

Recent COMPASS results on Transverse Spin Asymmetries in SIDIS

Franco Bradamante

Trieste Section of INFN, Trieste, Italy,
on behalf of the COMPASS Collaboration

Abstract. After reviewing the most important COMPASS results on transverse spin effects in SIDIS, I will present the recent work we have done on weighted Sivers asymmetries and “transversity induced” Λ polarisation. Using the high statistics data collected in 2010 on a transversely polarised proton target COMPASS has evaluated the transverse momentum weighted Sivers asymmetries both in x - and in z -bins. The results are also compared with the standard unweighted asymmetries. Using the whole data sample collected over the years on transversely polarised deuteron and proton targets COMPASS has measured the transversity induced Λ polarisation in the reaction $\mu N \rightarrow \mu' \Lambda X$. Possible future SIDIS COMPASS measurements will also be briefly mentioned.

1. Introduction

In 1996, the COMPASS spectrometer was proposed as a “Common Muon and Proton Apparatus for Structure and Spectroscopy”, capable of addressing a large variety of open problems in both hadron structure and spectroscopy. By now, we have published a large number of results, and in this workshop several COMPASS contributions will cover the various facets of the hadron structure, namely the longitudinal spin structure of the nucleon in semi-inclusive deeply inelastic scattering (SIDIS), the transverse spin structure of the nucleon in SIDIS, in exclusive reactions, and in Drell-Yan scattering, and the hadron multiplicities in unpolarised SIDIS [1]. In this review I will shortly remind the most important results we have obtained on the transverse spin structure of the nucleon in SIDIS, then I will present our most recent work on the weighted Sivers asymmetries and on the Λ polarisation, and I will conclude mentioning the future measurements we are planning.

2. The TMD PDFs

The description of the nucleon structure in terms of collinear parton distributions functions (PDFs), i. e. distributions depending only on Bjorken x and the negative squared four-momentum transfer Q^2 , has recently been generalized to take into account the parton transverse momentum k_T . A complete picture of the nucleon at leading order needs a total of eight transverse momentum dependent (TMD) PDFs. After integration over the transverse momentum three of them reduce to the “collinear” PDFs, namely the number density, the helicity and the transversity distributions. The other five TMD PDFs are sensitive to the direction of the quark transverse momentum, they vanish when integrating over k_T , and their measurement provides important information on the dynamics of the partons in the transverse plane in momentum space.

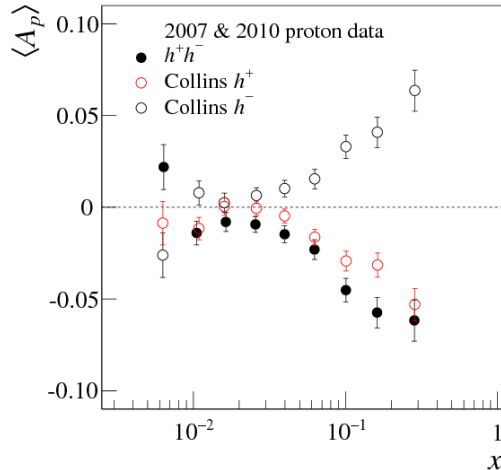


Figure 1. Comparison of the di-hadron asymmetry with the Collins asymmetry from the combined 2007 and 2010 proton data [6].

Particularly interesting is the measurement of the SIDIS cross-section when the target nucleon is transversely polarised. In this case 8 (5 in case of unpolarised lepton beam) different spin-dependent azimuthal modulations of the produced hadrons are expected, from which invaluable information on the TMD PDFs can be extracted. All these target spin dependent azimuthal modulations have been investigated by the HERMES and COMPASS Collaborations in pioneering experiments. In particular, HERMES [2, 3] and COMPASS [4, 5, 6] are up to now the only SIDIS experiments that have shown that the Sivers function [7], the transversity function and the Collins function [8] are different from zero. It is also of interest to remark that out of the 8 possible transverse spin azimuthal modulations in the SIDIS cross-section only the Collins and the Sivers asymmetries have been found to be different from zero, while the others have all been measured to be compatible with zero. And that there is no clear experimental evidence that the second T-odd TMD PDF, the so called Boer-Mulders function, which should show up in the azimuthal modulations of the unpolarised SIDIS cross-section, is different from zero. It has also to be added that the non-zero results for the asymmetries have been obtained scattering leptons on a proton target, while the corresponding asymmetries on a deuteron target (as measured by COMPASS) are compatible with zero [9, 10], hinting at a cancellation between the u- and d- quarks PDFs.

3. Transversity induced asymmetries

Some of the most beautiful results of COMPASS are shown in Fig. 1, where the Collins asymmetries for positive and negative hadrons are compared to the dihadron asymmetry, namely to the azimuthal modulation of the plane containing two oppositely charged hadrons. This dihadron asymmetry can be expressed as the product of the quark transversity distribution and a chiral-odd dihadron fragmentation function, which survives after integration over the two hadron momenta, and thus can be analyzed in the framework of collinear factorization. The mirror symmetry of the Collins asymmetry of positive and negative hadrons and the similarity between the positive hadron Collins asymmetry and the dihadron asymmetry suggested us an in-depth comparison between the two asymmetries. The conclusion of this investigation [11] was that both the single hadron and the dihadron transverse-spin dependent fragmentation functions are driven by the same elementary mechanism, which is very well described in the 3P_0 recursive string fragmentation model [12].

4. The Sivers asymmetries

The Sivers effect was experimentally observed in SIDIS on transversely polarised proton targets, first by the HERMES Collaboration [2, 3] and then by the COMPASS Collaboration [13, 5], while the COMPASS measurements on a transversely polarised deuteron target [9, 10] gave asymmetries compatible with zero. Combined analysis of the proton and deuteron data soon allowed for first extractions of the Sivers function for u- and d-quarks [14, 15, 16, 17], which turned out to be different from zero, with similar strength and opposite sign, a most important result in TMD physics.

In the standard Amsterdam notation the Sivers asymmetry can be written as

$$A_{Siv}(x, z) = \frac{\sum_q e_q^2 x f_{1T}^{\perp q}(x) \otimes D_1^q(z)}{\sum_q e_q^2 x f_1^q(x) \cdot D_1^q(z)} \quad (1)$$

where x is the Bjorken variable, z is the fraction of the available energy carried by the hadron, and \otimes indicates a convolution over the transverse momenta of the Sivers function f_{1T}^{\perp} and of the fragmentation function D_1 . In all those analyses, due to the presence of the convolution, some functional form had to be assumed for the transverse momentum dependence of the quark distribution functions and of the fragmentation functions. In most of the analyses these functions were assumed to be Gaussian. In this case the Sivers asymmetry becomes

$$A_{Siv,G}(x, z) = a_G \frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) \cdot D_1^q(z)}{\sum_q e_q^2 x f_1^q(x) \cdot D_1^q(z)}. \quad (2)$$

where

$$f_{1T}^{\perp(1)}(x) = \int d^2 \vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp}(x, k_T^2) \quad (3)$$

and $a_G = \sqrt{\pi} M / \sqrt{\langle k_T^2 \rangle_S + \langle p_{\perp}^2 \rangle / z^2}$ and \vec{p}_{\perp} the transverse momentum of the hadron with respect to the quark direction. The procedure allows to evaluate from the measured Sivers asymmetries the first moment of the Sivers function $f_{1T}^{\perp(1)}$, and not the Sivers function itself.

Already twenty years ago an alternative method was proposed [18, 19, 20] to determine $f_{1T}^{\perp(1)}$ without making any assumption on the functional form neither of the distribution functions nor of the fragmentation functions. The method consists in measuring asymmetries weighted by the measured transverse momentum of the hadron P_T^h as described in the next Section. For some reasons the method was not pursued: the only results (still preliminary) came from HERMES [21]. Recently, much interest has been dedicated again to the weighted asymmetries (see, e.g. [22]). In this contribution the first COMPASS results [23, 24] on the weighted Sivers asymmetries from the data collected in 2010 with the transversely polarised proton target are presented.

5. $P_T^h/(zM)$ weighted Sivers asymmetries

To extract the weighted asymmetries, only the spin-dependent part of the cross-section has to be weighted, leaving unweighted the unpolarised cross-section. In this section the weighting is done with $P_T/(zM)$, where M is the nucleon mass. After some algebra one gets the simple result that in the numerator of eq. (1) the convolution becomes the product of the first transverse moment of the Sivers function and the fragmentation function D_1 , so that the weighted Sivers asymmetry is

$$A_{Siv}^w(x, z) = 2 \frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) D_1^q(z)}{\sum_q e_q^2 x f_1^q(x) D_1^q(z)}. \quad (4)$$

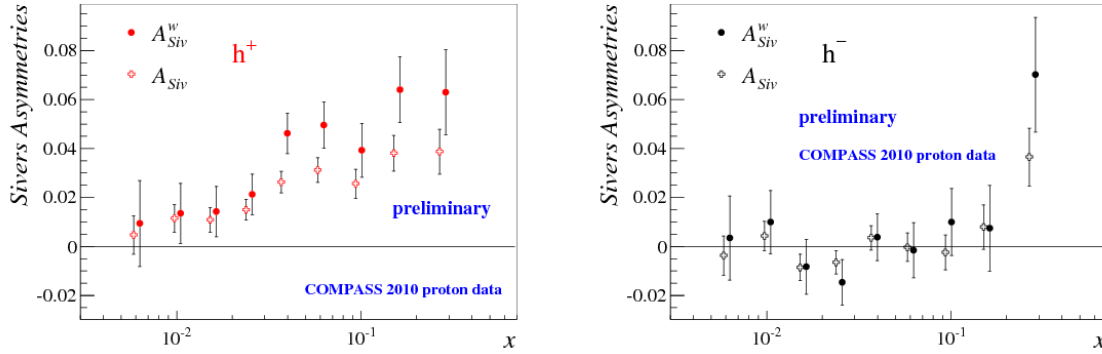


Figure 2. Full points: A_{Siv}^w in the nine x bins for positive (left panel) and negative (right panel) hadrons. The open crosses are the standard Siviers asymmetries A_{Siv} from Ref. [5].

Assuming u-dominance for positive hadrons produced on a proton target, the fragmentation function cancels out and the asymmetry simply becomes

$$A_{Siv}^w(x, z) \simeq 2 \frac{f_{1T}^{\perp(1)u}(x)}{f_1^u(x)}. \quad (5)$$

Since the comparison with the standard Siviers asymmetry is also important, the data production and all the cuts to select the muons and the hadrons are the same as for the published data [5]. In particular, the selected phase space is defined by $0.004 < x < 0.7$, $Q^2 > 1 \text{ GeV}^2/c^2$, $0.1 < y < 0.9$, $W > 5 \text{ GeV}/c^2$, $P_T > 0.1 \text{ GeV}/c$, and $z > 0.2$.

As shown in [24], the distributions of the weight factor $P_T/(zM)$ in the different x bins are very similar. Also, the P_T/z acceptance of the spectrometer is about 60% and rather flat. The results in the case of positive hadrons are given in Fig. 2 left, while Fig. 2 right gives the results for negative hadrons. In both cases the standard Siviers asymmetries published in [5] are also plotted for comparison. As expected, the trend of the asymmetries is similar both for positive and negative hadrons. Assuming u-dominance, the results for positive hadrons which are clearly different from zero in particular at large x , where $\langle Q^2 \rangle$ reaches $\sim 20 \text{ GeV}^2/c^2$, constitute the first direct measurement of $f_{1T}^{\perp(1)u}(x)/f_1^u(x)$.

Given the similar trend of the weighted asymmetries A_{Siv}^w and of the standard asymmetries A_{Siv} , we have evaluated in each x bin their ratios $R^w = A_{Siv}^w/A_{Siv}$. The values of R^w are given in Fig. 3 for positive hadrons, which exhibit a large Siviers asymmetry. In spite of the large statistical uncertainties the ratios are compatible with a constant value, which is rather well determined (1.6 ± 0.1). Also, the values in the different x bins agree rather well with those of $\langle P_T/(zM) \rangle$, as expected.

In Fig. 4 the weighted Siviers asymmetries measured in our "standard" z -range ($z > 0.2$) are compared with the corresponding ones in the range $0.1 < z < 0.2$. It is interesting to see that the positive hadron asymmetries are basically unchanged, hinting again at u-dominance, and supporting the idea that factorisation works also at small z in the COMPASS kinematical range. The negative hadron asymmetries receive contributions from both the u- and the d- quark, and become larger and similar to the positive hadron asymmetries. It is of interest to look at A_{Siv}^w as a function of z , after integration over x . The results in the range $0.1 < z < 1$ are shown in Fig. 5. For positive hadrons the values look constant, within the statistical uncertainties, as expected in the case of u dominance.

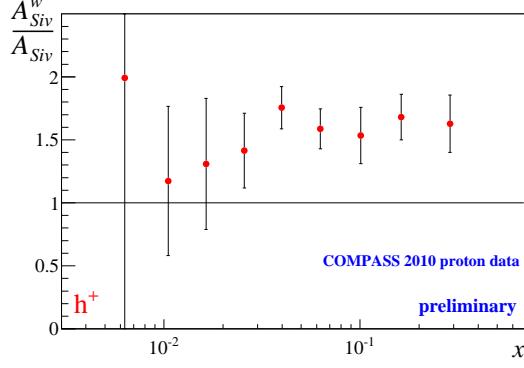


Figure 3. The ratios R^w between A_{Siv}^w and A_{Siv} in the nine x -bins for positive hadrons.

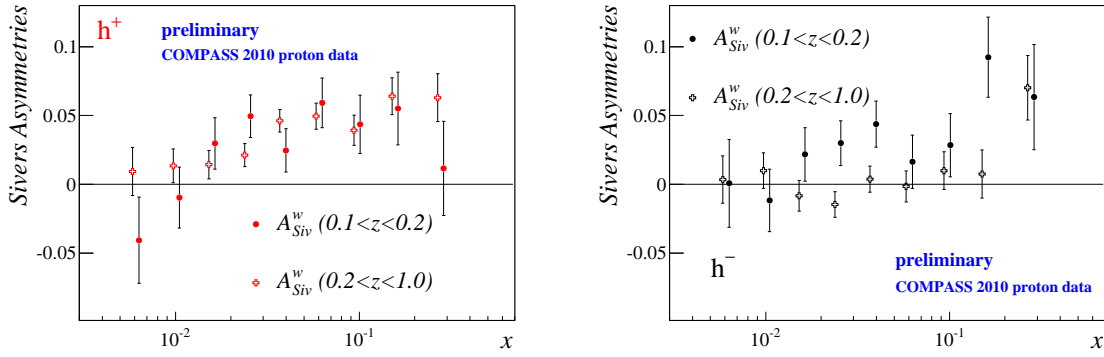


Figure 4. Comparison of the weighted asymmetries vs. x measured in our "standard" z range ($z > 0.2$) and the corresponding ones in the range ($0.1 < z < 0.2$) for positive (left) and negative (right) hadrons.

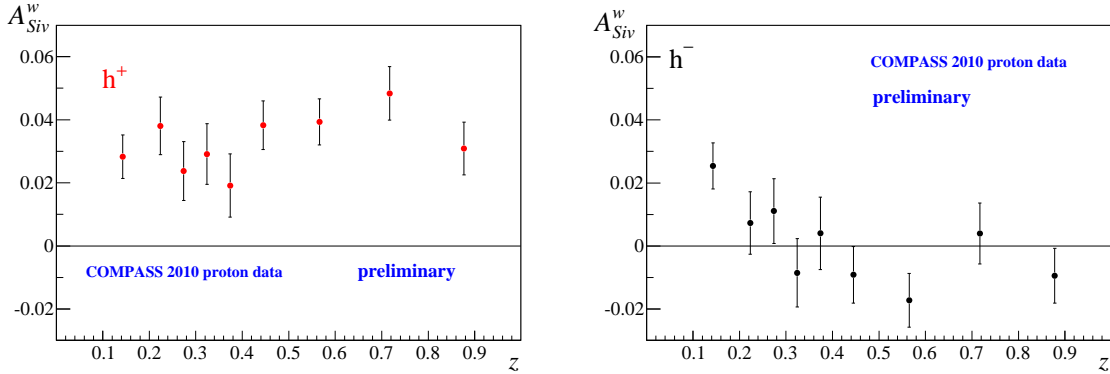


Figure 5. Weighted Sivers asymmetries vs z for positive (left) and negative (right) hadrons.

6. P_T^h/M weighted Sivers asymmetries

These weighted asymmetries are of interest because their values should exhibit a z dependence close to that of the Sivers asymmetries in the Gaussian model. Using as weight $w' = P_T^h/M$, eq.

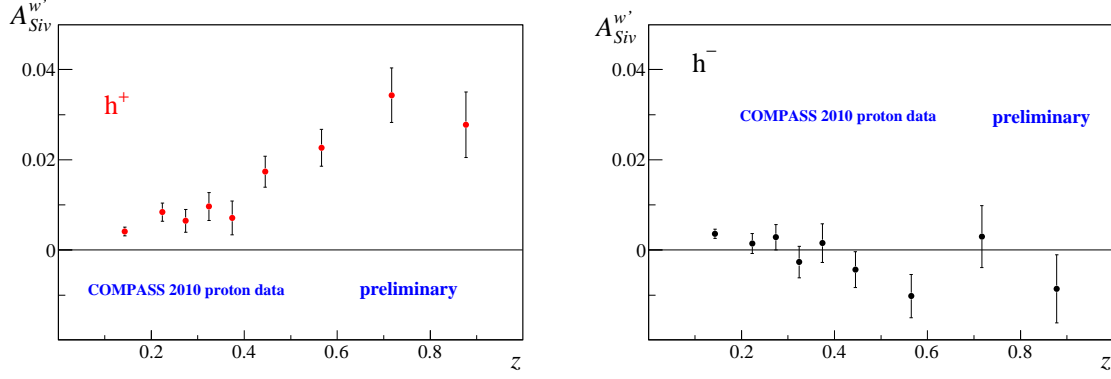


Figure 6. P_T^h/M weighted Siverts asymmetries vs z for positive (left) and negative (right) hadrons.

(4) becomes

$$A_{Siv}^{w'}(x, z) = 2 \frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) z D_1^q(z)}{\sum_q e_q^2 x f_1^q(x) D_1^q(z)} \quad (6)$$

By assuming that the mean value $\langle P_T^h \rangle$ is independent on z in the measured range and that the slopes of the Siverts and the unpolarised PDFs are the same, one gets $a_G \simeq \pi M z / 2 \langle P_T^h \rangle$ [25] and thus the Siverts asymmetry with the Gaussian ansatz in eq.(2) can be written as

$$A_{Siv,G}(x, z) = \frac{\pi M}{2 \langle P_T^h \rangle} \frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) z D_1^q(z)}{\sum_q e_q^2 x f_1^q(x) D_1^q(z)}, \quad (7)$$

which is similar to the expression $A_{Siv}^{w'}(x, z)$ given in eq. (6). In particular it is $R_G^{w'} = A_{Siv}^{w'} / A_{Siv,G} = 4 \langle P_T^h \rangle / \pi M \simeq 0.7$. The results for the x -integrated asymmetry $A_{Siv}^{w'}$ obtained using $w = P_T^h/M$ are shown in fig. 6 as a function of z for positive (left) and negative (right) hadrons. The values for positive hadrons are in qualitative agreement with the expectation:

$$A_{Siv}^{w'}(z) = 2z \frac{\int_{\Omega_x} dx C(x) x f_{1T}^{\perp(1)u}(x)}{\int_{\Omega_x} dx C(x) x f_1^u(x)} \quad (8)$$

7. Λ polarisation

The measurement of the transverse polarisation of Λ hyperons produced in SIDIS off transversely polarised nucleons has always been indicated as a promising channel to access transversity [26]. The basic idea is that, if transversity is different from zero, the polarisation of the fragmenting quark is transferred to the Λ according to the transversely polarised fragmentation function $H_1^{\Lambda/q}$, so that the Λ is polarised. Now we know that both the u- and the d- quark transversity are different from zero, so it is possible to check whether there is any transfer of polarisation from them to the lambda, and obtain information on $H_1^{\Lambda/q}$. Summing over all quark species, we get:

$$\vec{P}_\Lambda = \frac{\sum_q e_q^2 h_1^q(x) H_1^{\Lambda/q}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{\Lambda/q}(z)} D_{NN} R \vec{P}_N \quad (9)$$

where R is the rotation about the normal to the scattering plane which brings the initial proton momentum along the Λ momentum [27]. Λ hyperons are a natural choice to investigate such transversity transmitted polarisation: their weak decay channel $\Lambda \rightarrow p\pi^-$ is in fact self-analysing, that is, the polarisation is revealed through the angular asymmetry of the decay proton:

$$\frac{dN}{d\cos\theta} \propto 1 + \alpha P_\Lambda \cos\theta \quad (10)$$

where α is the Λ weak decay parameter and θ is the angle between the proton momentum and the polarisation vector, assumed to be coincident with that of the outgoing quark.

Studies of Λ transversity transmitted polarisation were already carried out in COMPASS using 2002-2004 deuteron data and 2007 proton data, but the results have never been published. Now the analysis has been resumed and extended to the proton data collected in 2010. Since some aspects of the analysis are new, the 2007 data have also been re-analysed and results are presented here for the whole set of proton data. The $\bar{\Lambda}$ polarisation has also been extracted from the complete proton data set.

In Fig. 7 both the Armenteros-Podolanski plots and the mass distribution for Λ candidates from 2010 data are shown after all cuts. The results for the polarisation are given in Fig 8 as a function of x . All the values are compatible with zero.

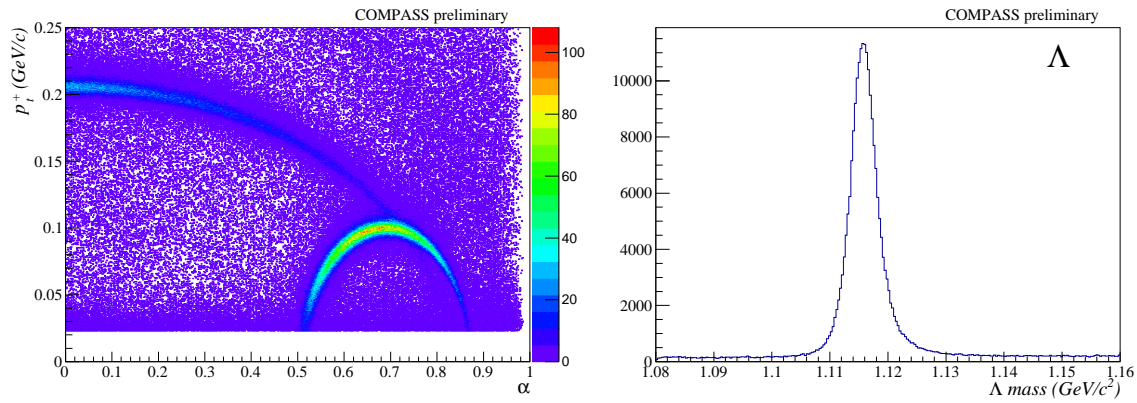


Figure 7. Armenteros plot after all but mass cuts and invariant mass spectrum for Λ candidates.

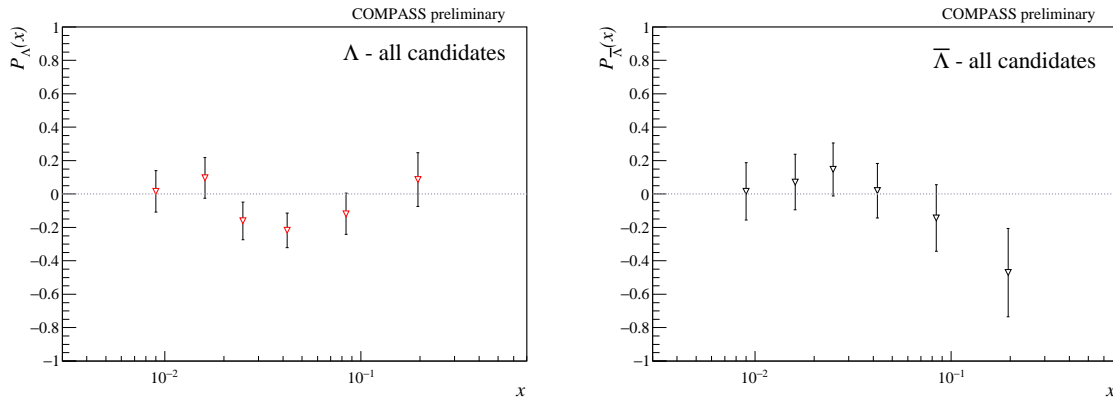


Figure 8. Polarisations for all Λ (left) and $\bar{\Lambda}$ (right) candidates as function of x .

8. Future SIDIS measurements

The Collaboration has submitted to the CERN SPS Committee a proposal for an extension of the present COMPASS-II experimental programme to perform in the years 2021 and 2022 two new measurements, muon SIDIS on a transversely polarised deuteron target and elastic muon proton scattering [28]. The first program is the missing piece in the COMPASS data sets on transverse target spin orientations. While in 2010 a good statistics sample of SIDIS data on transversely polarised proton target was collected, in the years 2002, 2003 and 2004, due to the late delivery of the new polarised target magnet and to the shortness of the periods of data taking, we provided only a marginal (albeit unique) data set for the isoscalar deuteron target. With one additional year of deuteron target data taking accurate flavor separation for the new PDFs will be possible, improving in particular our knowledge of the d-quark distribution functions. The second measurement hopefully will provide a decisive contribution to the solution of the so-called proton radius puzzle.

References

- [1] Contributions of Y. Bedfer, of A. Ivanov, of B. Marianski, of A. Sandacz, of M. Pesek, of J. Matousek, and of N. Mitrofanov to this workshop
- [2] Airapetian A *et al.* (HERMES) 2005 *Phys. Rev. Lett.* **94** 012002 (*Preprint hep-ex/0408013*)
- [3] Airapetian A *et al.* (HERMES) 2009 *Phys. Rev. Lett.* **103** 152002 (*Preprint 0906.3918*)
- [4] Adolph C *et al.* (COMPASS) 2012 *Phys. Lett.* **B717** 376–382 (*Preprint 1205.5121*)
- [5] Adolph C *et al.* (COMPASS) 2012 *Phys. Lett.* **B717** 383–389 (*Preprint 1205.5122*)
- [6] Adolph C *et al.* (COMPASS) 2014 *Phys. Lett.* **B736** 124–131 (*Preprint 1401.7873*)
- [7] Sivers D W 1990 *Phys. Rev.* **D41** 83
- [8] Collins J C 1993 *Nucl. Phys.* **B396** 161–182 (*Preprint hep-ph/9208213*)
- [9] Alexakhin V Yu *et al.* (COMPASS) 2005 *Phys. Rev. Lett.* **94** 202002 (*Preprint hep-ex/0503002*)
- [10] Ageev E S *et al.* (COMPASS) 2007 *Nucl. Phys.* **B765** 31–70 (*Preprint hep-ex/0610068*)
- [11] Adolph C *et al.* (COMPASS) 2016 *Phys. Lett.* **B753** 406–411 (*Preprint 1507.07593*)
- [12] Artru X 2002 *10th Rhodanien Seminar: The Spin in Physics Turin, Italy, March 3-8, 2002* (*Preprint hep-ph/0207309*)
- [13] Alekseev M G *et al.* (COMPASS) 2010 *Phys. Lett.* **B692** 240–246 (*Preprint 1005.5609*)
- [14] Efremov A V, Goeke K and Schweitzer P 2003 *Phys. Lett.* **B568** 63–72 (*Preprint hep-ph/0303062*)
- [15] Vogelsang W and Yuan F 2005 *Phys. Rev.* **D72** 054028 (*Preprint hep-ph/0507266*)
- [16] Collins J C, Efremov A V, Goeke K, Menzel S, Metz A and Schweitzer P 2006 *Phys. Rev.* **D73** 014021 (*Preprint hep-ph/0509076*)
- [17] Anselmino M, Boglione M and Melis S 2012 *Phys. Rev.* **D86** 014028 (*Preprint 1204.1239*)
- [18] Kotzinian A M and Mulders P J 1996 *Phys. Rev.* **D54** 1229–1232 (*Preprint hep-ph/9511420*)
- [19] Kotzinian A M and Mulders P J 1997 *Phys. Lett.* **B406** 373–380 (*Preprint hep-ph/9701330*)
- [20] Boer D and Mulders P J 1998 *Phys. Rev.* **D57** 5780–5786 (*Preprint hep-ph/9711485*)
- [21] Gregor I M (HERMES) 2005 *Acta Phys. Polon.* **B36** 209–215
- [22] Kang Z B, Vitev I and Xing H 2013 *Phys. Rev.* **D87** 034024 (*Preprint 1212.1221*)
- [23] Sbrizzai G (COMPASS) *QCD-N 4rd Workshop on the QCD Structure of the Nucleon, Getxo, Bilbao, Spain, 11-15 July, 2016.*
- [24] Bradamante F (COMPASS) 2017 *22nd International Symposium on Spin Physics (SPIN 2016) Urbana, IL, USA, September 25-30, 2016* (*Preprint 1702.00621*)
- [25] Martin A, Bradamante F and Barone V 2017 *Phys. Rev.* **D95** 094024 (*Preprint 1701.08283*)
- [26] Artru X and Mekhfi M 1991 *Nucl. Phys.* **A532** 351–358
- [27] Artru X 1993 *QCD and high-energy hadronic interactions. Proceedings, Hadronic Session of the 28th Rencontres de Moriond, Moriond Particle Physics Meeting, Les Arcs, France, March 20-27, 1993* pp 47–52
- [28] The COMPASS Collaboration, Addendum to the COMPASS-II Proposal, CERN-SPSC-2017-034 ; SPSC-P-340-ADD-1. October 2, 2017.