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COMPASS results: TMD measurements in SIDIS off unpolarized targets

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Summary. — The study of the transverse-spin and transverse-momentum structure of the nucleon is part of the scientific program of COMPASS, a fixed-target experiment at the CERN SPS. By studying the distributions of the hadrons produced in SIDIS off unpolarized targets one can have insights on the structure of the nucleon and on the possible correlations between transverse spin and intrinsic transverse momentum of the quarks. In this presentation the new results for the azimuthal asymmetries and for the hadron multiplicities are presented. They are obtained from the COMPASS data collected with a 160 GeV/c positive muon beam impinging on a ^{6}LiD target.

PACS 13.60.-r – Photon and charged-lepton interactions with hadrons.
PACS 13.60.Hb – Total and inclusive cross sections (including deep-inelastic processes).
PACS 13.87.Fh – Fragmentation into hadrons.

1. – Introduction

The investigation of the spin structure of the nucleon is one of the main topics of the COMPASS experiment. It is carried on by studying the hadrons distributions produced in deep inelastic scattering (DIS) of 160 GeV/c positive muons off polarized nucleons. The high-momentum resolution of the spectrometer, the large angular acceptance and the periodical reversal of the target polarization allow to measure the spin-dependent asymmetries with a great accuracy and to span a wide kinematical region. In particular the results on the Collins and Sivers asymmetries measured from the hadron distribution of the azimuthal angle around the virtual photon direction, have been published for both transversely polarized deuteron [1] and protons [2] and new results have been presented at this workshop [3]. There is a lot of interest in these measurements because they assess the quark transverse polarization and the correlation between the transverse spin and the intrinsic transverse momentum of the quarks. Complementary information on the nucleon structure, in particular on the relevance of the transverse momentum and higher-twist effects is given by the measurements of the spin-averaged distributions.

The new COMPASS results on the spin-averaged azimuthal asymmetries and on the hadron multiplicities are presented here. The kinematical dependencies of the most interesting kinematical variables, the Bjorken scaling variable x, the fraction of the available energy carried by the hadron z, and its transverse momentum with respect to the virtual photon direction P_T^h, are studied separately for positive and negative hadrons.

The measured distributions have to be corrected for the acceptance, evaluated using Monte Carlo (MC) simulations. The results presented here are obtained from the data taken in 2004. The spectrometer behavior for that year is now very well understood and a great effort has been put to best reproduce its features and to achieve a good description of the measured distributions.

2. – Results on the unpolarized azimuthal asymmetries

In semi-inclusive DIS (SIDIS) cross section of longitudinally polarized leptons off unpolarized targets [4] three modulations are expected in the distribution of the hadron azimuthal angle ϕ_h calculated in the Gamma Nucleon System. The amplitudes of the $\cos\phi_h$ modulation is mainly given by the so called Cahn effect [5], a pure kinematical effect in the elastic scattering between the incoming lepton and the struck quark. This effect contributes also to the $\cos 2\phi_h$ amplitude but it is kinematically suppressed by a factor $1/Q$. The Boer-Mulders transverse momentum dependent (TMD) PDF [6] is expected to give an higher twist contribution to the amplitude of the $\cos\phi_h$ modulation and a leading twist contribution to the amplitude of the $\cos 2\phi_h$ modulation. This function is very interesting and describes the correlation between transverse momentum and transverse polarization of a quark inside an unpolarized nucleon. In some model calculations [7] the contribution of the Boer-Mulders function to the $\cos 2\phi_h$ asymmetry is comparable with that of the Cahn effect. The amplitude of the $\sin\phi_h$ modulation has no clear interpretation in terms of Parton Model and can only be expressed in terms of higher-twist effects.

All the 3 amplitudes have been extracted in the DIS region: $Q^2 > 1\,(\mathrm{GeV}/c)^2$, $0.1 < y < 0.9$, $W > 5\,\mathrm{GeV}/c^2$. A cut on the transverse hadron momentum $0.1 < P_T^h < 1.0\,\mathrm{GeV}/c$ is also applied. The lower limit is chosen in order to have a good resolution on the azimuthal angle, while the upper limit ensures a negligible contribution from the gluon radiation. Finally, cuts on the virtual photon angle (calculated with respect to the nominal beam direction), asking $\theta_{\gamma^*}^{lab} < 60$ mrad, and $y > 0.2$ are applied to avoid large acceptance corrections.

The azimuthal acceptance has been evaluated as: $Acc^{mc}(\phi_h) = N_{rec}^{mc}(\phi_h)/N_{gen}^{mc}(\phi_h)$, where $N_{rec}^{mc}(\phi_h)$ is the number of hadrons in the MC sample reconstructed after all the analysis cuts. $N_{gen}^{mc}(\phi_h)$ is the corresponding number of generated hadrons. The hadron azimuthal distributions corrected for the apparatus acceptance $N_{corr}(\phi_h) = N(\phi_h)/Acc^{mc}(\phi_h)$ are fitted using a four parameter function: $N_{corr}(\phi_h) = N_0 \cdot (1 + p_{\cos(\phi_h)} \cdot \cos(\phi_h) + p_{\cos(2\phi_h)} \cdot \cos(2\phi_h) + p_{\sin(\phi_h)} \cdot \sin(\phi_h))$, binning alternatively in x, z and P_T^h, for positive and negative hadrons separately.

A different procedure has been also used to correct the measured azimuthal distributions. In each bin they are weighted for the acceptance calculated as function of one more kinematical variable. The final results obtained with the two procedures are identical. The acceptance has been calculated using 3 different Monte Carlo sets of data produced

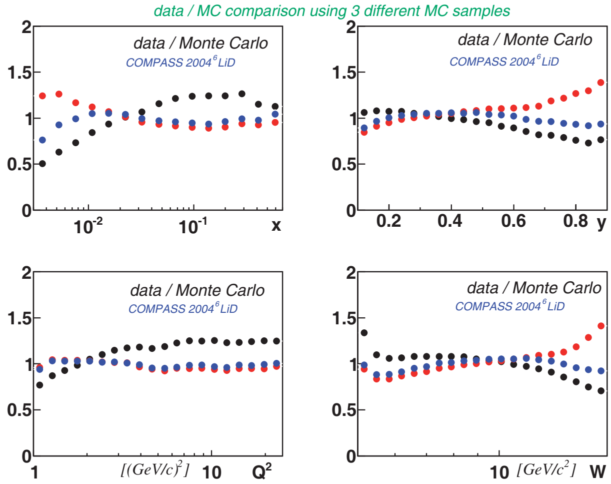

Fig. 1. – Ratios of the kinematical distributions obtained from real data and for the 3 different MC sets of data for the DIS variables: x, y, Q^2 and W.

by changing the PDFs set and the LEPTO parameters relative to the transverse momentum distribution in the fragmentation process and the Lund Fragmentation Function. The ratios between the data and MC distributions for some kinematical variables are shown in fig. 1. The blue points refer to the MC sample used to extract the results. In spite of the large differences in reproducing the kinematical distributions it has been checked that the difference between the asymmetries extracted using the three MC samples is small, giving confidence in the method used to evaluate the acceptance. This difference has been used in the evaluation of the systematic error. Another contribution comes from the comparison with the results extracted using different sets of data, taken with different apparatus set-ups and described by independent MC. Other possible effects, like unknown detector inefficiencies in the large angle region, kinematical smearing and radiative effects have been evaluated to be negligible. The systematic errors have been estimated to be twice the statistical ones.

The results of the amplitudes of the azimuthal modulations divided by the corresponding y-dependent kinematical factors, $A^{UU}_{\cos\phi_h}$, $A^{UU}_{\cos 2\phi_h}$ and $A^{LU}_{\sin\phi_h}$, are shown in fig. 2 as functions of x, z and P^h_T, for positive hadrons. The $A^{LU}_{\sin\phi_h}$ azimuthal asymmetries show a positive signal for the positive hadrons and are compatible with zero for the negative ones. The largest signal is given by the $A^{UU}_{\cos\phi_h}$ amplitude: it is up to 15% and shows a strong dependence both on z, constant up to ~ 0.4 and then rising sharply, and P^h_T, small for low values and then more or less linear. The $A^{UU}_{\cos 2\phi_h}$ asymmetry is smaller and has a strong dependence on all the three studied kinematical variables x, z or P^h_T. Its P^h_T dependence has a clear structure at variance with the present models predictions, a very interesting results which needs to be understood. The dependence of $A^{UU}_{\cos 2\phi_h}$ and $A^{UU}_{\cos\phi_h}$ on the hadron charge, clearly visible in fig. 3, could be related to the Boer-Mulders function or to a possible flavor dependence of the quark intrinsic transverse momentum. It is interesting to compare the $A^{UU}_{\cos\phi_h}$ results as function of z with the model calculations of refs. [8] and [9]. Both sets of theoretical predictions shown in fig. 4 are based on Gaussian distributions of the quark intrinsic transverse momentum, both inside the nucleon and in

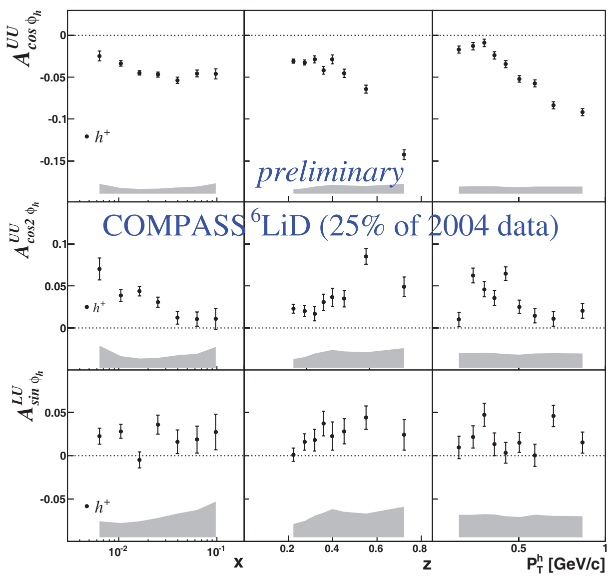

Fig. 2. – Results for the $A^{UU}_{\cos\phi_h}$ (upper plot), $A^{UU}_{\cos 2\phi_h}$ (middle plot) and $A^{LU}_{\sin\phi_h}$ (lower plot) azimuthal asymmetries as functions of x, z and P_T^h, obtained for positive hadrons. Grey bands are the systematic error ($\sigma_{sys} = 2 \cdot \sigma_{stat}$).

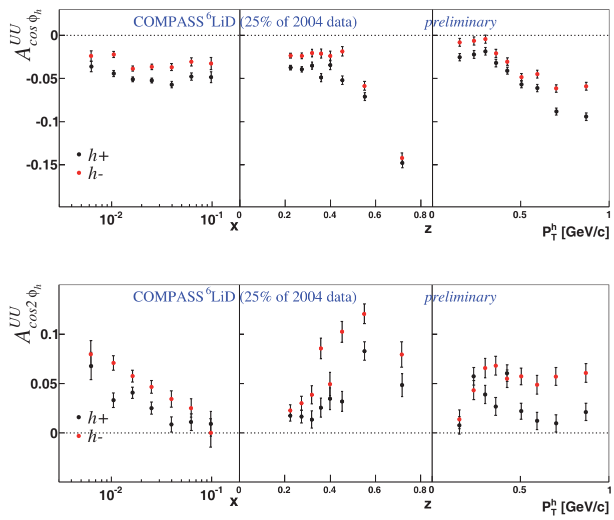

Fig. 3. – (Colour on-line) Comparison between the results obtained from positive (black points) and negative (red points) hadrons. The $A^{UU}_{\cos\phi_h}$ (upper plot) and $A^{UU}_{\cos 2\phi_h}$ azimuthal asymmetries are shown as functions of x, z and P_T^h.

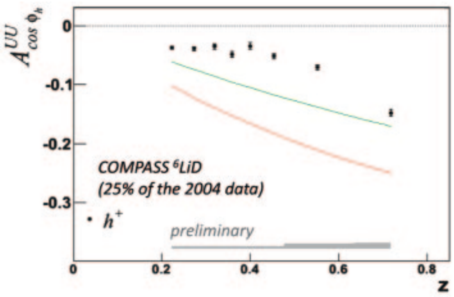

Fig. 4. – (Colour on-line) COMPASS results for $A^{UU}_{\cos\phi_h}$ (black points), together with the theoretical predictions from ref. [8] (green curve) and ref. [9] (red curve).

the fragmentation process. They also assume that its mean value, which is a parameter to be extracted from the data, depends nor on the quark flavor nor on the kinematics. The only difference between the two curves are the magnitude of the mean values of the intrinsic transverse momentum of the struck quark $\langle k_\perp^2 \rangle$ and of the fragmenting quark $\langle p_\perp^2 \rangle$ which are taken to be respectively $0.25\,(\mathrm{GeV}/c)^2$ and $0.20\,(\mathrm{GeV}/c)^2$ in ref. [8], and $0.38\,(\mathrm{GeV}/c)^2$ and $0.16\,(\mathrm{GeV}/c)^2$ in ref. [9]. It can be seen that the magnitude and the trend of the COMPASS results are not reproduced.

3. – Results on hadron multiplicities

The acceptance corrected hadron distributions are also extracted from the 2004 deuteron COMPASS data, separately for positive and negative hadrons. In particular we have measured the P_T^h dependence of the hadron multiplicities in different bins of x and Q^2. In each bin the $(P_T^h)^2$ mean values, $\langle (P_T^h)^2 \rangle$, are extracted by fitting the $(P_T^h)^2$ hadron multiplicity obtained for different intervals in z with the function $\mathrm{const} \cdot \exp[-(P_T^h)^2/\langle (P_T^h)^2 \rangle]$. As an example the distributions for positive hadrons in the bins $\langle Q^2 \rangle = 1.48\,(\mathrm{GeV}/c)^2$, $x = 0.0070$ and $\langle Q^2 \rangle = 7.57\,(\mathrm{GeV}/c)^2$, $x = 0.0932$ are shown in fig. 5 together with the fitted functions. These distributions are evaluated with very

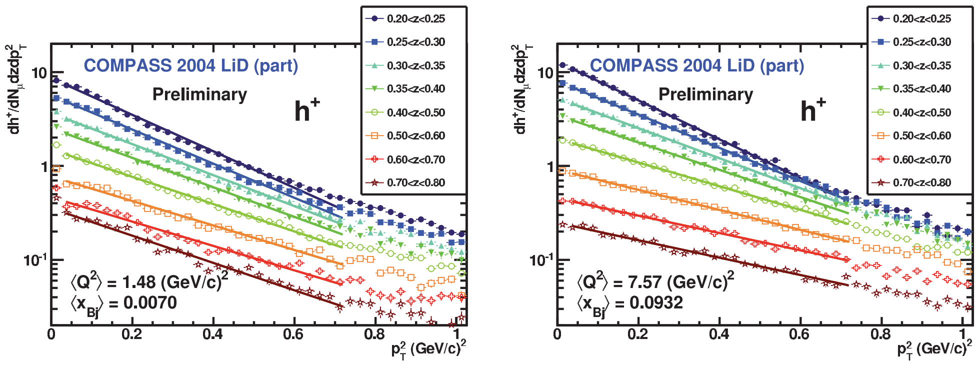

Fig. 5. – Positive hadron multiplicities as function of $(P_T^h)^2$ calculated separately in different z intervals given in the upper left corner of the plot. The mean values of x and Q^2 are given in the lower right corner of the plot for the considered kinematical bin.

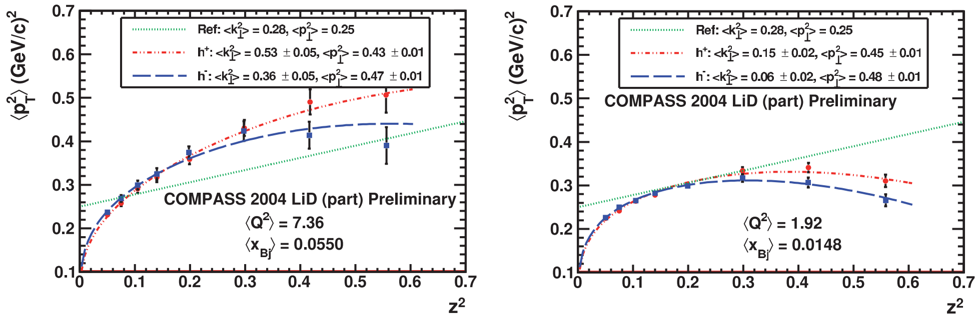

Fig. 6. – (Colour on-line) Measured $\langle (P_T^h)^2 \rangle$ as function of z^2 in 2 different bins of x and Q^2, for positive (red points) and negative (blue points) hadrons. The green dotted line is the linear dependence expected from ref. [8]. The red and blue lines are the fit to the points using $z^2 \cdot \langle k_\perp^2 \rangle + z^{\frac{1}{2}}(1-z)^{\frac{3}{2}} \langle p_\perp^2 \rangle$.

small statistical errors in each bin of the explored kinematical domain.

The goal of this very complex analysis is to evaluate $\langle k_\perp^2 \rangle$ using the relation of ref. [8]

$$\langle (P_T^h)^2 \rangle = z^2 \cdot \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle \,, \tag{1}$$

expected to hold in the region characterized by $(P_T^h)^2 < 1\,(\mathrm{GeV}/c)^2$, where the contribution of the perturbative QCD to the transverse momentum of the hadron is negligible. The relation given in eq. (1) is tested by fitting the z^2 dependence of the measured $\langle (P_T^h)^2 \rangle$ with a function linear in z^2. The procedure is repeated for each bin of x and Q^2. As can be seen in fig. 6 the resulting trend is not linear, confirming the results observed by other experiments with lower statistics [10, 11], and it shows a clear dependence on x and Q^2. The values of $\langle k_\perp^2 \rangle$ and $\langle p_\perp^2 \rangle$ given in the labels of fig. 6 are obtained by using

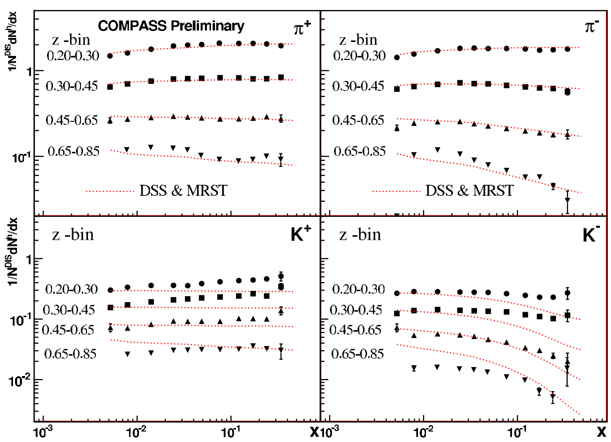

Fig. 7. – Acceptance corrected hadron multiplicities for π (upper 2 plots) and K (lower 2 plots) as function of x and for different z intervals. They are extracted separately for positive (left plots) and negative (right plots) hadrons. The curves are obtained using MRST and DSS parametrization.

$z^2 \cdot \langle k_\perp^2 \rangle + z^{\frac{1}{2}}(1-z)^{\frac{3}{2}} \langle p_\perp^2 \rangle$ instead of eq. (1).

The last COMPASS results presented here are the hadron multiplicities extracted for identified hadrons, π and K, separately for positive and negative hadrons. The kinematical dependence on x and z is studied and the preliminary results are already interesting. They are shown in fig. 7, together with the results obtained using MRST to parametrize the Parton Distribution Functions (PDF) and DSS for the Fragmentation Functions (FF). This measurement allows to extract the FF for the quark strange and the same method can be used to extract other FF in the future.

In this work the results obtained from the measurement of the spin-averaged distributions at COMPASS are shown. The hadron multiplicities and the azimuthal asymmetries have been extracted as functions of the most relevant kinematical variables. Both the measurements of the azimuthal asymmetries and of the transverse-momentum dependence of the hadron multiplicities are very precise and give valuable input to the theoretical models. The effects of the quark intrinsic transverse momentum and its correlation with the quark spin, described by the Boer-Mulders function, are sizable and have strong kinematical dependences, sometimes unexpected. The future SIDIS measurement at COMPASS, in parallel with the DVCS dedicated run and using a spectrometer optimized for cross section measurements, will allow for a finer analysis of the kinematical dependencies of the azimuthal asymmetries and more extensive studies on the identified hadron multiplicities.

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