Study of the left-right asymmetry A_{UT} of pions and kaons produced by photo-production on a transversely polarised target

Abstract

Recently HERMES presented the preliminary results for the azimuthal A_{UT} asymmetry measuring Collins and Sivers amplitudes. For these measurements, data with $Q^2 > 1$ GeV^2 from 2002 to 2005 are considered.
Since the cross section is proportional to $\frac{1}{Q^4}$, a lot of data is available at small Q^2 $(Q^2 \backsim 0)$ GeV^2. For this reason we decided to repeat the measurement of the A_{UT} asymmetry considering these so called photoproduction events in the 2005 data. For these events only Sivers moments can be measured. The results of this analysis are shown in this report.

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I Asymmetry and Semi-Inclusive Deep-Inelastic Scattering at HERMES

The HERMES experiment is one of the four experiments at the HERA electron-proton collider at DESY. Now, all the experiments and the HERA accelerator are shut down, but the data analysis is going on.
One of the fundamental processes studied at HERMES is Semi-Inclusive Deep-Inelastic Scattering. The figure below shows a schematic view of this process.
In DIS one lepton, in our case one positron, interacts with a quark in the nucleon in such a way that the target breaks up and final hadron states are formed. For SIDIS, one or more final hadrons are detected; besides the scattered lepton

$$l + N \rightarrow l' + h + X. \quad (1)$$

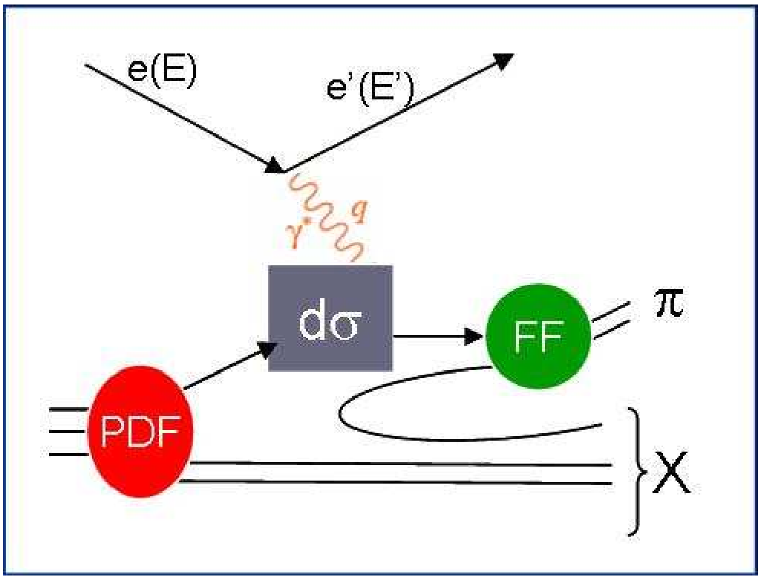

Figure 1: Scattering process

The kinematics of a scattering event is given by four-momenta of the lepton before ($\mathbf{k} = (E, \vec{k})$) and after ($\mathbf{k'} = (E', \vec{k'})$) the scattering, as well as by the corresponding four vector of the target nucleon $\mathbf{P} = (E_N, \vec{P})$. With these vectors we can define some quantities which characterise the event:

$$Q^2 = -q^2 = -(\mathbf{k} - \mathbf{k'}) \stackrel{(lab)}{=} 4EE' \sin^2(\theta/2) \quad (2)$$

$$W^2 = (\mathbf{P} + \mathbf{q})^2 \stackrel{(lab)}{=} M^2 + 2M\nu - Q^2 \quad (3)$$

$$\nu = \frac{\mathbf{P} \cdot \mathbf{q}}{M} \stackrel{(lab)}{=} E - E' \quad (4)$$

$$y = \frac{\mathbf{P} \cdot \mathbf{q}}{\mathbf{P} \cdot \mathbf{k}} \stackrel{(lab)}{=} \nu/E \quad (5)$$

$$x_{\mathrm{Bj}} = \frac{Q^2}{2\mathbf{P} \cdot \mathbf{q}} \stackrel{(lab)}{=} Q^2/2M\nu \quad (6)$$

Studying SIDIS processes we can investigate the inner structure of the nucleon by, for example, measuring azimuthal asymmetries.
The momentum and the spin distribution of the quarks inside the nucleon are described by three parton distribution functions: the unpolarised distribution function $q(x, Q^2)$ (Unpolarised DF) which represents the quark distribution

inside the nucleon, i.e. the probability to find a quark inside the nucleon with a momentum fraction equal to x, the helicity distribution $\Delta q(x, Q^2)$, which represents the distribution of longitudinally polarised quarks in a longitudinally polarised nucleon and the transversity $\delta q(x, Q^2)$ which describes the distribution of transversally polarised quarks in a transversally polarised nucleon. The first two DFs are well know, the third one is quite unknown and its measurement is one of the main goals of HERMES.

I.1 Cross section of Semi-Inclusive Deep-Inelastic Scattering (SIDIS): a combination of Distribution Functions (DFs) and Fragmentation Functions (FFs)

If we look at the cross section of the Semi-Inclusive DIS we can see that it is composed of three different parts

$$\sigma^{ep\to ehX} = \sum_q \mathrm{DF}^{p\to q} \times \sigma^{eq\to eq} \times \mathrm{FF}^{q\to h}, \tag{7}$$

where DF is the Distribution Function, $\sigma(eq \to eq)$ is the cross section for the point-point interaction between the positron and the quark and the FF is the Fragmentation Function which describes the quark fragmentation into hadronic final states.

The figures below show different DFs and FFs.

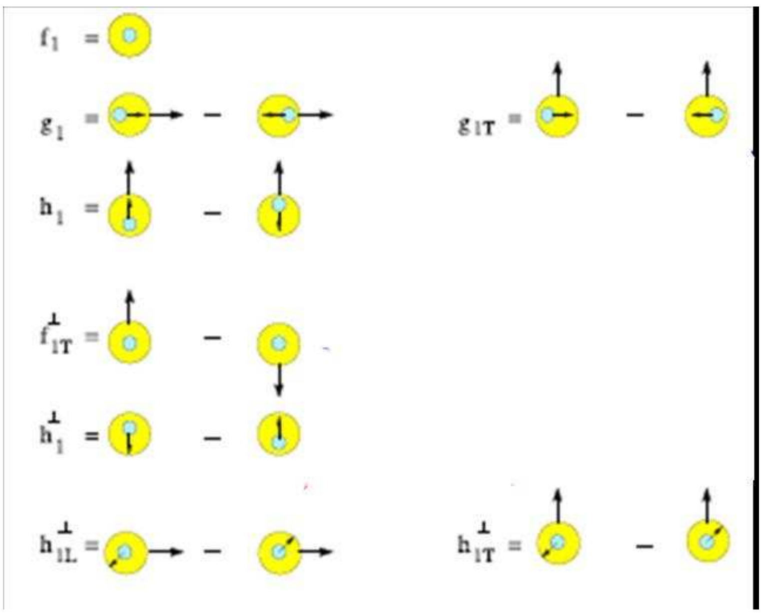

Figure 2: Distribution Functions

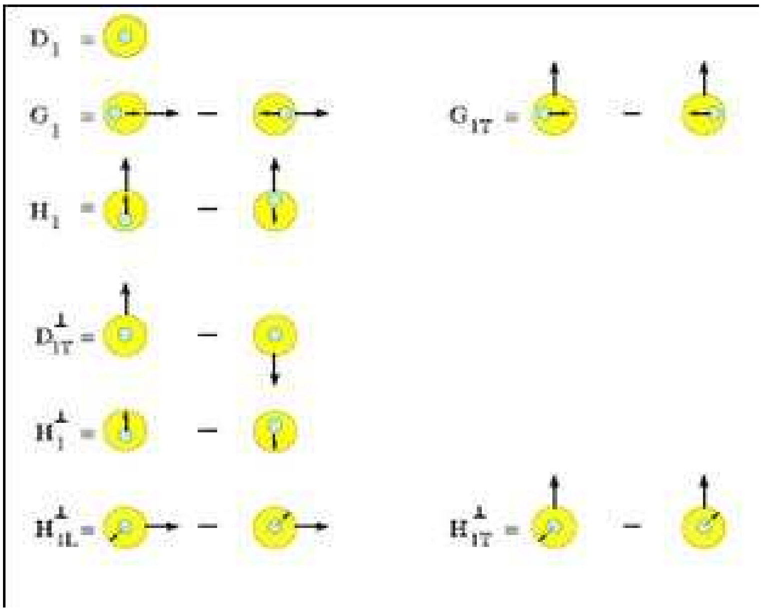

Figure 3: Fragmentation Functions

At this point it is evident how several different combinations are possible. If we look at the DFs in the picture, we can recognise the three DFs necessary to describe the momentum and the spin distribution of the quarks inside the nucleon, i.e. the Unpolarised DF, the helicity distribution and the transversity, here called f_1, g_1 and h_1 respectively.
Another significant DF is the *Sivers Distribution Function*, here $f_{1T}^{\perp}$, which combined with the unpolarised FF forms the so called *Sivers effect*, instead the transversity function h_1 combined with the Collins FF, here called $H_1^{\perp}$, gives us information about the so called *Collins effect*. The total differential cross section has different contributions, depending on the beam and target polarisation:

$$\begin{aligned} d\sigma = d\sigma_{UU}^0 + \cos 2\phi d\sigma_{UU}^1 + \frac{1}{Q}\cos\phi d\sigma_{UU}^2 + \lambda_e \frac{1}{Q}\sin\phi d\sigma_{LU}^3 \\ + S_L\{\sin 2\phi d\sigma_{UL}^4 + \frac{1}{Q}\sin\phi d\sigma_{UL}^5 + \lambda_e[d\sigma_{LL}^6 + \frac{1}{Q}\cos\phi d\sigma_{LL}^7]\} \\ + S_\perp\{\sin(\phi-\phi_s)d\sigma_{UT}^8 + \sin(\phi+\phi_s)d\sigma_{UT}^9 + \sin(3\phi-\phi_s)d\sigma_{UT}^{10} + \frac{1}{Q}(\sin(2\phi-\phi_s)d\sigma_{UT}^{11} \\ + \sin\phi_s d\sigma_{UT}^{12}) + \lambda_e[\cos(\phi-\phi_s)d\sigma_{LT}^{13} + \frac{1}{Q}(\cos(\phi_s)d\sigma_{LT}^{14} + \cos(2\phi-\phi_s)d\sigma_{LT}^{15})]\}. \end{aligned} \tag{8}$$

The first part of the equation is a combination of differential cross sections for both target and beam unpolarised, and the second one is a combination of different elements depending on the beam polarisation λ_e, on the longitudinal target polarisation S_L and on the transverse target polarisation $S_\perp$. For a measurement of the transversity function we are interested only in the part of the formula which depends on the transversely polarised target $S_\perp$.
We will look only at two factors of the $S_\perp$ contribution to the SIDIS cross section, $\sin(\phi-\phi_s)d\sigma_{UT}^8$ and $\sin(\phi+\phi_s)d\sigma_{UT}^9$.These two factors are related to the *Sivers effect* and to the *Collins effect* which are accessible through the study of the single spin asymmetry (SSA) in SIDIS.

$$A_{UT}(\phi,\phi_s) = \frac{1}{\langle|S_\perp|\rangle}\frac{N_h^{\uparrow}(\phi,\phi_s) - N_h^{\downarrow}(\phi,\phi_s)}{N_h^{\uparrow}(\phi,\phi_s) + N_h^{\downarrow}(\phi,\phi_s)} \tag{9}$$

So the A_{UT} function measured for a certain hadron is the difference between the number of hadrons with target polarised UP and the number of hadrons with target polarised DOWN normalised to the sum of these two terms times the inverse of the transverse target polarisation. For our data the transverse target polarisation was around 80%.The asymmetry was normalized with $\frac{1}{\langle |S_\perp| \rangle}$ for the fact that the target polarisation wasn't 100%.

This asymmetry measurement depends on the azimuthal angles ϕ and ϕ_s, where the ϕ angle is the angle between the scattering plane and the plane formed from the direction of the virtual photon and the vector of the detected hadron and the ϕ_s angle is the angle between the scattering plane and the vector of the transversely polarised target (see the Figure 4 below).

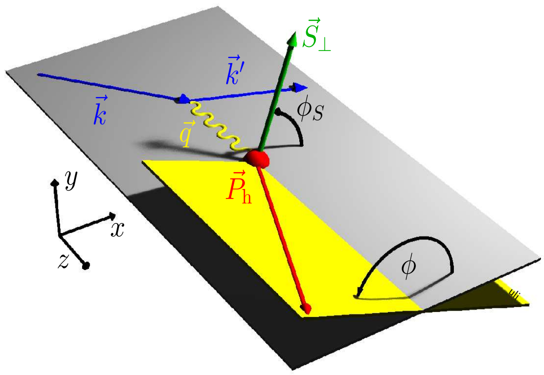

Figure 4: Azimuthal angles ϕ and ϕ_s

The asymmetry is proportional to a $\sin(\phi + \phi_s)$ and a $\sin(\phi - \phi_s)$ term:

$$A_{UT} \backsim \sin(\phi + \phi_s) \bigotimes h_1 \bigotimes H_1^\perp + \sin(\phi - \phi_s) \bigotimes f_{1T}^\perp \bigotimes D_1 + \cdots. \tag{10}$$

where $h_1 \otimes H_1^\perp$ is the Collins moment and $f_{1T}^\perp \otimes D_1$ represents the Sivers moment.

II Studies of the Azimuthal Single Spin Asymmetry

II.1 Asymmetry analysis at HERMES

From 2002 to 2005 HERMES collected data taken with a transversely polarised hydrogen target. For this data set, the A_{UT} asymmetry was measured at $Q^2 > 1\, GeV^2$. This was done for negative and positive pions and kaons. The results are shown in figures 5 and 6.

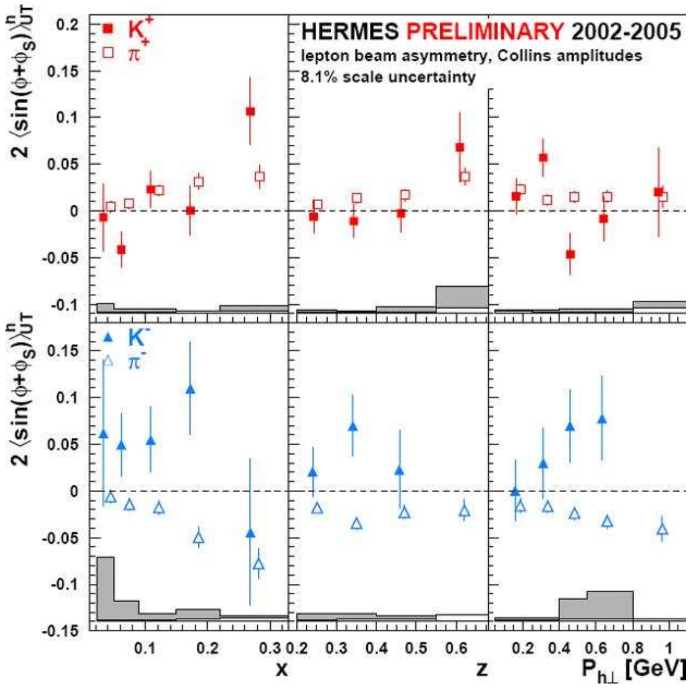

Figure 5: Preliminary results for the Collins moments at HERMES

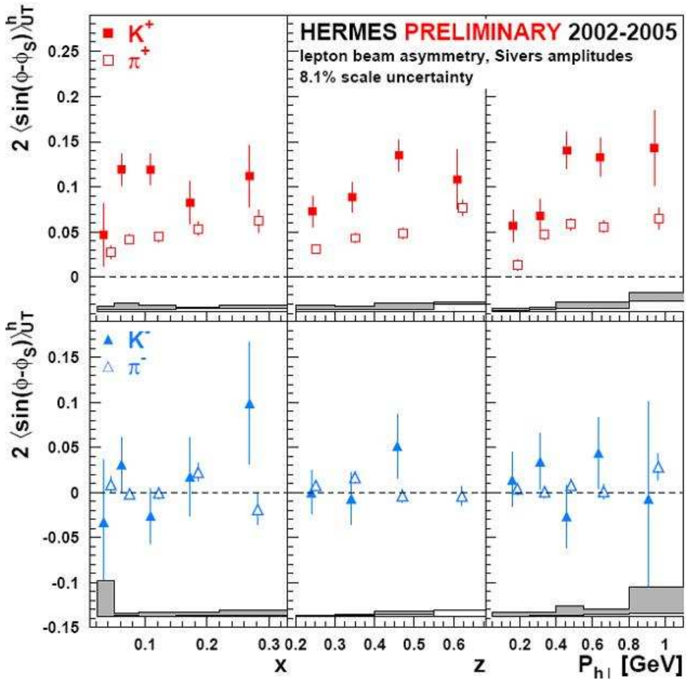

Figure 6: Preliminary results for the Sivers moments at HERMES

We can see that for π^+ particles, both the Collins and the Sivers effects produce a clearly positive asymmetry. In contrary the K^+ particles show a positive asymmetry only for the Sivers case, while for the Collins case the asymmetry is around zero. For negative particles, the Collins amplitude is negative for the pion case and slightly positive or zero for the kaon case. For Sivers, the results for negative particles are compatible with zero.

III Study of the left-right A_{UT} asymmetry in this work

III.1 From electroproduction to photoproduction

During the year 2005, HERMES collected a huge amount of data. Compared to the previous asymmetry analysis where only events with $Q^2 > 1\ GeV^2$ were considered, the statistics increase a lot analysing events at low Q^2. This can be seen in figure 7. Thus it was decided to measure the asymmetry for photoproduction, namely for events at low Q^2. In this regime the virtual photon is likely to fluctuate into a vector meson.

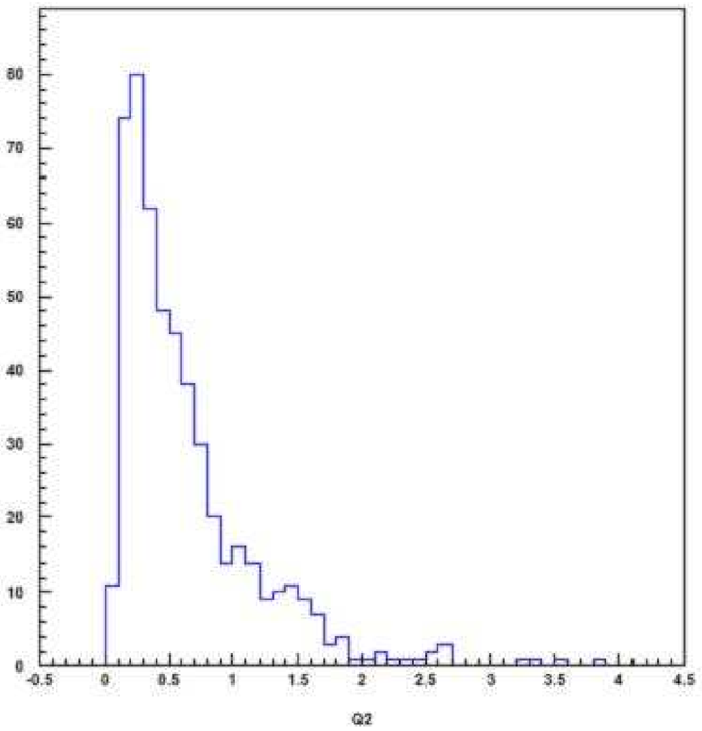

Figure 7: Q^2 for 2005 data

If we look at the Q^2 formula we can see a direct proportionality between Q^2 and the polar scattering angle θ,

$$Q^2 = -q^2 = 4EE' \sin^2(\theta/2). \tag{11}$$

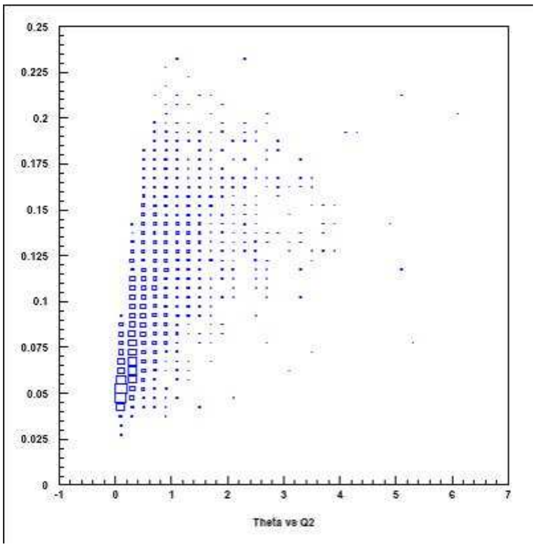

Figure 8: θ versus Q^2

So, for a Q^2 around zero the scattered lepton is very close to the beam and our spectrometer is not able to detect it. Thus we lose the information of the lepton and of the virtual photon and we are not able to define individually the azimuthal angles ϕ and ϕ_s. Only one of the two combinations between these angles still exist, namely $(\phi - \phi_s)$ because we still have the information of the hadron produced after the interaction.

III.2 Particle identification at HERMES

At HERMES the particle identification (PID) is provided by the signal of several detectors:

- lead-glass calorimeter
- pre-shower detector (H2)
- transition radiation detector (TRD)
- RICH detector.

The response of the four PID detectors are combined into probabilities using a Bayesan algorithm to provide a good separation between leptons and hadrons and between pions (π), kaons (K) and protons (p). The goal of using a Bayesan algorithm is to calculate the probabilities $P(H_{l(h)}|E,p)$ for the hypothesis $H_{l(h)}$ that the track is a lepton or hadron given a track momentum $\vec{p}$ and an energy deposition E in the chosen detector.
By means of Bayes Theorem this conditional probability may be written as

$$P(H_{l(h)}|E,p) = \frac{P(H_{l(h)}|p)P(E|H_{l(h)},p)}{P(E,p)}. \tag{12}$$

where $P(H_{l(h)}|p)$ represents the probability for the hypothesis that the track is a lepton (hadron) given a track momentum $\vec{p}$. $P(E|H_{l(h)},p)$ is the probability for a certain energy deposition given that the track is a lepton (hadron) with momentum $\vec{p}$ and $P(E,p)$ is the probability to have a track with momentum $\vec{p}$ and energy E.
The probability defined in equation 12 is commonly called *parent distribution*. At HERMES the parent distributions are extracted from real data by imposing cuts on the PID detectors other than the one considered. For example, to

generate the lepton parent distribution for the TRD, cuts are imposed on the responses of the Calorimeter and the Preshower detectors.

Once the probabilities $P(H_l|E,p)$ and $P(H_h|E,p)$ are obtained they are combined in the PID ratio:

$$P(H_{l(h)}|E,p) = \log_{10} \frac{P(H_l|E,p)}{P(H_h|E,p)} \tag{13}$$

At HERMES the following combinations of PID values are commonly defined:

- PID2 = PIDcal + PIDpre
- PID3 = PIDcal + PIDpre + PIDrich
- PID5 = PIDtrd

To distinguish between leptons and hadrons we use the information of the PID3 and PID5 added together. In this way an evident distribution between the two different kind of particles is achieved, see figure 9.

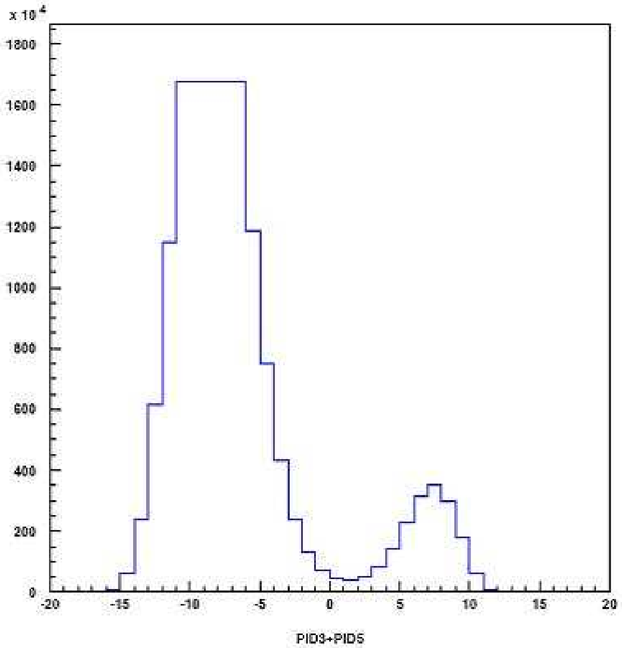

Figure 9: Lepton and hadron separation in the $PID3 + PID5$ function

To remove all the leptons from the data sample, PID3+PID5 was required to be smaller than zero.

At this point we need to distinguish between pions, kaons and protons.To obtain this information we use the signals from the RICH detector.

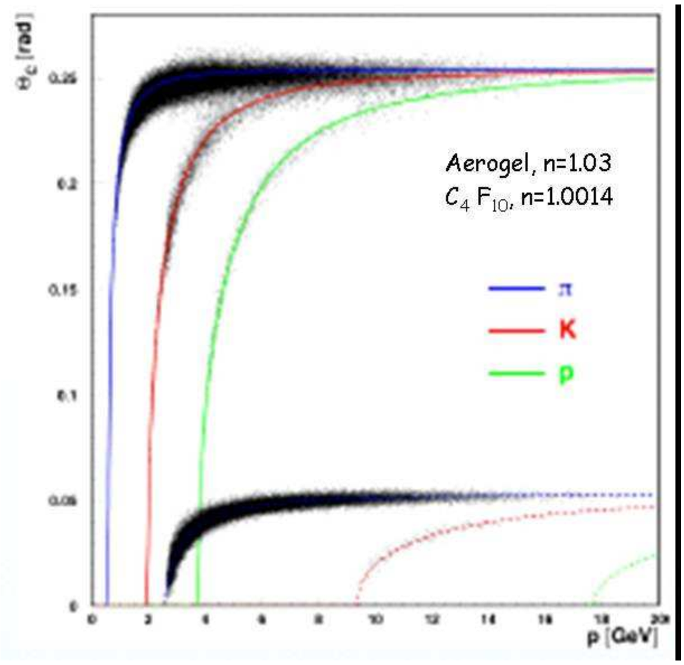

Figure 10: Hadron identification with the HERMES RICH detector

The RICH detector is a particle detector that uses the Cerenkov effect and thanks to this allow the determination of the velocity, *v*, of a certain particle. This is done by an indirect measurement of the Cerenkov angle θ_c, i.e. the angle between the emitted Cerenkov radiation and the particle path. This is related to the velocity by $\cos(\theta_c) = c/nv$, where *c* is the speed of light and n is the refractive index of the medium. In combination with the known momentum, the mass of the particle can be calculated, and thus the hadron type can be determined.

In a RICH detector a cone of Cerenkov light is produced when a high speed particle traverses a suitable medium with a velocity greater than the speed of light in that medium. This light cone is detected on a position sensitive planar photon detector, which allows reconstructing a ring, the radius of which is a measure for the Cerenkov emission angle. In our case the photons are collected by a spherical mirror with a certain focus length *f* and focused onto the photon detector placed at the focal plane. The result is a circle with a radius $r = f\theta_c$, independent of the emission point along the particle track.

Our RICH uses two radiators, C_4F_{10}, a heavy fluorocarbon gas, and a wall of silica aerogel tiles.The aeorgel radiator covers a lower momentum region. Combining the information of these two different materials the RICH detector provides particle identification for pions, kaons and protons in the momentum range from 2 to 15 GeV (see figure 10).

With the information of the RICH detector we are able to identify hadrons with an efficiency of 98% for pions, 88% for kaons and 85% for protons. We now can start our measurement of the A_{UT} asymmetry.

III.3 False asymmetry

To measure the A_{UT} asymmetry we counted the number of particles produced on the right (yellow arrow in figure 11) and on the left side (green arrow) of the target polarisation vector (Figure 11).

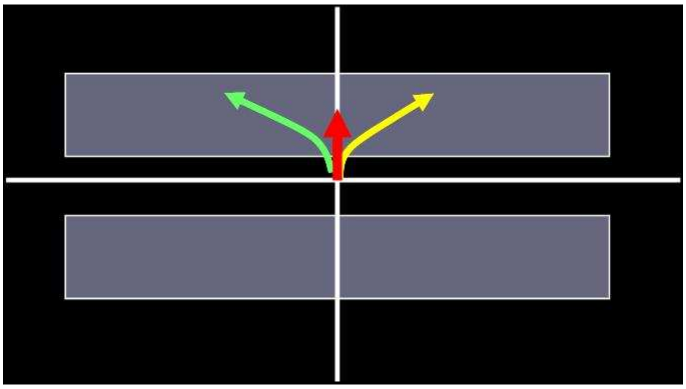

Figure 11: Target polarisation in HERMES and particles produced on the left or on the right side of the polarisation vector

At the HERMES experiment every 60 seconds the target polarisation is flipped between UP and DOWN state (see Figure 12). This is done to remove detector effects that might introduce a false asymmetry.

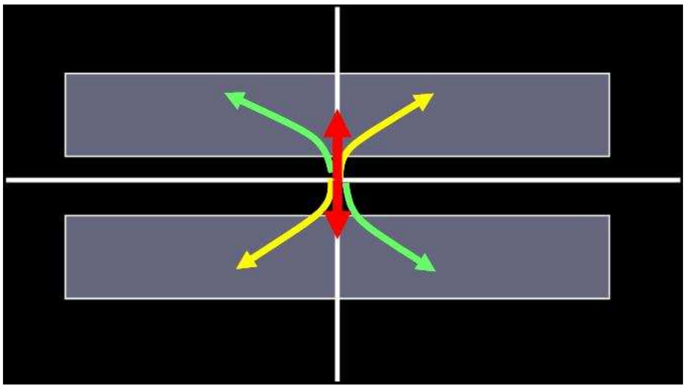

Figure 12: Target polarisation in HERMES: UP and DOWN

One such false asymmetry is introduced by the influence of the spectrometer magnet. Imagine that there would be no left-right asymmetry related to a physics process, then the probability that a particle is produced on the left or on the right side of the target spin should be the same. After its production, the particle moves inside the spectrometer and arrives at the magnet. The magnet force pushes the particle in a certain direction, depending on its charge. For example: consider a particle produced on the left side of the target polarisation vector, when it passes through the magnet it is bend (for example) to the left (see Figure 13). If this particle has a very low momentum it will be bend a lot and there is a chance that the particle is bend out of the spectrometer acceptance. For another particle produced to the right and pushed to the left, the probability to remain inside the spectrometer acceptance is higher. At the end we will count different amounts of particles produced on the left side and on the right side.

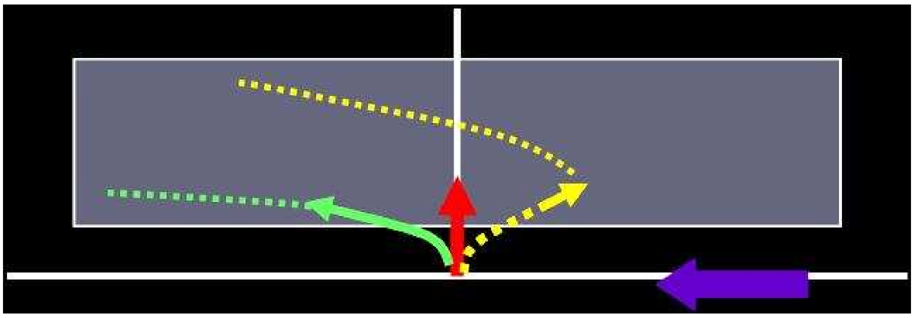

Figure 13: False asymmetry (a).

This would cause a false asymmetry. If we now flip the target polarisation, we will lose more particles produced on the right side of the target spin (yellow arrow in figure 14) than particles produced on the left (green arrow in figure 14). Thus by flipping the target polarisation, we are able to cancel out the false asymmetry and only the A_{UT} asymmetry which is of physics interest, remains.

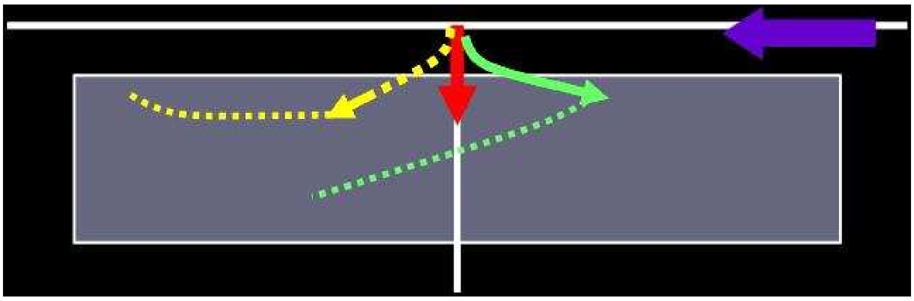

Figure 14: False asymmetry (b).

III.4 Measurement of the A_{UT} asymmetry

To have a measurement of our A_{UT} asymmetry we used the formula below, different from the usual one

$$A_{UT} = \frac{1}{\langle|S_\perp|\rangle} \frac{N_R - N_L}{N_R + N_L} \tag{14}$$

where N_R represents the number of particles produced on the right side of the target polarisation vector and N_L the number of particles on the left side. The counts were normalized to the respective luminosities for the two data set (target spin up and down).
From the data of 2005 we selected pions and kaons and counted how many particles we had on the left side and of the right side with respect to the target polarisation vector. The results are shown in figure 15 and 16.
The graphs 15 and 16 show the asymmetry versus the transverse component of the particles momentum p_t and versus the ratio $\frac{p_z}{E_{beam}}$, where p_z is the longitudinal component of the particles momentum and E_{beam} is the energy of our positron beam.
For π^+, we found an evident positive asymmetry both for p_t and for $\frac{p_z}{E_{beam}}$. The preliminary HERMES results, which measured $2(\sin(\phi - \phi_s))$ versus p_t, show a positive asymmetry for π^+ too so we can say that we are in the same trend with the HERMES results. We have the same situation if we look at K^+ asymmetry: our results present a clear positive asymmetry and the same situation is presented by the HERMES results (figure 6). The HERMES results

also show the π^+ asymmetry with a value around 0.05 and the K^+ asymmetry around 0.15, instead for our result the asymmetry for π^+ and for K^+ are both around 0.035. For π^- our asymmetry is slightly negative in contrary to the HERMES results where the asymmetry is clearly around zero. Instead, for K^- our results are consistent with zero like the HERMES results.

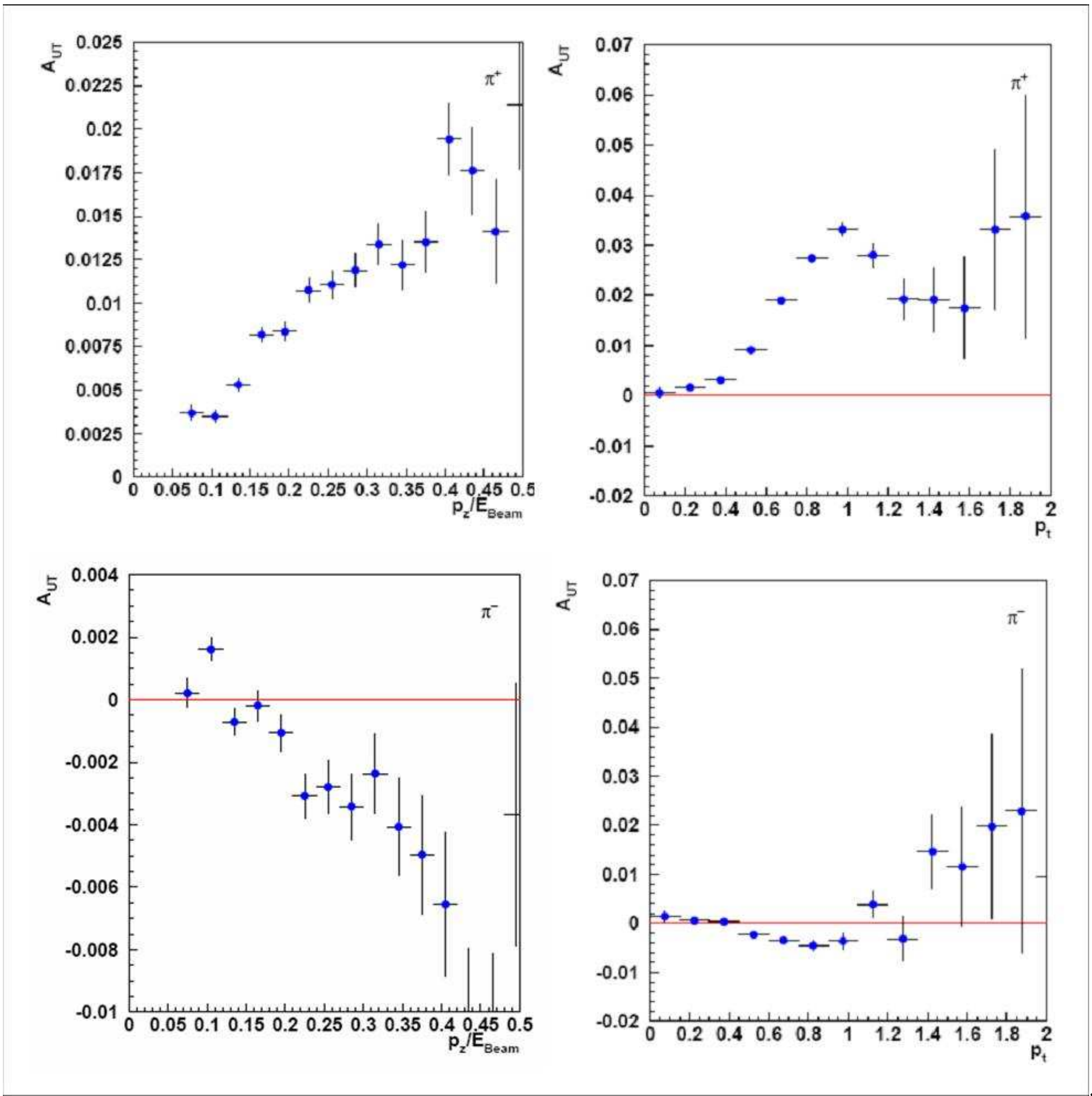

Figure 15: π^+ and π^- asymmetry

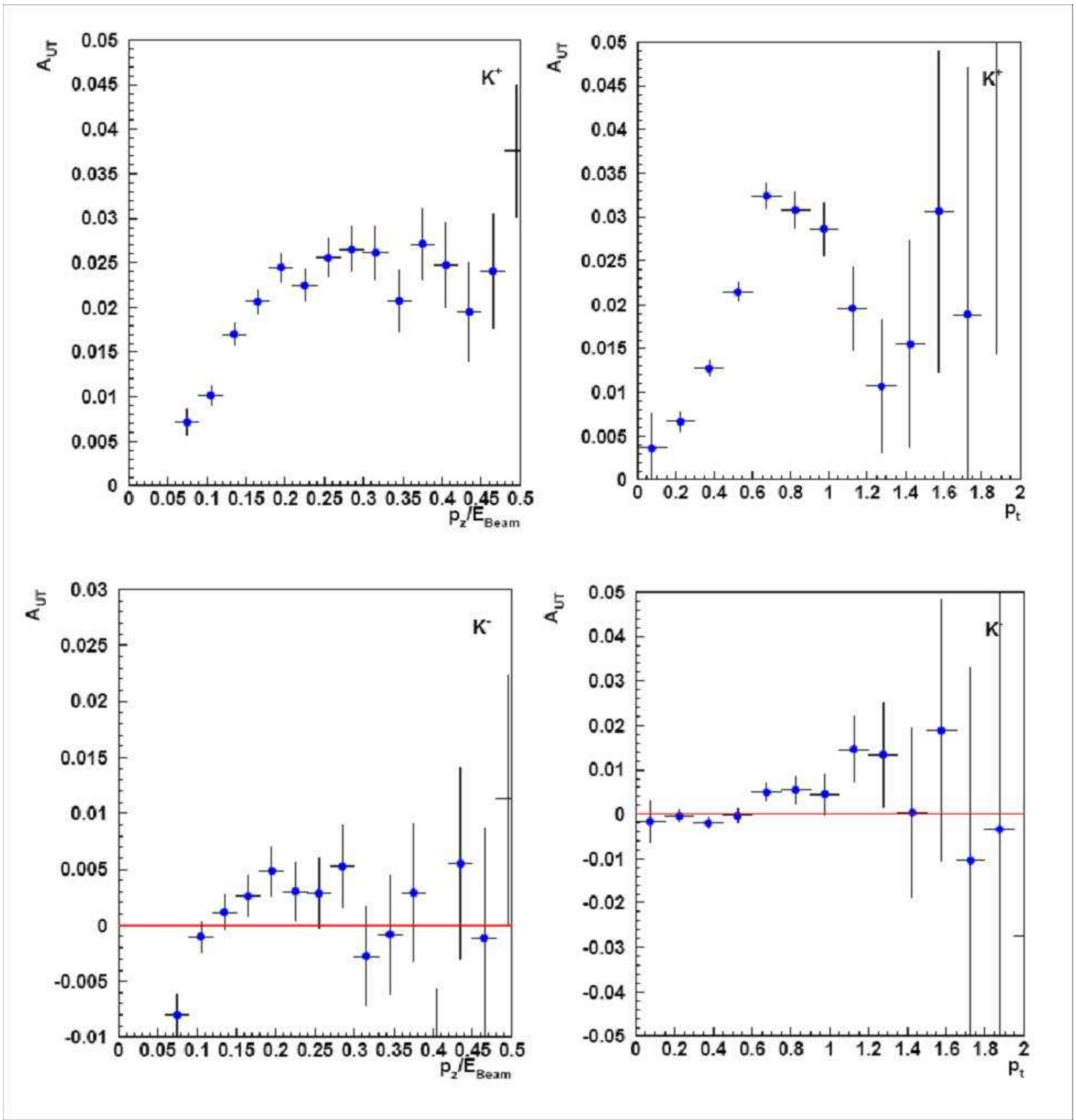

Figure 16: K^+ and K^- asymmetry

III.5 Interpretation of the asymmetry by the Burkardt Model

For the Burkardt Model we know that, if we have a nucleon with quarks inside it with a certain angular momentum, the quark momentum fraction x_{obs} observed at the interaction with the virtual photon γ^* depends on the impact parameter b (see Figure 17).

Let us have a look at the quark distribution function versus the momentum fraction x_{Bj}: if the quark which participates at the interaction with the γ^* is on the left side of the nucleon (see figure 17, top), i.e. it comes toward the virtual photon motion,x_{obs} will be bigger than x_{Bj} and the quark distribution function will be shifted to the right. On the other hand, if our quark is on the right side of the nucleon x_{obs} will be lower than x_{bj} and its distribution function will be shifted to the left. As both the quark and the target remiant are coler changed abjects, the struck quark will experience an attraction towards the nucleon's centre. Due to this so called Final State Interactions (FSI) a qurk hit on the left is actually deflected to the right. We can say that the left-right distribution asymmetry, is converted into a right-left hadron production asymmetry (see figure 18).

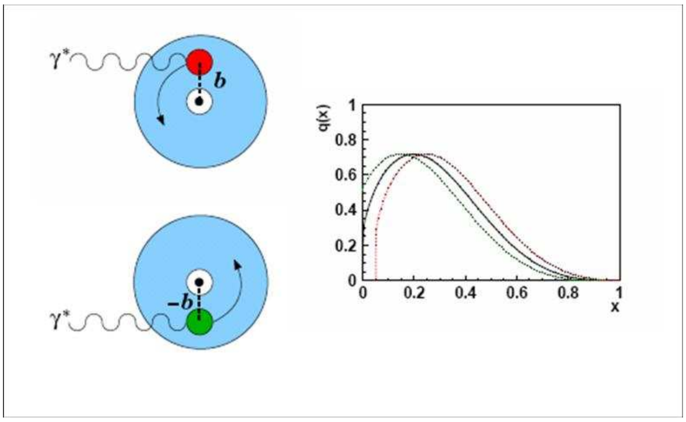

Figure 17: Quark distribution function versus x_{Bj} in the Burkardt model

For example,considering π^+ production where u-quark scattering for dominates, if we measure an asymmetry $A_{UT} > 0$ we can say that the Sivers moment is positive and this yields $L_z^u > 0$.

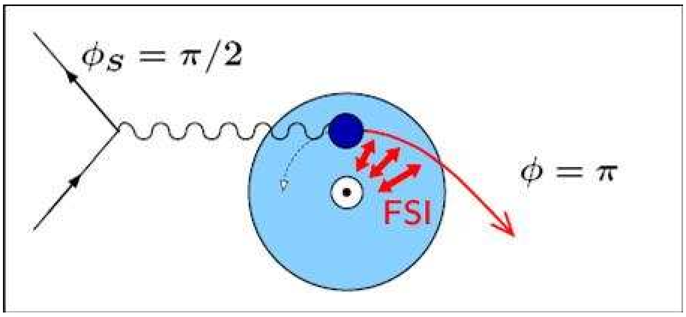

Figure 18: Left-right distribution asymmetry leads to a right-left hadron production asymmetry

it should be noted that model relise on the fact that the virtual photon resolves the quark structure of the nucleon, which is only fully fulfilled at enough Q^2.

IV Conclusion

In this work we measured the A_{UT} asymmetry at low Q^2 for π^+, π^-, K^+ and K^- versus $\frac{p_z}{E_{Beam}}$ and p_t. The analysis of the A_{UT} asymmetry is positive for positive particles like the HERMES results for $Q^2 > 1\ GeV^2$. Instead for negative pions we find a slightly negative asymmetry, contrary to the HERMES results, while for negative kaons, the results are consistent with zero.

From the Burkardt Model the positive A_{UT} for π^+ and K^+ yields from the combination of the u quark of the proton (with L_z^u) and $\bar{d}$ or $\bar{s}$.