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TRANSVERSE SPIN AND MOMENTUM EFFECTES IN THE COMPASS EXPERIMENT

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Abstract

The study of the spin structure of the nucleon is part of the scientific program of COMPASS, a fixed target experiment at the CERN SPS. COMPASS investigates transverse spin and transverse momentum effects by studying the azimuthal distributions of the hadrons produced in deep inelastic scattering of naturally polarized 160 GeV/c muons on transversely polarized target. The results obtained using a ^6LiD from the data collected in 2002-2004, and new results obtained using a NH_3 target, from the data collected in 2007, are presented.

1 Introduction

A powerful method to access the nucleon structure is the measurement of the azimuthal modulations of the distribution of the hadrons inclusively produced in the deep inelastic scattering. On the basis of general principles of quantum field theory in the one photon exchange approximation, the semi inclusive deep inelastic scattering (SIDIS) cross section can be written in a model independent way [1].
In its expression there are 18 structure functions, 8 of them are leading order. They can be accessed measuring the corresponding modulation in different combinations of the azimuthal angle of the hadron and of the nucleon spin vector, all of them independent. Most of them have a clear interpretation in terms of the Parton Model and can be written as the convolution of a distribution function of the quarks inside the nucleon (PDF) and a function which describes the fragmentation of the struck quark into a specific hadron (FF).

Recent data on single spin asymmetries in SIDIS off transversely polarized nucleon targets [2], [3] triggered a lot of interest towards the transverse momentum dependent and spin dependent distributions and fragmentation functions. Correlations between spin and transverse momentum give rise to effects, which would be zero in the absence of intrinsic motion of the quarks inside the nucleon.

One of the most famous PDF is the transversity distribution which gives the difference of the number of quarks with momentum fraction x with their transverse spin parallel and anti-parallel to the nucleon spin [4]. The transversity distribution, together with the better known spin-averaged distribution and helicity distribution functions, is necessary to fully specify the nucleon structure at leading order. Since it is chiral odd it can be measured only coupled to another chiral odd function. In SIDIS one candidate is the Collins fragmentation function which is the spin dependent part of the FF of a polarized quark in an unpolarized hadron. The convolution of the two functions generates the so called Collins asymmetry in the hadrons distribution. A second SIDIS channel to access the transversity distribution is in conjunction with the interference fragmentation function of the polarized quark in two hadrons giving rise to an azimuthal modulation of the plane of inclusively produced hadrons pairs with respect to the scattering plane.

Of special interest among the transverse momentum dependent distribution functions are: the Sivers function [5] which describes a possible deformation of the quark intrinsic transverse momentum distribution in a transversely polarized nucleon, and the Boer-Mulders function [6] which gives the correlation of the quark transverse momentum and its transverse spin in an unpolarized nucleon. The measurements of these functions can give further insights on the connection between the transverse spin and transverse momentum and are needed to progress towards a more structured picture of the nucleon structure, beyond the collinear partonic representation.

2 The COMPASS experiment

COMPASS is an high energy experiment at the CERN SPS with a wide physics program focused on the study of the nucleon spin structure and hadron spectroscopy using muon and hadron beams. The data used to investigate the transverse spin and transverse momentum structure of the nucleon have been taken with a positive muon beam of 160 GeV/c on a transversely polarized target. The scattered muon and the produced hadrons are detected in a two stage spectrometer with a wide angular acceptance and an excellent particle identification [2]. For the data taking with a transversely polarized target, in the years 2002 2003 and 2004, deep inelastic scattering data have been collected using a ^6LiD target material, while in 2007 a NH_3 target material was used.

The target material was placed in 2 (during 2004) or 3 (during 2007) cells oppositely transversely polarized and the direction of the target polarization has been reversed every 5 days in each target cell.

Many results have been determined from these data, in this report i will only discuss the results for unpolarized asymmetries from 2004 data and the results for the Sivers and Collins asymmetries from 2002-2004 and 2007 data.

3 Unpolarized target azimuthal asymmetries

The cross section for the hadron production of the lepton nucleon deep inelastic scattering off an unpolarized is [1]:

$$\begin{aligned}\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dp_T^2} &= \frac{2\pi\alpha^2}{xyQ^2}\cdot \\ &\left\{\frac{1+(1-y)^2}{2}\right)F_{UU} + \\ &+(2-y)\sqrt{1-y}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \\ &+(1-y)\cos 2\phi_h\,F_{UU}^{\cos 2\phi_h} + \\ &\left.+\lambda_l\,y\sqrt{1-y}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}\right\} \qquad (1)\end{aligned}$$

There are three independent modulations on the azimuthal angle of the hadron with respect to the scattering plane. The $\sin\phi_h$ modulation is proportional to the beam polarization and the structure function $F_{LU}^{\sin\phi_h}$ has no clear explanation in term of the parton model. Both the $\cos\phi_h$ and the $\cos 2\phi_h$ modulations can be explained in terms of the Cahn effect and the already introduced Boer Mulders distribution function and are related to the transverse momentum of the quark inside the nucleon. One has to notice that the magnitude of the Boer Mulders function can depend upon the quark flavor while the Cahn effect is a pure kinematical effect which depends only from the struck quark $\vec{k_T}$ and is expected to be the same for positive and negative hadrons. Moreover the Cahn effect is the main contribution to the $\cos\phi_h$ asymmetry [7].

Also pQCD gives rise to azimuthal modulations in the hadron production but it has been shown [7] that these effects are negligible for the range of transverse momentum p_T of the hadrons produced in COMPASS.

3.1 Analysis of unpolarized asymmetries

The analysed data have been taken during 2004 with a polarized deuteron target. The kinematical cuts which have been applied to select the DIS region are:
- the squared four momentum transfer $Q^2 > 1$ (GeV/c)^2,
- the hadronic invariant mass $W > 5$ GeV/c^2 and
- the fractional energy transfer of the muon $0.1 < y < 0.9$.

The analysed hadrons sample include all charged hadrons coming from the interaction with:
- transverse momentum $p_T > 0.1$ GeV/c to have a good p_T resolution and
- fraction of the available energy $z > 0.2$ to exclude hadrons coming from the target fragmentation region.

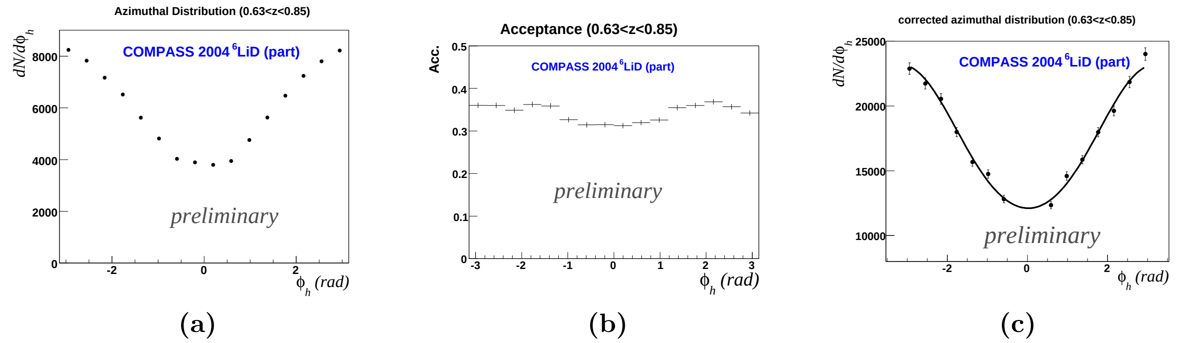


Figure 1: **(a)** measured spin averaged azimuthal distribution of the hadrons for $0.63 < z < 0.85$.
(b) azimuthal acceptance calculated from the ratio between Monte Carlo generated and Monte Carlo reconstructed hadrons distribution in the same z bin.
(c) corrected azimuthal distribution corrected by the acceptance with the fit superimposed.

- $p_T < 1.5$ GeV/c and $z < 0.85$, specific for the unpolarized asymmetries analysis.

Since the data were taken with the polarized target (longitudinally or transversely), both the two spin configurations (up/down) collected from the transverse data taking and the two spin configurations (forward/backward) collected from the longitudinal data taking where individually combined in order to cancel spin related effects.

In the extraction of the unpolarized asymmetries there is no cancellation of the apparatus acceptance and a Monte Carlo simulation is needed to evaluate it. The Monte Carlo chain used in COMPASS starts from Lepto for the generation of SIDIS events, while the particle interactions in the materials and the detectors response simulation is performed by COMGEANT, based on GEANT3. The Monte Carlo data are finally reconstructed by the same software used for the real data.

The experimental apparatus acceptance as a function of the azimuthal angle ϕ_h is then calculated as the ratio between the generated and the reconstructed hadrons azimuthal distribution performed in a given kinematical range. An example of the apparatus acceptance correction is shown in figure 1.

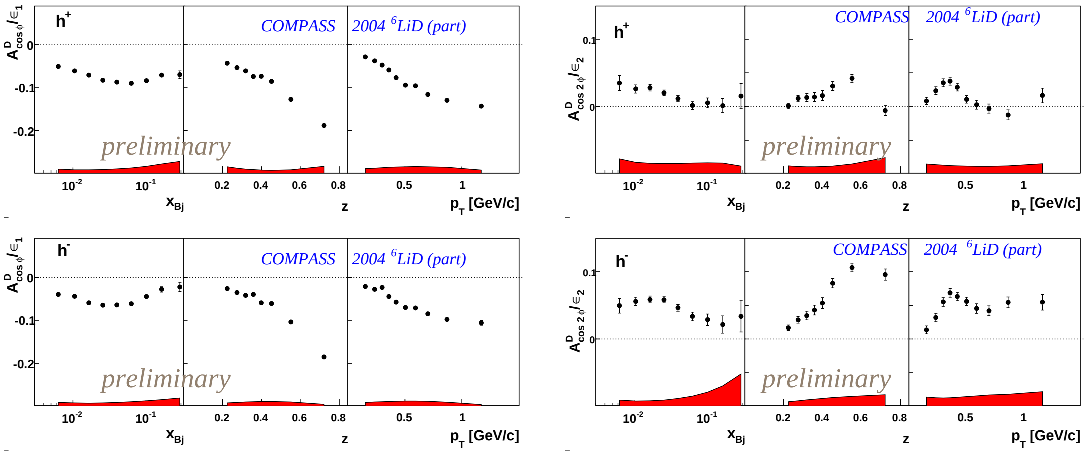
The measured unpolarized hadron azimuthal distributions are divided by the acceptance and the resulting distributions are fit with the function:
$N_{corr}(\phi_h) = N_0 \cdot (1 + A^D_{cos(\phi_h)} \cdot cos(\phi_h) + A^D_{cos(2\phi_h)} \cdot cos(2\phi_h) + A^D_{sin(\phi_h)} \cdot sin(\phi_h))$.
The $A^D_{cos(\phi_h)}, A^D_{cos(2\phi_h)}, A^D_{sin(\phi_h)}$ amplitudes are extracted for each considered bin of x, z and p_T; when extracting the asymmetries as function of one of these three variables, the other two are integrated over all their SIDIS kinematical range. The Monte Carlo simulation plays an important role in the unpolarized asymmetries measurement. Two different sets of Lepto parameters have been used to evaluate a possible source of systematic errors. Both of them give a satisfactory description of the COMPASS data in the main kinematical variables, both for data collected with transversely and longitudinally polarized deuteron target. All the asymmetries extracted with different Monte Carlo have been compared in order to estimate the systematic errors. Further systematic tests, like splitting the data sample according to the event topology and the time of the measurement gave no significant contributions.

3.2 Results

The $sin(\phi_h)$ asymmetries measured by COMPASS are compatible with zero over the full range of x, z and p_T both for positive and for negative hadrons and suggest a beam polarization effect compatible with zero on the deuteron target.

The COMPASS results for all $cos(\phi_h)$ asymmetries are shown in figure 2**a**, for positive (upper plot) and negative (bottom plot) hadrons. The measured asymmetries are large and slightly different for positive and negative hadrons. The COMPASS results for all $cos(2\phi_h)$ asymmetries are shown in figure 2**b**, for positive (upper plot) and negative (bottom plot) hadrons.

A comparison of the $cos(\phi_h)$ asymmetries with the theoretical predictions for the COMPASS kinematics [7] is shown in figure 3**a**. In [7] only Cahn effect was considered. The differences between positive and negative hadrons measured from COMPASS data could hint to a possible Boer-Mulders PDF con-



(a) (b)

Figure 2: **(a)** Top picture: $cos(\phi_h)$ asymmetries extracted from positive hadrons. Bottom picture: $cos(\phi_h)$ asymmetries extracted from negative hadrons. **(b)** Top picture: $cos(2\phi_h)$ asymmetries extracted from positive hadrons. Bottom picture: $cos(2\phi_h)$ asymmetries extracted from negative hadrons. All asymmetries shown in each picture are extracted as a function x (left plot), z (middle plot) and p_T (right plot), the red bands are the systematic errors. The shown quantities are the amplitudes of each modulation divided by the y dependent corresponding kinematical factor.

tribution.

The results for the $cos(2\phi_h)$ asymmetry are compared to theoretical predictions [8], made for the COMPASS kinematical region, in figure 3**b**. In [8] different contributions were taken into account: the Cahn effect (blue dashed line in the picture), the Boer-Mulders PDF (green dashed line) and the first order pQCD contribution which is negligible as shown by the black dashed-dotted line. In this work the Boer-Mulders PDF was assumed to be proportional to the better known Sivers function. Comparing the results obtained for positive and negative hadrons one can see that only the contribution coming from the Boer-Mulders PDF changes significantly with the hadron charge. COMPASS measurements confirm this trend and agree quite well with these predictions.

4 Transverse spin dependent azimuthal asymmetries

4.1 The Collins asymmetry

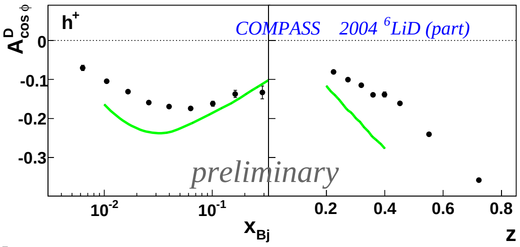
In semi inclusive deep inelastic scattering the transversity distribution function $\Delta_T q(x)$ can be measured combined with the Collins fragmentation function $\Delta_T^0 D_q^h(z, p_T)$. According to Collins, the fragmentation of a transversely polarized quark into an unpolarized hadron generates an azimuthal modulation in the hadron distribution with respect to the scattering plane [12]. The hadron yield $N(\Phi_{Coll})$ can be written as:

$$N(\Phi_{Coll}) = N_0 \cdot (1 + ... + f \cdot P \cdot D_{NN} \cdot A_{Coll} \cdot sin(\Phi_{Coll})), \tag{2}$$

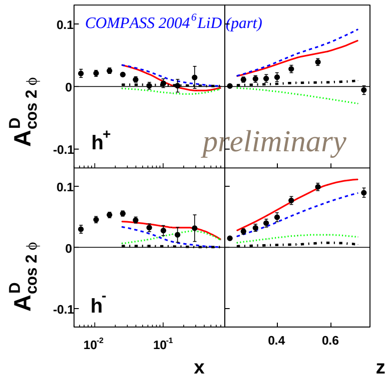
where N_0 is the average hadron yield, f is the fraction of polarized material in the target, P is the target polarization, $D_{NN} = (1-y)/(1-y+y^2/2)$ is the depolarization factor and y is the fractional energy transfer of the muon. The dots stand for the other terms of the SIDIS cross section, all of them are proportional to independent azimuthal modulation. The Collins angle is $\Phi_{Coll} = \phi_h + \phi_s - \pi$ where ϕ_h is the hadron azimuthal angle and ϕ_s is the azimuthal angle of the nucleon spin, with respect to the scattering plane [4]. The Collins asymmetry can be expressed as:

$$A_{Coll} = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot \Delta_T^0 D_q^h(z, p_T)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, p_T)}, \tag{3}$$

where the sum runs over the quark flavors and e_q is the quark charge, $D_q^h(z, p_T)$ is the unpolarized fragmentation function, $q(x)$ is the unpolarized parton distribution function.



(a)



(b)

Figure 3: **(a)** Comparison with theoretical predictions. Black points are the $cos(\phi_h)$ amplitude extracted from COMPASS data, positive hadrons, as a function of x and z and in green are shown the values predicted in [7] for COMPASS kinematics without considering the Boer Mulders effect. **(b)** Comparison with theoretical predictions. Black points are the $cos(2\phi_h)$ amplitude extracted from COMPASS data, for positive hadrons (upper two plots) and negative hadrons (lower raw), as a function of x and z. The red line shows the predictions from [8], and is the sum of Cahn contribution (blue line), Boer Mulders contribution (green dashed line) and perturbative QCD (black dotted line). These values have been calculated for the COMPASS kinematical region.

4.2 Transversely polarized two hadrons asymmetries

The transversity distribution can also be measured in SIDIS combined with the interference fragmentation function $H_1^{\sphericalangle}(z, M_{inv}^2)$ where M_{inv} is the invariant mass of the hadrons pair [13]. The fragmentation of transversely polarized quarks into two hadrons can give an azimuthal modulation in the produced hadrons distribution which, for two hadrons of opposite charge, can be written as:

$$N_{h^+h^-} = N_0 \cdot (1 + f \cdot P \cdot A_{RS} \cdot sin(\Phi_{RS}) \cdot sin(\theta)), \qquad (4)$$

where the angle $\Phi_{RS} = \phi_R + \phi_s - \pi$ is given by the sum of the azimuthal angle of the spin vector ϕ_s and the azimuthal angle of $\vec{R_T}$ with respect to the lepton scattering plane. $\vec{R_T}$ is the transverse component, with respect to the virtual photon direction, of the vector $\vec{R}$ defined as:

$$\vec{R} = (z_2 \cdot \vec{p_1} - z_1 \cdot \vec{p_2})/(z_1 + z_2), \qquad (5)$$

where $\vec{p_1}$ and $\vec{p_2}$ are the momenta in the laboratory frame of h^+ and h^- respectively. θ is the angle between the momentum vector of h^+ in the center of mass frame of the hadrons pair and the momentum vector of the two hadron system. The measured amplitude is proportional to the product of the transversity distribution and the polarized two-hadrons interference fragmentation function:

$$A_{RS} \propto \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_1^{\sphericalangle}(z, M_{inv}^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^{2h}(z, M_{inv}^2)}, \qquad (6)$$

where $D_q^{2h}(z, M_{inv}^2)$ is the unpolarized two-hadron interference fragmentation function.

The hadrons used in the analysis have $z > 0.1$ and $x_F > 0.1$ to exclude hadrons coming from the target fragmentation region; $z_1 + z_2 < 0.9$ to exclude pairs from exclusively produced ρ^0 mesons and $R_T > 0.07$ GeV/c to have a good resolution on the azimuthal angle ϕ_R.

4.3 The Sivers asymmetry

According to Sivers, the coupling of of the intrinsic transverse momentum $\vec{k_T}$ of unpolarized quarks with the spin of a transversely polarized nucleon can give an asymmetry in the hadrons azimuthal distribution [5]. The correlation between the transverse nucleon spin and the quark transverse momentum is described by the transverse momentum dependent PDF $\Delta_0^T q(x, \vec{k_T})$ called the Sivers function. The hadron yield can be written as:

$$N(\Phi_{Siv}) = N_0 \cdot (1 + ... + f \cdot P \cdot D_{NN} \cdot A_{Siv} \cdot sin(\Phi_{Siv})), \qquad (7)$$

where the Sivers angle $\Phi_{Siv} = \phi_h - \phi_s$. The Sivers asymmetry can be expressed as:

$$A_{Siv} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q(x, \vec{k_T}) \cdot D_q^h(z, p_T)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, p_T)}, \tag{8}$$

Since Collins and Sivers asymmetries are given by independent azimuthal modulations in the SIDIS hadrons distribution, they can be measured from the same data set. The kinematical selection is similar to the one applied for unpolarized asymmetries analysis, previously described in section 3.1.

4.4 Results

The Collins and Sivers asymmetries measured from the 2004 transversely polarized deuteron data are compatible with zero [9], within the statistical and systematical errors, over the full range of x, z and p_T. A global fit to the COMPASS results on deuteron and of the HERMES measurements on proton of the Collins asymmetries and to the BELLE results on the Collins fragmentation function, led to the first extraction of the transversity distribution function [10]. The emerging picture is that the transversity distributions are different from zero, of the same magnitude and opposite sign for the u and d quark leading to a cancellation of the Collins asymmetry for an isoscalar target like deuteron. A global fit to HERMES proton data and COMPASS deuteron data suggested that a similar cancellation for the deuteron target occurs for the Sivers function [11].

Obviously there was a great interest for the results on polarized proton at the COMPASS energy. In 2007 a polarized NH_3 (proton) target was used and the first preliminary results where produced in 2008.

In figure 4 the results for the Collins asymmetries on proton are shown. The measured asymmetry is small and compatible with zero up to $x = 0.05$ and then increases up to about 10% in the x valence region, with opposite sign for positive and negative hadrons. The asymmetry has the same sign and size of the one measured by HERMES. The COMPASS measurement confirms the HERMES result at an higher energy, i.e. in a region where higher twist effects are less important.

In figure 5 the two-hadrons asymmetries are shown. At variance with the deuteron results the asymmetry is evident in the x-valence region and there is a strong signal in M_{inv} around the ρ^0 mass.

In figure 6 the Sivers asymmetries are shown. They are small and compatible with zero over all the x range both for positive and negative hadrons. This is a surprising result since no strong Q^2 dependence is expected for the Sivers distribution function.

5 Outlook

An important contribution to the understanding of the nucleon structure comes from these SIDIS results. The work is still ongoing and more precise high energy data, complementary to the measurement performed at JLAB, are needed and COMPASS will have a full year dedicated data taking with polarized proton in 2010.

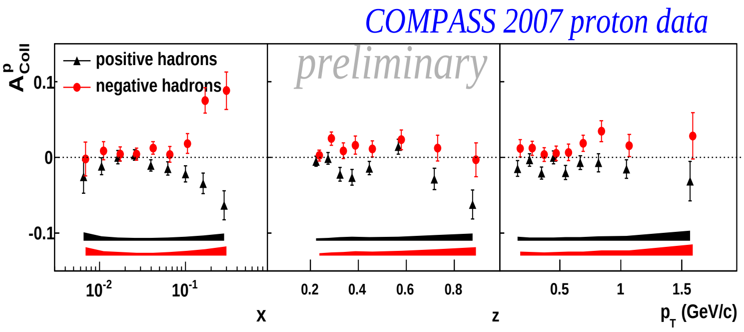


Figure 4: COMPASS Collins asymmetries on polarized proton for positive (black triangles) and negative (red circles) hadrons as a function of x, z, and p_T. The red bands stand for the systematic errors.

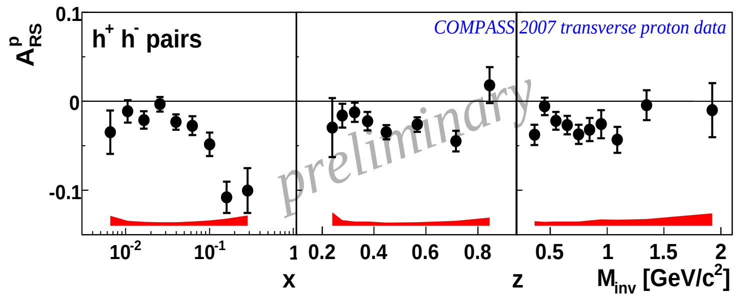


Figure 5: COMPASS two-hadrons asymmetries on polarized proton for positive (black triangles) and negative (red circles) hadrons as a function of x, z, and M_{inv}. The red bands stand for the systematic errors.

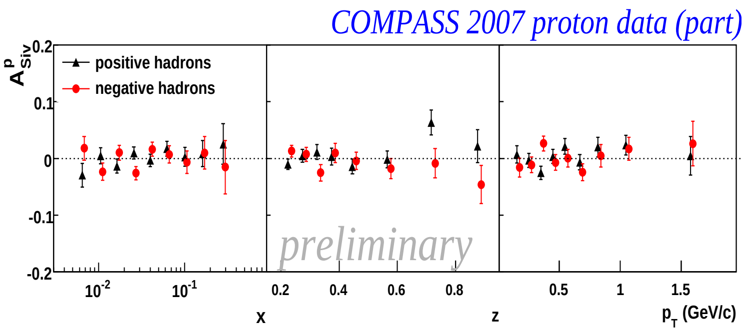


Figure 6: COMPASS Sivers asymmetries on polarized proton for positive (black triangles) and negative (red circles) hadrons as a function of x, z, and p_T. The systematic errors are about 0.5 of the statistical ones.

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