Azimuthal asymmetries in SIDIS off unpolarized targets at COMPASS

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Azimuthal asymmetries measured in unpolarized semi-inclusive deep inelastic scattering bring important information on the inner structure of the nucleons, and can be used both to estimate the average quark transverse momentum $k_\perp$ and to access the so-far unmeasured Boer-Mulders functions. COMPASS results using part of the 2004 data collected with a ^{6}LiD target and a 160 GeV μ^+ beam are presented separately for positive and negative hadrons.

1 Introduction

After years of study to understand how the nucleon spin originates from the constituent partons, an exhaustive answer is still missing. Moreover, while a lot of information has been gathered concerning the longitudinal structure of a fast moving nucleon (with respect to its direction of motion), very little is known about the transverse structure. In recent years these aspects have raised a lot of interest and after important theoretical developments and experimental findings, transverse spin and transverse momentum $k_\perp$ of the quarks are by now considered as fundamental ingredients in the description of the hadron structure. Spin-$k_\perp$ correlations give rise to various observables in hard hadronic processes such as the azimuthal asymmetries seen both in unpolarized or transversely polarized semi-inclusive deep-inelastic scattering (SIDIS), and led to the introduction of transverse momentum dependent (TMD) parton distribution functions (PDF) and fragmentation functions (FF). Among these functions of special interest are the Sivers functions $f_{1T}^{\perp}(x, k_\perp)$ [2], which describe an azimuthal asymmetry in the parton distributions inside a transversely polarized nucleon, and by their chirally-odd partner $h_1^{\perp}(x, k_\perp)$, the Boer-Mulders functions [3], describing the transverse parton polarization inside an unpolarized hadron, and generating azimuthal asymmetries in unpolarized SIDIS. COMPASS results on the Sivers asymmetries are given elsewhere [4] while here the unpolarized azimuthal asymmetries are presented.

The cross-section for hadron production in lepton-nucleon DIS $\ell N \to \ell' h X$ for unpolarized targets and an unpolarized or longitudinally polarized beam is the following [5]:

$$\frac{d\sigma}{dx dy dz d\phi_h dp_{h,T}^2} = \frac{\alpha^2}{xyQ^2}\frac{1+(1-y)^2}{2}\Big[F_{UU,T} + F_{UU,L} + \varepsilon_1 \cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon_2 \cos(2\phi_h) F_{UU}^{\cos\,2\phi_h} + \lambda_\mu \varepsilon_3 \sin\phi_h F_{LU}^{\sin\phi_h}\Big]$$

where α is the fine structure constant, x, y and Q^2 are the inclusive DIS variables, z is the fraction of the virtual photon energy carried by the detected hadron, ϕ_h is the azimuthal angle of the outgoing hadron in the γ-nucleon system. $F_{UU,T}$, $F_{UU,L}$, $F_{UU}^{\cos\phi_h}$, $F_{UU}^{\cos\,2\phi_h}$ and $F_{LU}^{\sin\phi_h}$ are structure functions, with the first and second subscripts which indicate the beam and target polarization respectively, and the last subscript which, if present, indicates the polarization of the virtual photon. Finally λ_μ is the beam longitudinal polarization and:

$$\begin{aligned} \varepsilon_1 &= \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2} \\ \varepsilon_2 &= \frac{2(1-y)}{1+(1-y)^2} \\ \varepsilon_3 &= \frac{2y\sqrt{1-y}}{1+(1-y)^2} \end{aligned}$$

are depolarization factors. The Boer-Mulders PDFs contribute to both the $\cos\phi$ and the $\cos 2\phi$ structure functions, together with the so called Cahn effect [6] which arises from the fact that the kinematics is non collinear when the $k_\perp$ is taken into account (i.e. a kinematical higher twist), and with the perturbative gluon radiation, resulting in order α_s QCD processes. pQCD effects are becoming important for high transverse momenta p_T of the produced hadrons, while are small for p_T up to 1 GeV/c. The $\sin\phi_h$ modulation, which arises from the natural polarization of the muon beam, does not have a clear interpretation in the parton model.

In the past, azimuthal asymmetries have been measured by the EMC collaboration [7, 8], with a liquid hydrogen target and a muon beam at a slightly higher energy, but without separating hadrons of different charge. These data have been used [9] to extract the average $\langle k_\perp^2 \rangle$. Azimuthal asymmetries have been also measured by E665 [10] and at higher energies by ZEUS [11]. More recent are the COMPASS results first presented at [12], and the measurements done by HERMES, first shown at [13].

2 The COMPASS experiment

The COMPASS experiment has been set up at the CERN SPS M2 beam line. It combines high rate beams with a modern two stage magnetic spectrometer[14].

COMPASS has collected data with a 160 GeV positive muon beam impinging on a polarized solid target. The beam is naturally polarized by the $\pi-$decay mechanism, and the beam polarization is estimated to be $\sim 80\%$ with a $\pm 5\%$ relative error. The beam intensity is 2×10^8 muons per spill.

Up to 2006 the experiment has used ^{6}LiD as deuteron target because its favorable dilution factor of $\simeq$0.4, particularly important for the measurement of $\Delta G/G$. In 2007 an ammonia NH_3 target has been used as proton target. Polarizations of 50% and 90% have been reached, respectively for the two target materials.

3 Analysis and Systematic Studies

The event selection requires standard DIS cuts, i.e. $Q^2 > 1$ (GeV/c)^2, mass of the final hadronic state $W > 5$ GeV/c^2, $0.1 < y < 0.9$, and the detection of at least one hadron in the final state. Moreover only events with a vertex in the forward target cell are used in order to minimize nuclear interactions and for a better data/Monte Carlo agreement. Finally, for the detected hadrons it is also required that:

- the fraction of the virtual photon energy carried by the hadron be $0.2 < z = E_h/E_\gamma < 0.85$ to select hadrons from the current fragmentation region;

- $0.1 < p_T < 1.5$ GeV/c, where p_T is the hadron transverse momentum with respect to the virtual photon direction, for a better determination of the azimuthal angle ϕ_h.

Data taken both with a longitudinally polarized and a transversely polarized target have been used, mixing positive or negative orientations in order to cancel effects depending on the polarization of the nucleons. This statistics corresponds to almost 1 month of the 2004 data taking and after all the cuts consists of 5×10^6 positive hadrons and 4×10^6 negative hadrons entering the asymmetry calculations.

In the measurement of unpolarized asymmetries all the methods used to cancel the experimental acceptance cannot be adopted and the correction for this effect is mandatory before fitting the azimuthal modulation. This is done by using a full Monte Carlo chain, which starts from the SIDIS event generation performed by Lepto[15], simulate the experimental setup and the particle interactions in the passive and active material of the detectors (also including the detector response done by COMGEANT), and ends with the reconstruction of the generated events by the same program (CORAL) used to analyze the real data. The quality of this chain is evaluated by comparing distributions of real data and of generated events both for the DIS variables and for the hadronic variables.

The experimental acceptance as a function of the azimuthal angle $A(\phi)$ is then calculated as the ratio of reconstructed over generated events for each bin of x, z and p_T on which the asymmetries are measured. The overall y, z and p_T acceptances are quite constant over the range used in the analysis, so that the effect coming by the integration over the unlooked variables when the asymmetries in one of the variables are extracted is well within the systematic error. The measured distribution, corrected for acceptance is fitted with the following

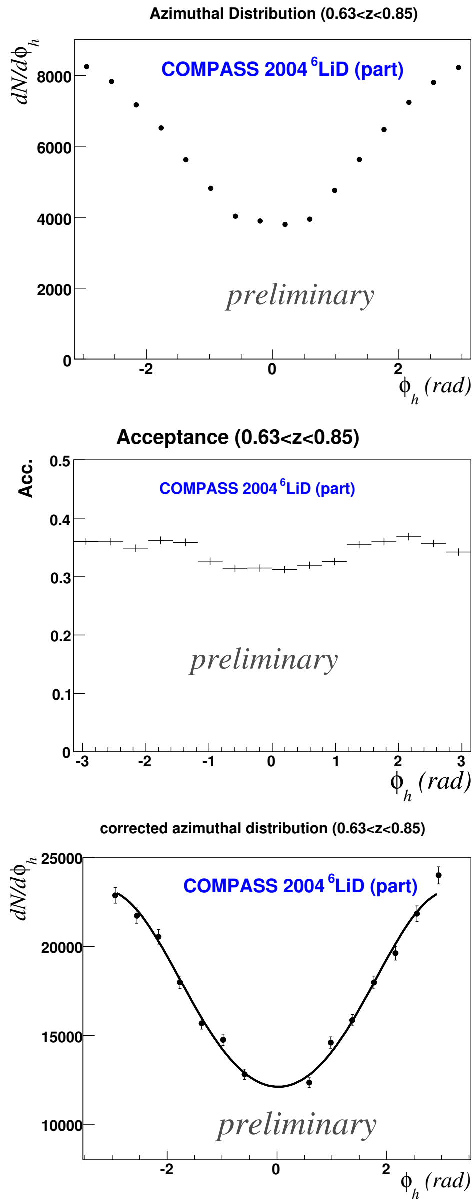

Figure 1: Top:measured azimuthal distribution after weighting for the two target polarization. Middle: acceptance distribution as calculated by the Monte Carlo data. Bottom: azimuthal distribution corrected for the acceptance effects.

functional form:

$$N(\phi) = N_0 \Big(1 + A^D_{\cos\phi} \cos\phi + A^D_{\cos 2\phi} \cos 2\phi + A^D_{\sin\phi} \sin\phi\Big)$$

An example of a measured azimuthal distribution, acceptance corrections and corrected azimuthal distribution is shown in Fig. 1, together with the resulting fit.

The contribution of the acceptance corrections to the systematic error has been studied with care. As the asymmetries were extracted from data taken both with longitudinal and transverse target configurations, comparing the two results gives the effect of the acceptance changes due to the different configuration (solenoid vs. dipole) of the target magnet and to the different direction of the incoming beam (for the transverse setup the beam is bent in order to leave the target with the same direction as in the longitudinal case). In order to check the effect of the simulation parameters the acceptances have been calculated using two different sets of Lepto parameters. All the resulting asymmetries were compared in order to quantify the systematic error in each kinematical bin. Further systematic tests, like splitting the data sample according to the event topology and to the time of the measurement, gave no significant contributions.

4 Results and Comments

The $\sin\phi$ asymmetries, not shown here, measured by COMPASS are compatible with zero, at the present level of statistical and systematic errors, over the full range of x, z and p_T covered by the data.

The $\cos\phi$ asymmetries extracted from COMPASS deuteron data are shown in Fig. 2 for positive (upper row) and negative (lower row) hadrons, as a function of x, z and p_T. The bands indicate the size of the systematic error. The asymmetries show the same trend for positive and negative hadrons with a slightly larger values for the positive one. Values as large as 30÷40% are reached in the last point of the z range. The theoretical predictions [16] in Fig. 2 takes into account the Cahn effect only, which does not depend on the hadron charge. The Boer-Mulders PDFs are not taken into account in this case.

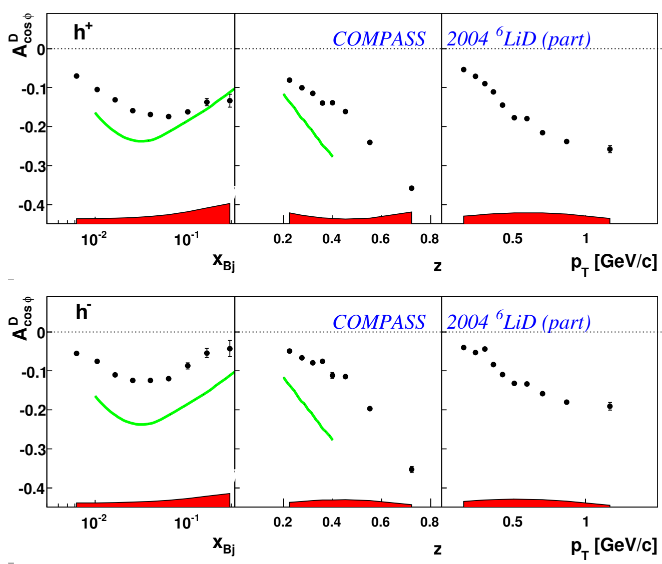

Figure 2: $\cos\phi$ asymmetries from COMPASS deuteron data for positive (upper row) and negative (lower raw) hadrons; the asymmetries includes the kinematical factor ε_1 and the bands indicate the size of the systematic errors. The superimposed curves are the values predicted by [16] taking into account the Cahn effect only.

The $\cos 2\phi$ asymmetries are shown in Fig. 3 together with the theoretical predictions of [17], which take into account the kinematical contribution given by the Cahn effect, first order pQCD (which, as expected, is negligible in the low p_T region), and the Boer-Mulders PDFs (coupled to the Collins FF), which give a different contribution to positive and negative hadrons. In [17] the Boer-Mulders PDFs are assumed to be proportional to the Sivers function as extracted from the preliminary HERMES data. The COMPASS data show different amplitude for positive and negative hadrons, a trend which confirms the theoretical predictions. There is a satisfactory agreement between the data points and the model calculations, which hints to a non zero Boer-Mulders PDFs.

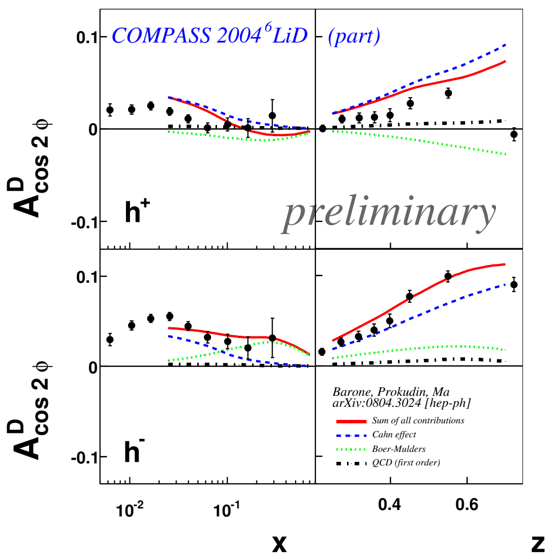

Figure 3: $\cos 2\phi$ asymmetries from COMPASS deuteron data for positive (upper row) and negative (lower raw) hadrons; the asymmetries are divided by the kinematical factor ε_1 and the red bands indicate size of the systematic errors.

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