad x g_{1T}(x)\oplus D_1(z)\cos(\phi-\phi_S),$$

where $\oplus$ is a convolution in parton's internal transversal momentum, k_T, on which PDF and PFF depend, ϕ_s=0 for the LPT. The structure of the partial cross sections and physics interpretations of the new PDF's and PFF's, entering in a(ϕ), are given in [9-11].

So, the aim of this study is to see the AA in the hadron production from LTP, as a manifestation of new PDF and PFF, their possible sin(ϕ), sin(2ϕ), sin(3ϕ) and cos(ϕ) modulations and the x, z and p_h^T- dependence of corresponding amplitudes.

2. Method of analysis

The COMPASS polarized target [8] in 2002-2004 years has 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, f.e. 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 polarizations. Suppose that 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, after some time the same configuration of polarizations is realized by means of microwave field with negative (opposite to the beam) solenoid field. Microwave reversals are repeated several times during data taking. In order to minimize the time dependent variation of acceptance between the microware reversals, the polarizations are frequently reversed by rotation of the solenoid field.

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

$$R_f(\phi) = \left[N^U_{+,f}(\phi) / N^D_{-,f}(\phi) \right] \cdot \left[N^D_{+,f}(\phi) / N^U_{-,f}(\phi) \right], \quad (4)$$

where $N^t_{p,f}(\phi)$ 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 expression as

$$N^t_{p,f} = C^t_f(\phi) L^t_{p,f} \left[(B_0 + B_1 \cos(\phi) + B_2 \sin(\phi) + ...) \pm P_p (A_0 + A_1 \cos(\phi) + A_2 \sin(2\phi) + ...) \right] \ , (5)$$

where $C^t_f(\phi)$ is the acceptance factor (source of false asymmetries), $L^t_{p,f}$ 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 and the luminosity factors also, if the beam muons cross the both cells. So, the ratio $R_f(\phi)$ depends only on physics characteristics of the SIDIS process. The $R_f(\phi)$ is expressed via asymmetry $a(\phi)$, Eq. (2), in the quadratic equation, approximate solution of which with respect to $a_f(\phi)$ is :

$$a_f = \left[R_f(\phi) - 1 \right] / (P^U_{+,f} + P^D_{+,f} + P^U_{-,f} + P^D_{-,f}). \quad (6)$$

Because 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 solenoid field dependent contributions non-factorisable in Eq. (5). But these contributions have different signs and canceled in the sum $a(\phi)=a_+(\phi)+a_-(\phi)$. So, for the final results on azimuthal asymmetries, the weighted sum $a(\phi)=a_+(\phi)+a_-(\phi)$, calculated separately for each year of data taking and averaged at the end, is obtained. Prior of the analysis of the full set of data, the method has been checked using a fraction of COMPASS data.

3. Data selection

The data selection, aiming to have 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 vertexes with incoming and outgoing muons and one or more additional outgoing track.

1. "GOOD SIDIS EVENTS" have been selected out of the preselected ones applying more stringent cuts on the quality of reconstructed tracks and vertexes, 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 these cuts.
2. "GOOD TRACKS" (about 157 M) have been selected out of the total tracks (about 290 M) from GOOD SIDIS EVENTS excluding tracks identified as muons and tracks with z>1 and $p^T_h < 0.1\ GeV/c$.
3. "GOOD HADRONS" from GOOD TRACKS have been identified using the information from the hadron calorimeters HCAL1 and HCAL2. Each of the GOOD TRACK is considered as the GOOD HADRON if: this track hits one of the calorimeter, the calorimeter have an 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 HADRON enters in considerations of asymmetries.

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

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

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

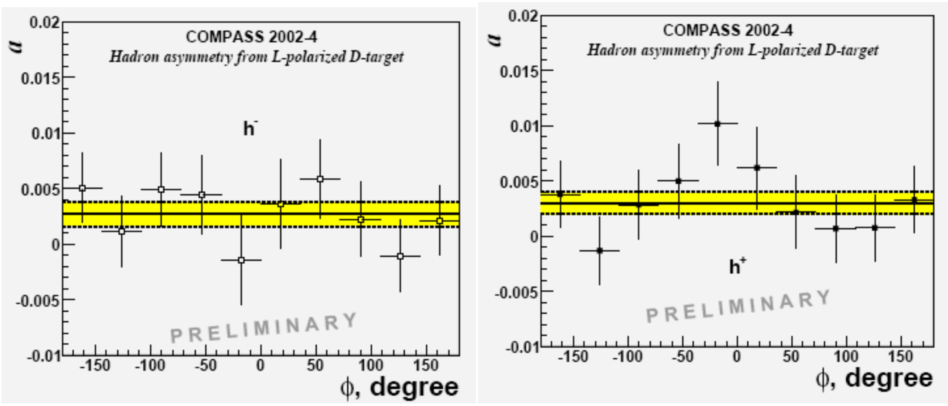

Fig.2. The azimutal asymmetries a(ϕ) for negative (left) and positive (right) hadrons and results of fits by the costants with chsq/df equal to 3.4/5 (5.2/5) , respectively.

Remind, that 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 non-polarized hadron. For the deuteron target this contribution is expected to be charge independent.

Dependences of the AA fit parameters on the kinematical variables are shown in Figs.3-7. Particular comments are given after each figure and the general ones – in Conclusions.

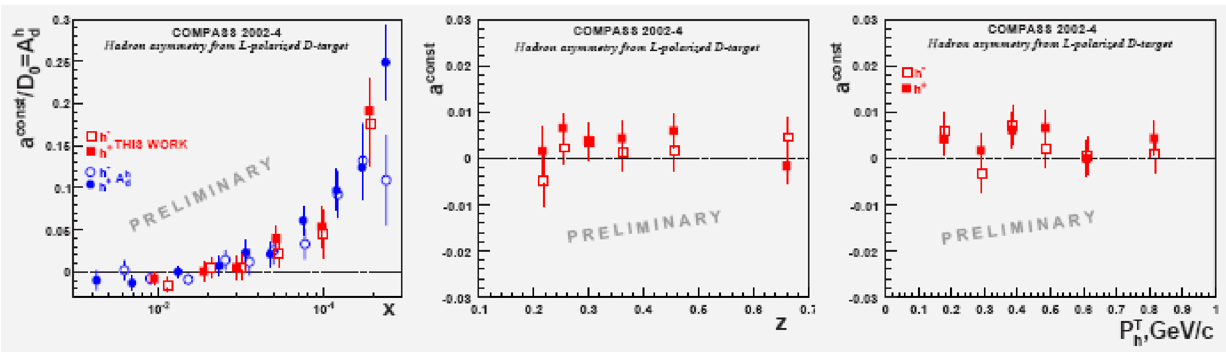

Fig.3. Dependences of the AA fit parameters a^{const} on kinematical variables.

The parameters a^{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 [12]. Agreement of these data and data of the present analysis demonstrate internal consistency of the COMPASS results.

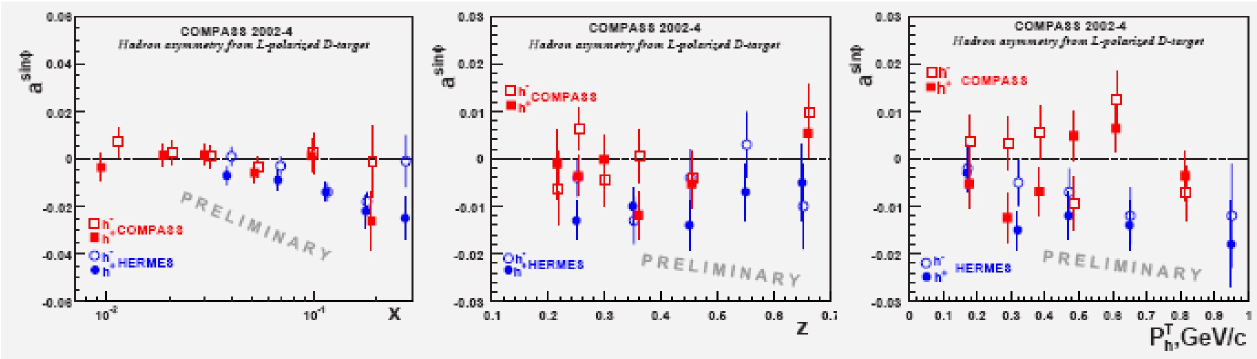

Fig.4. Dependences of the AA fit parameters $a^{\sin\phi}$ on kinematical variables and similar data of HERMES [7] for identified pions.

The x-dependence of the sin(ϕ) modulations of the AA, observed for the first time by HERMES, is less pronounced at COMPASS. But if one recalculates the COMPASS data to the Q2, W^2 – domain of HERMES, one could not see the contradiction between the two experiments. Remind that this modulation is due to pure twist-3 PDF entering from the $d\sigma_{0L}$ contribution to the AA with a factor Mx^2/Q.

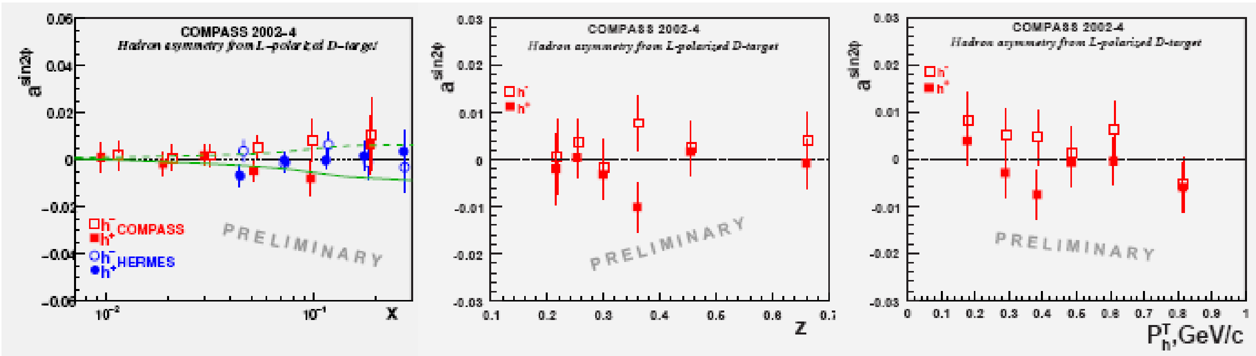

Fig.5. Dependences of the AA fit parameters $a^{\sin 2\phi}$ on kinematical variables compared to the data of HERMES and to calculations of H.Avakian et al. [13]: dashed line – h^-, solid line – h^+.

The amplitudes of the $\sin 2\phi$ modulations are small, consistent with zero within the errors. Remind, that they could be due to PDF $h_{1L}^{\perp}$ entering in $d\sigma_{0L}$.

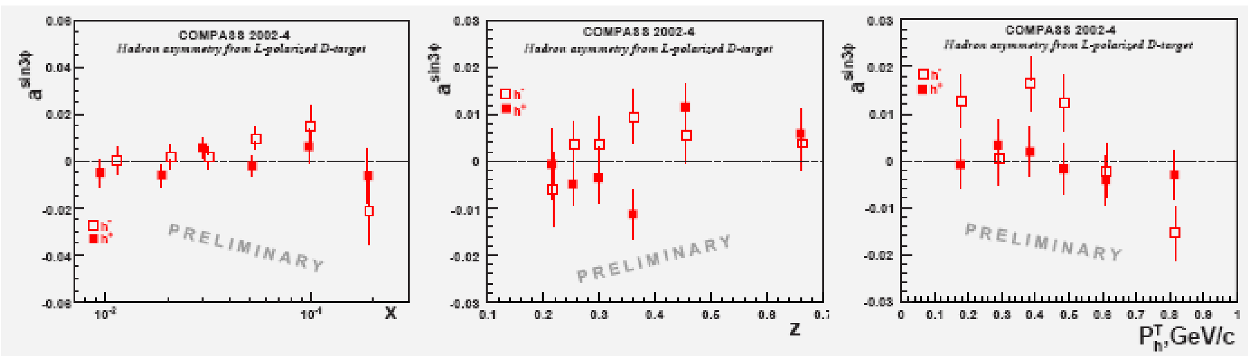

Fig.6. Dependences of the AA fit parameters $a^{\sin 3\phi}$ on kinematical variables.

Some peculiarities of data on the $a^{\sin 3\phi}$ are seen from this Figure, f.i. the points for h^- are mostly positive and for h^+ are mostly negative, as for COMPASS data from the transversally polarized target [14]. Remind, that this modulation could come from the pretzelosity PDF in $d\sigma_{0T}$, additionally suppressed by $\sin\theta_\gamma \sim xM/Q$.

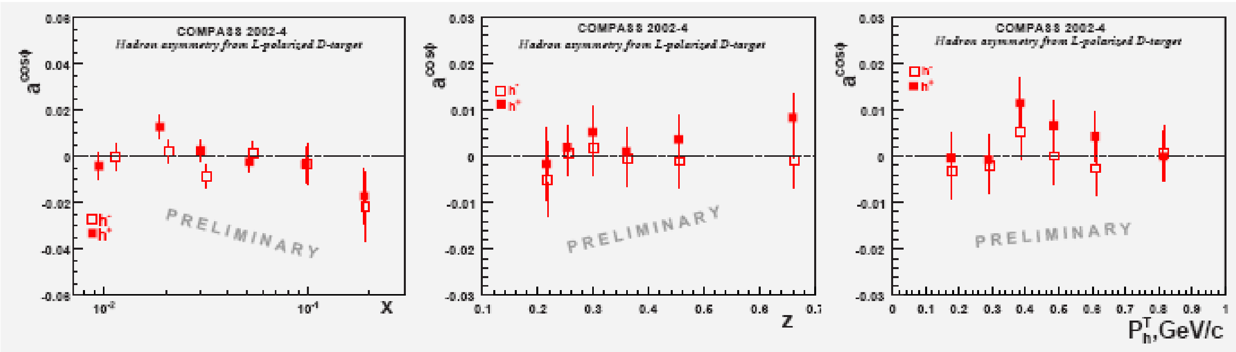

Fig.7. Dependences of the AA fit parameters $a^{\cos\phi}$ on kinematical variables.

The cos(ϕ) modulation of the AA is studied for the first time. Remind, that it is mainly due to a pure twist-3 PDF $g_L^{\perp}$, entering in $d\sigma_{LL}$, an analog to the Cahn effect [15] in unpolarized SIDIS.

5. Conclusions and prospects.

1. The azimithal asymmetries in the SIDIS production (Q^2>1 GeV^2, y>0.1) of negative (h^-) and positive (h^+) hadrons by 160 GeV muons on the longitudinally polarized deuterium target are observed and parameterized by the function

$$a(\phi)=a^{const}+a^{\sin\phi}.\sin(\phi)+a^{\sin2\phi}.\sin(2\phi)+a^{\sin3\phi}.\sin(3\phi)+a^{\cos\phi}.\cos(\phi)$$

with parameters a^i which can depend on kinematic variables.

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

3. The parameters of the a(ϕ) as functions of kinematical variables are studied in the region x=0.004-0.7, z=0.2-0.9, $p_h^T = 0.1 - 1.0$ GeV/c. It was found that:

- parameters $a^{const}(x)/D_0 \equiv A_d^h(x)$, where D_0 is a virtual photon depolarization factor, are in agreement with the COMPASS published data [12] on $A_d^h(x)$, calculated by different method and using different cuts;
- parameters $a^{\sin\phi}(x,z,p_h^T)$ are small and in general do not contradict to the HERMES data [7], if one takes into account the difference in Q^2 and W between the two experiments;
- parameters $a^{\sin2\phi}$, $a^{\sin3\phi}$ and $a^{\cos\phi}$ are consistent with zero within errors of about 0.5%.

The errors shown in the plots are statistical. Systematic errors are estimated to be much smaller.

4. Results of this analysis are obtained with the z-cut z>0.2, which removes almost one half of statistics. Tests have shown that with lower cut z>0.05 the results are identical. For the further analysis we probably will use the lower z-cut.

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

6. References.

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