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Newest COMPASS results on longitudinal and transverse nucleon spin structure.

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The COMPASS experiment at CERN has performed a rich programme in inclusive and semi-inclusive deep inelastic scattering of longitudinally polarised muons off longitudinally, transversely polarised and unpolarised nucleons. The main topic is the investigation of the spin structure of the nucleon in terms of quark and gluons, both through accessing the spin dependent collinear parton distribution functions and studying the transverse momentum dependent TMD PDFs and FFs The newest results on the spin structure function of the proton and the deuteron, on the transversity and Sivers PDFs and the measurements of hadron multiplicities will be shown. Plans for the near future will also be presented. In this proceeding only the results obtained using a muon beam will be reported.

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1. Introduction

The COMPASS spectrometer[1] is in operation on the M2 beam line of CERN since 2002. Two magnetic stages are used to ensure large angular and momentum acceptance. A variety of tracking detectors is used to cope with the different requirements of position accuracy and rate capability at different angles. Particle identification is provided by a large acceptance RICH detector, calorimeters, and muon filters. The target consists of cylindrical cells polarised in opposite directions, longitudinally or transversely with respect to the incoming beam direction, so that data with both spin directions are recorded at the same time. In order to minimise the effects due to different spectrometer acceptance for different target cells, polarisation reversal is performed by changing the microwave frequencies in the cells. ^{6}LiD and NH_3 are used as target material.

2. Longitudinal spin structure functions

The determination of the longitudinal spin structure of the nucleon became one of the important issues in particle physics after the surprising EMC result that the quark contribution to the nucleon spin is very small or even vanishing [2]. The present knowledge on the longitudinal spin structure function of the proton, g_p^1, originates from measurements of the asymmetry A_p^1, in polarised lepton nucleon scattering. In all these experiments, longitudinally polarised high-energy leptons were scattered off longitudinally polarised nucleon or nuclear targets. In this proceeding, the most recent

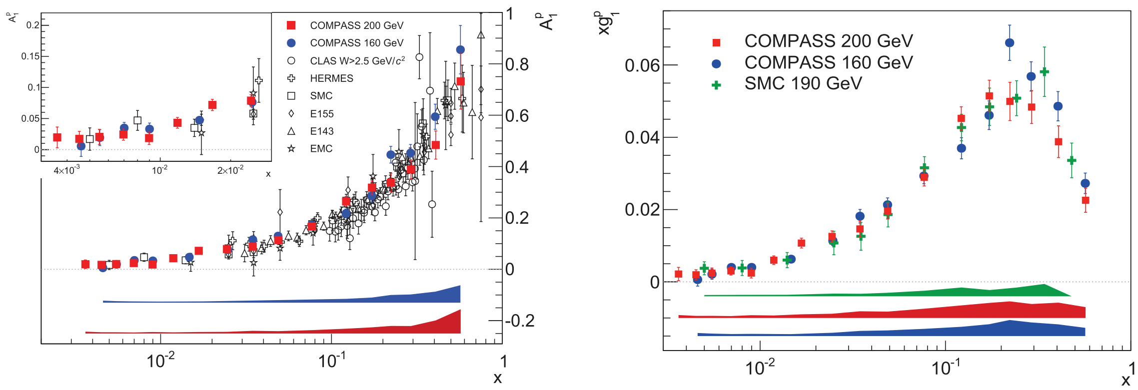

Figure 1: Left:The asymmetry A_1^p as a function of x at the measured values of Q^2 as obtained from the COMPASS data at 200 GeV. The new data are compared to the COMPASS results obtained at 160 GeV and to the other world data (EMC [2],CLAS [4], HERMES [5], E143 [6], E155 [7], SMC [8]). The bands at the bottom indicate the systematic uncertainties of the COMPASS data at 160 GeV (upper band) and 200 GeV (lower band). Right:The spin-dependent structure function xg_1^p at the measured values of Q^2 as a function of x. The COMPASS data at 200 GeV (red squares) are compared to the results at 160 GeV (blue circles) and to the SMC results at 190 GeV (green crosses) for $Q^2 > 1\ (GeV/c)^2$. The bands from top to bottom indicate the systematic uncertainties for SMC 190 GeV, COMPASS 200 GeV and COMPASS 160 GeV.

results from the COMPASS experiment at CERN are reported. By measuring A_1^p, results on g_1^p are obtained in the deep inelastic scattering (DIS) region. They cover the range from 1 (GeV/c)^2 to 190 (GeV/c)^2 in the photon virtuality Q^2 and from 0.0025 to 0.7 in the Bjorken scaling variable

x. The latest data, which were collected in 2011 at a beam energy of 200 GeV, complement earlier data taken in 2007 at 160 GeV that covered the range $0.004 < x < 0.7$. In the newly explored low-x region, COMPASS results significantly improve the statistical precision of g_1^p and thereby allow us to decrease the low-x extrapolation uncertainty in the determination of first moments. The data are analysed in terms of A_1^p and g_1^p as a function of x and Q^2. The x dependence of A_1^p averaged over Q^2 in each x bin is shown in Fig. 1 (left) together with the previous COMPASS results obtained at 160 GeV [9] and with results from other experiments [2, 4, 5, 6, 7] including those by SMC at 190 GeV [8]. The new data improve the statistical precision at least by a factor of two in the low-x region, which is covered by the SMC and COMPASS measurements only. The good agreement between all experimental results reflects the weak Q^2 dependence of A_1^p. The longitudinal spin structure function g_1^p is calculated from A_1^p and the parametrisation from Ref. [8] and [10]. The new results are shown in Fig. 1 (right) at the measured values of Q^2 in comparison with the previous COMPASS results obtained at 160 GeV and with SMC results at 190 GeV. The systematic uncertainty of g_1^p is of 2÷3 % [8]. Compared to the SMC experiment, the present systematic uncertainties are larger due to a more realistic estimate of false asymmetries, which is based on real events.
The results on the longitudinal double-spin asymmetry A_1^d and the longitudinal spin structure function g_1^d of the deuteron are also presented In Fig. 2. They are obtained from data taken in 2002, 2004 and 2006 with the CERN 160 GeV longitudinally polarised muon beam and a longitudinally polarised ^{6}LiD target. The double-spin asymmetry A_1^d and the spin-dependent structure function g_1^d are calculated in bins of x and Q^2 as done for A_1^p. In Fig. 2 (left), the combined COMPASS results on A_1^d are compared to the world data on A_1^d at the measured values of Q^2. All data sets agree well with one another. The data confirm the well-known weak Q^2 dependence of the asymmetry. The x dependence of the structure function g_1^d is shown in Fig. 2 (right) together with the results from SMC [8] that were obtained at a higher beam energy of 190 GeV. In the figure, the two COMPASS data points at lowest x are obtained as averages from the four lowest x bins. The systematic uncertainties are shown by bands at the bottom. The COMPASS data do not support large negative values of the structure function at low x, an indication of which may be seen in the SMC data. Instead, g_1^d is compatible with zero for x decreasing towards the lower limit of the measured range. The final g_1^d values together with the final COMPASS results on g_1^p [9, 11] are used to re-evaluate the Bjorken sum rule [11]obtaining $\Gamma_1^{NS} = 0.192 \pm 0.007_{stat} \pm 0.015_{syst}$ and $|g_A/g_V| = 1.29 \pm 0.05_{stat} \pm 0.10_{syst}$. The results on the spin-dependent structure function together with the world data in bins of x and Q^2, constitute the final COMPASS results and they improve the statistical precision of the combined world data on g_1^d, in particular at low x where SMC is the only other experiment that contributes.

3. Collins and Sivers asymmetries

In the SIDIS $\ell(l) + N(P) \to \ell(l') + h(p_h) + X$ cross-section, the convolution of TMD PDFs and FFs are describing the strength of modulations as a function of the azimuthal angle of hadrons ϕ_h and quark transverse spin ϕ_S [12]. There are five Single-Spin Asymmetries (SSA), which depend only on the transverse target spin S_T and three Double-Spin Asymmetries (DSA), both S_T and P_B (beam polarisation) dependent. In the QCD parton model approach four of the eight TSAs have leading twist interpretation. The remaining four asymmetries are higher-twist effects, though

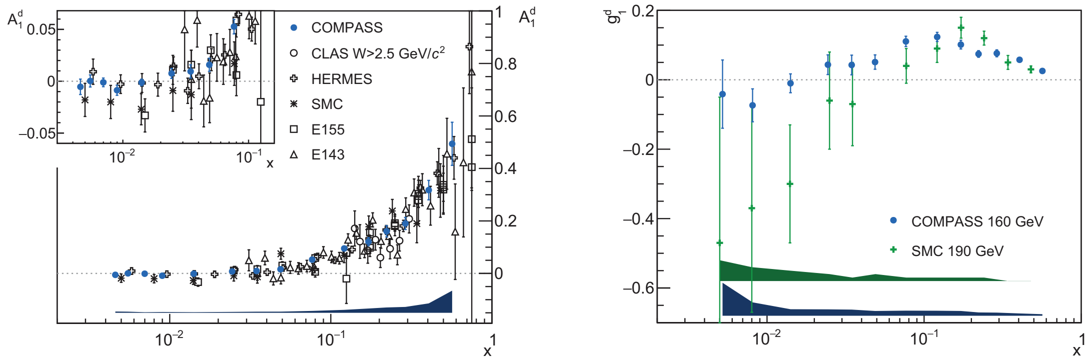

Figure 2: Left:Comparison between the combined COMPASS results on A_1^d and the world data (CLAS [4], HERMES [5], SMC [8], E155 [13] and E143 [6]). All data points are shown at their measured Q^2 values. Right:Comparison between SMC [8] and combined COMPASS results on g_1^d. The systematic uncertainty is illustrated by the bands at the bottom. All data points are shown at their measured Q^2 values.

they can be interpreted as Cahn kinematic corrections to twist-two spin effects on the transversely polarised nucleon. In the following only Sivers and Collins asymmetries will be shortly discussed.

3.1 Collins asymmetries

The main source of information on the transversity PDFs is at present the Collins asymmetry, which couples h_1 to the Collins fragmentation function $H_1^{\perp}$:

$$A_{UT}^{\sin(\phi_h+\phi_S)}(x) \simeq \frac{\sum_q e_q^2 h_1^q(x) \otimes H_1^{\perp,q\to h}}{\sum_q e_q^2 f_1^q(x) \otimes D_1^{q\to h}}$$

. The Collins asymmetry has been measured by COMPASS on deuterons (^{6}LiD) [14, 15] and on protons (NH_3) [16, 17] for unidentified hadrons (dominated by pions), π and K. Keeping in mind the COMPASS convention for the Collins angle, the Collins asymmetries measured for charged π on protons show a clear negative signal for π^+ and a positive signal for π^- as a function of x, z and p_T. The asymmetries measured by COMPASS and HERMES have the same amplitude once the HERMES data are corrected for the depolarisation factor, giving important information on the kinematic dependencies of the transversity PDF and Collins FF. The trend is confirmed for K^+, while K^- and K^0 signals are smaller (or absent) as shown in Fig. 3. The null COMPASS results on deuteron allows to constrain h_1^d. A global analysis of COMPASS, HERMES and Belle data allowed first extractions of transversity PDFs and Collins FFs [18, 19], showing that transversity function is sizeable and different from zero, with opposite sign and similar amplitude for the u and d quark, while at the same time favoured and unfavoured Collins FF are also large, with similar amplitude but opposite sign.

3.2 Weighted Sivers asymmetries

The difference between the probability to find an unpolarised quark with transverse momentum $\vec{k}_\perp$ and the probability to find it or with transverse momentum $-\vec{k}_\perp$ inside a transversely polarised

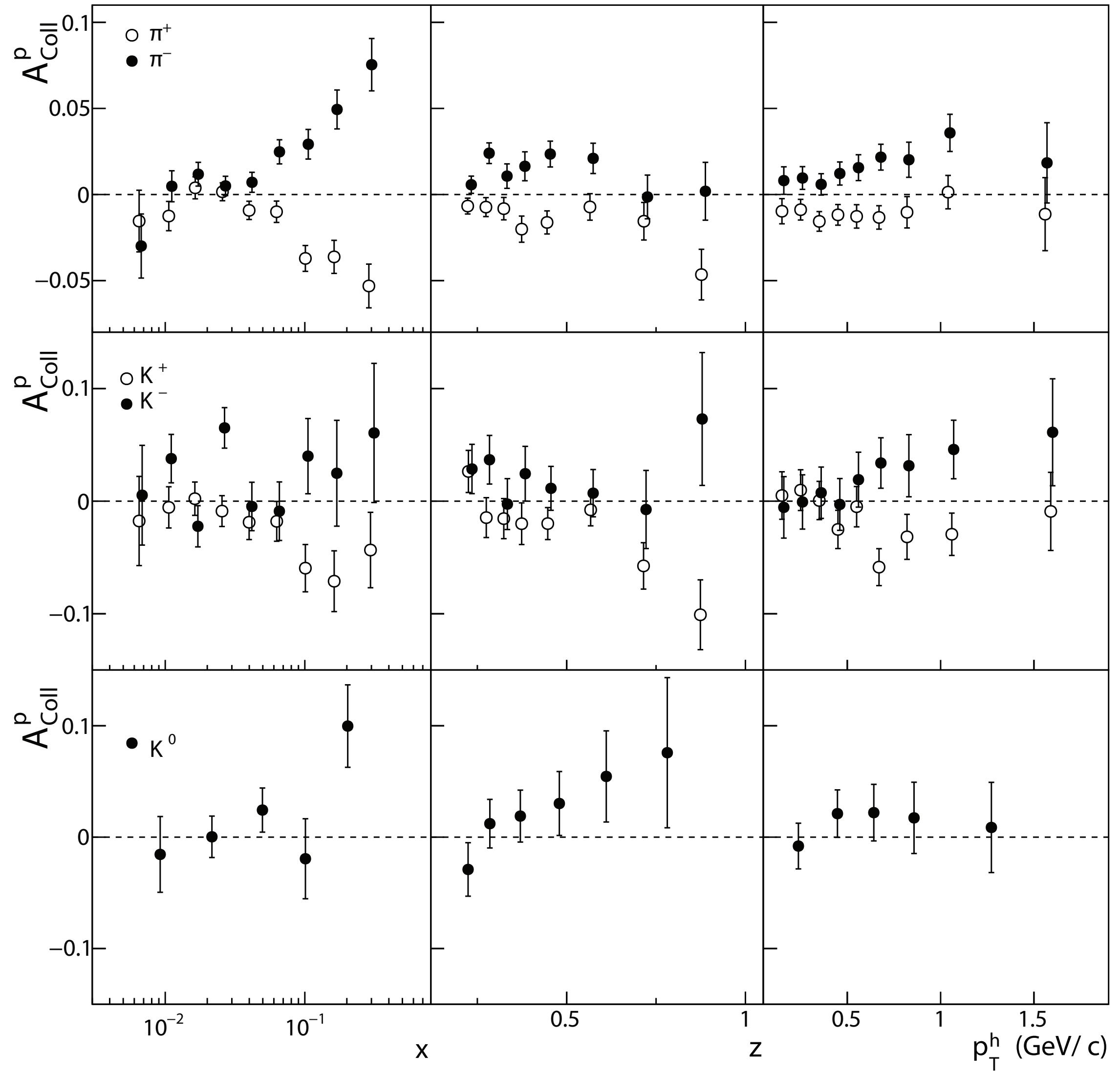

Figure 3: Collins asymmetries for positive and negative identified hadrons, as a function of x (left), z (middle-left) and p_T (right), on top for $\pi^{\pm}$, in the centre for $K^{\pm}$ and in the bottom for K^0. The results shown are for $z > 0.1$ and $p_T > 0.1$ GeV$/c$.

nucleon is proportional to the Sivers function $f_{1T}^{\perp}$ and modulated by the time-reversal odd correlations $(\hat{P} \times \vec{k}_{\perp}) \cdot \vec{S}$. If not null, such azimuthal asymmetry will therefore show that unpolarised quarks in a transversely polarised nucleon have a preferential motion direction. Interesting results on the Sivers asymmetries weighted with p_T^h, the transverse momentum of the final state hadrons with respect to the virtual photon direction, have been recently obtained. The method consists in measuring the asymmetries obtained by weighting only the spin-dependent part of the cross-section with appropriate powers of p_T^h , the measured transverse momentum of the hadron with respect to the virtual photon direction, leaving unweighted the unpolarised part of the cross-section. The main advantage of these asymmetries is that the convolution integrals over transverse momenta of the TMD PDFs and FFs, which appear in the standard definition of the asymmetries, become products of the transverse moments of the PDFs and of the FFs. Thus no parametrisation of the unknown transverse momentum dependence of PDFs and FFs is needed. The analysis is done for the Sivers asymmetry using as weight $w = p_T^h / zM$, where M is the nucleon mass. The weighted Sivers asymmetry simply result in

$$A_{Siv}^{w} = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) D_1^q(z)}{\sum_q e_q^2 x f_1^q(x) D_1^q(z)} \tag{3.1}$$

namely the convolution becomes the product of the first transverse moment of the Sivers function

$$f_{1T}^{\perp(1)}(x) = \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp}(x, k_T^2) \tag{3.2}$$

and of the fragmentation function D_1. Using the high statistics COMPASS data collected in 2010 on a transversely polarised proton target the weighted Sivers asymmetries have been determined as a function of x for $z > 0.2$. The results for positive and negative hadrons are given in Fig.4. Also shown, for comparison, are the values of the non weighted Sivers asymmetries. The measurement for positive hadrons is particularly interesting since, assuming u dominance, it is simply:$A_{Siv}^{w}(x) \approx 2 f_{1T}^{\perp(1)u}(x) / f_1^u(x)$.

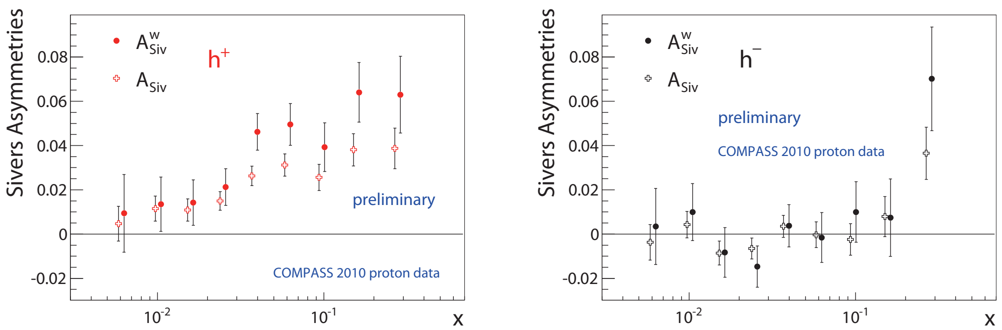

Figure 4: Full points: A_{Siv}^{w} in the nine x bins for positive (left panel) and negative (right panel) hadrons. The open crosses are the standard Sivers asymmetries from Ref. [20].

An other interesting result is that, integrating over x and assuming u-dominance, the asymmetries for positive hadrons which exhibit a large Sivers asymmetry, should not depend on z. The results for $A_{Siv}^{w}(z)$ as function of z look indeed constant within the statistical errors, confirming what expected.

4. Transverse-momentum-dependent hadron multiplicities

Unpolarised transverse-momentum-dependent parton densities (TMD-PDFs) and fragmentation functions (TMDFFs), commonly often referred to as TMDs, can be assessed by measuring the hadron yields normalised to the yields of DIS interactions, i.e. hadron multiplicities. While the study of the z dependence of the hadron multiplicities is sensitive to the hadronisation in the collinear framework, the dependence upon the transverse momentum of the final hadron p_T gives access to the transverse structure of the nucleon and the formation process of the hadron. The transverse momentum is generated by the transverse momentum of the struck quark $k_\perp$ and the transverse momentum $p_\perp$ of the final hadron with respect to the fragmenting quark. The multiplicities are given by:

$$\frac{d^4M^h(x,Q^2,p_T^2)}{dxdQ^2dp_T^2} = \frac{\sum_q \mathrm{e_q^2 f_q(x, k_\perp, Q^2) D_{h/q}(z, p_\perp, Q^2)}}{\sum_q \mathrm{e_q^2 f_q(x, k_\perp, Q^2)}} \tag{4.1}$$

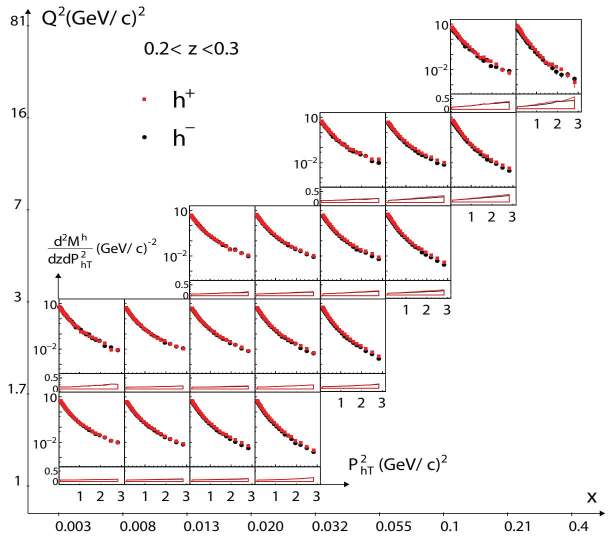

Figure 5: Multiplicities of positively (full squares) and negatively (full circles) charged hadrons as a function of P^2_{hT} in (x,Q^2) bins for $0.2 < z < 0.3$. Error bars on the points correspond to the statistical uncertainties. The systematic uncertainties (σ_{sys}/M^h) are shown as bands at the bottom.

A recent fit [3] to the existing data sets, including 2004 COMPASS data [21], was performed assuming Gaussian parametrisations for the TMDs $f_q(x,k_\perp)$ and $D_{h/q}(z,p_\perp)$. This fit has shown that this ansatz is not suitable to describe the shape of our data. In total 4.3 million positive hadrons and 3.4 million negative hadrons from ^{6} LiD target,in the range $0.2 < z < 0.8$ entered the analysis. The multiplicities of the positive hadrons are shown as example in Fig. 5 for $0.2 < z < 0.3$ [23]. Systematic uncertainties have been evaluated and are shown as bands at the bottom. The multiplicities can not be fitted using a single exponential, therefore a two-exponential function has been used [23]. The data provide valuable input for the QCD analysis of TMDs.

5. Conclusions

COMPASS contribution to the study of the spin structure of the nucleon in terms of quark and gluons, both through accessing the spin dependent collinear parton distribution functions and through studying the transverse momentum dependent TMD PDFs of hadrons has been and will be important. The results on the spin-dependent structure function together with the world data on

g_1^d are the final COMPASS results and they contribute to improve the statistical precision of the combined world data, in particular at low x.
TMDs are now a central field of research of many laboratories around the world. In the last years the important discoveries of the correlation between the spin of transversely polarised quarks and the $p_\perp$ of the hadrons created in the quark hadronisation process or the non-zero correlation between the spin of a transversely polarised nucleon and the intrinsic transverse momentum of the quarks, have been achieved. Still the available SIDIS data cover only a limited phase space: more data are needed to obtain the p^T and Q^2 dependence of the asymmetries in the different kinematical bins of x and z, so to extract the TMD functions in model independent way. In the near future more SIDIS data will be collected by JLab at 12 GeV, while COMPASS has presented at this conference [22] the results for the first ever polarised Drell-Yan process in $\pi^- p$, to verify the sign change of the Sivers function. COMPASS will also provide new measurements of azimuthal asymmetries in SIDIS on a unpolarised liquid hydrogen target.

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