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Transversity and Λ polarization in semi-inclusive DIS

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Several possible experimental channels have been proposed in the past to access the chiral-odd transversity distribution functions h_1. Among these, the measurements of target-transverse-spin asymmetries in single-hadron and hadron-pair production in Semi-Inclusive Deep Inelastic Scattering (SIDIS) gave clear evidence that transversity is measurable and sizable in the valence region. A third, independent channel is the measurement of the polarization of Λ hyperons produced in SIDIS off transversely polarized nucleons, where the transverse polarization of the struck quark might be transferred to the final-state hyperon. The COMPASS Collaboration at CERN has measured the transversity-induced polarization of Λ and $\bar{\Lambda}$ hyperons produced in SIDIS off transversely polarized protons, found compatible with zero. The results are shown here and discussed in the context of different models and approximations.

Keywords: Transversity; quantum-chromodynamics; lambda hyperon; SIDIS; COMPASS.

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1. Introduction

Soon after the introduction of the chiral-odd transversity quark distribution functions h_1 as an independent Parton Distribution Function (PDFs) of the nucleon, several decades ago [1–4], a variety of experimental approaches have been proposed to access it in Semi-Inclusive Deep Inelastic Scattering (SIDIS) off transversely polarized nucleons.

Convincing evidence that transversity is accessible and sizable came from the measurements of Collins asymmetries [5–8] and of azimuthal asymmetries of hadron pairs produced on transversely polarized protons [9–11]. For u- and d-quarks, transversity was found different from zero in the valence region, where h_1^u and h_1^d are almost of the same size but opposite in sign [12–16].

A third, independent experimental channel is the measurement of the polarization of baryons produced in the SIDIS process $\ell p^\uparrow \rightarrow \ell B^\uparrow X$, where ℓ denotes a lepton, $p^\uparrow$ a transversely polarized target proton and B a baryon [2, 17–19]. In the one-photon-exchange approximation, the elementary interaction is $\gamma^* q^\uparrow \rightarrow q'^\uparrow$, where $q'^\uparrow$ then fragments into the baryon B, to which it may transfer a fraction of the initial transverse polarization. Thus, a measurement of the polarization of the final-state baryon B allows accessing transversity [20, 21]. Due to their self-analysing decay, $\Lambda(\bar{\Lambda})$ hyperons are the most suited to polarimetry studies. Their polarization $P_{\Lambda(\bar{\Lambda})}$ can be accessed by inspecting the angular distribution of the protons (antiprotons) produced in their weak decay $\Lambda \rightarrow p\pi^-$ ($\bar{\Lambda} \rightarrow \bar{p}\pi^+$), which can be written as:

$$\frac{\mathrm{d}N_{p(\bar{p})}}{\mathrm{d}\cos\theta} \propto 1 + \alpha_{\Lambda(\bar{\Lambda})} P_{\Lambda(\bar{\Lambda})} \cos\theta, \qquad (1)$$

where θ is the proton (antiproton) emission angle with respect to the polarization axis of the fragmenting quark in the $\Lambda(\bar{\Lambda})$ rest frame and $\alpha_{\Lambda(\bar{\Lambda})}$ is the weak decay constant [22]. The polarization axis has been chosen as the direction S'_T of the outgoing quark, as in QED calculations for γ^* absorption [21, 23]. For the $\Lambda(\bar{\Lambda})$ hyperons produced in the current fragmentation region, the leading-order expression for the transversity-induced polarization reads [20]:

$$P_{\Lambda(\bar{\Lambda})}(x, z, Q^2) = \frac{\mathrm{d}\sigma^{\ell p^\uparrow \rightarrow \ell' \Lambda(\bar{\Lambda})^\uparrow X} - \mathrm{d}\sigma^{\ell p^\uparrow \rightarrow \ell' \Lambda(\bar{\Lambda})^\downarrow X}}{\mathrm{d}\sigma^{\ell p^\uparrow \rightarrow \ell' \Lambda(\bar{\Lambda})^\uparrow X} + \mathrm{d}\sigma^{\ell p^\uparrow \rightarrow \ell' \Lambda(\bar{\Lambda})^\downarrow X}} = f P_T D_{NN} \frac{\sum_q e_q^2 h_1^q(x, Q^2) H_{1,q}^{\Lambda(\bar{\Lambda})}(z, Q^2)}{\sum_q e_q^2 f_1^q(x, Q^2) D_{1,q}^{\Lambda(\bar{\Lambda})}(z, Q^2)}. \qquad (2)$$

Here, x is the Bjorken variable, Q^2 the photon virtuality and z the fraction of the virtual photon energy carried by the $\Lambda(\bar{\Lambda})$ hyperon in the target rest frame; P_T is the target polarization, f the target dilution factor (representing the fraction of nucleons effectively polarized in the target) and the virtual-photon depolarization factor $D_{NN} = 2(1-y)/(1+(1-y)^2)$ depends on y, the fraction of the initial lepton energy carried by the virtual photon in the target rest frame. The summations in Eq. (2) are meant to run over all quark and antiquark flavors. The transversity distribution functions $h_1^q(x, Q^2)$ appear coupled to the chiral-odd fragmentation functions $H_{1,q}^{\Lambda(\bar{\Lambda})}(z, Q^2)$ that describe the spin transfer from the struck quark to the $\Lambda(\bar{\Lambda})$ hyperon. At the denominator, h_1^q and $H_{1,q}^{\Lambda(\bar{\Lambda})}(z, Q^2)$ are replaced by their unpolarized counterparts f_1^q and $D_{1,q}^{\Lambda(\bar{\Lambda})}$.

The expression in Eq. (2) is valid at leading twist. Higher-order terms [24], among which is the one related to the spontaneous polarization [25], have not been taken into account, as their contribution is expected to average to zero. Clearly, a measurement of the $P_{\Lambda(\bar{\Lambda})}$ gives access to transversity only if $H_{1,q}^{\Lambda(\bar{\Lambda})}(z, Q^2) \neq 0$. Alternatively, $P_{\Lambda(\bar{\Lambda})}$ can be used to shed light on the size of the transverse-spin-dependent quark fragmentation function using the known information on transversity.

2. Data selection and available statistics

The data considered for the work presented here have been collected by COMPASS [26] in 2007 and 2010, with a 160 GeV/c muon beam from the CERN SPS and a transversely polarized NH_3 target with average polarization $\langle P_T \rangle = 0.80$ and dilution factor $\langle f \rangle = 0.15$.

In order to ensure the DIS regime, the events have been selected by requiring $Q^2 > 1$ (GeV/c)^2. The region of exclusive resonance production has been avoided by requiring the invariant mass of the final state produced in the γ^*-nucleon interaction to be $W > 5$ GeV/c^2. In addition, the constraints $0.003 < x < 0.700$ and $0.1 < y < 0.9$ have been applied: the upper limit in x to avoid a region of low statistics, and the lower and upper limits in y to guarantee a good event resolution and to limit the impact of radiative effects respectively.

The selected events have also been required to have an interaction vertex inside the fiducial target volume, the Λ and $\bar{\Lambda}$ reconstruction being based on the detection of their decay products originating from a decay vertex downstream of the interaction vertex, not connected to the latter by any charged track. A collinearity angle $\theta_{\text{coll}} \leq 7$ mrad between the reconstructed hyperon line of flight and the vector linking interaction and decay vertex has been required. The background from photon conversion $\gamma \to e^+e^-$ has been suppressed by setting a lower limit on the transverse momentum $p_\perp$ of each hadron ($p_\perp < 23$ MeV/c), calculated with respect to the line-of-flight of the hadron pair in the hyperon rest frame.

The particle identification has been performed using the RICH (Ring Imaging CHerenkov [27]) detector, used as a veto: assuming one of the two decay tracks as negative (positive) pion, the corresponding positive (negative) one has been considered to be a proton (antiproton) unless identified as a positive (negative) electron, pion or Kaon. The Armenteros-Podolanski plot [28, 29] obtained after all the aforementioned cuts is given in Fig. 1. It shows the transverse momentum of the decay particles in the hyperon rest frame $p_\perp$ versus the asymmetry in their longitudinal momentum $(p_\parallel^+ - p_\parallel^-)/(p_\parallel^+ + p_\parallel^-)$. This last quantity allows separating $\bar{\Lambda}$ candidates (on the left half of the plot) from Λ events (on the right).

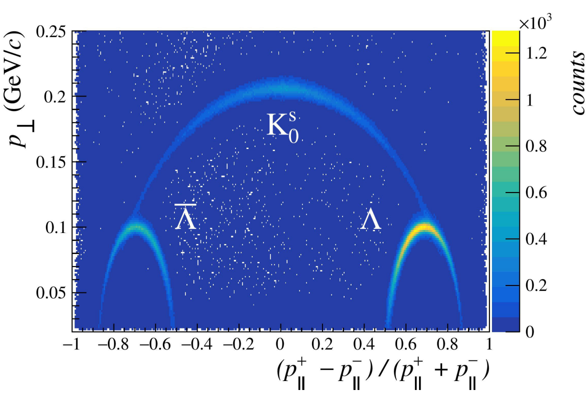

FIGURE 1. Armenteros-Podolanski plot.

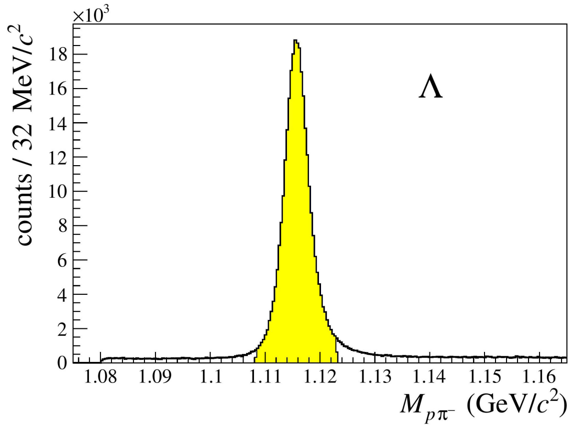

FIGURE 2. Invariant mass distribution of Λ hyperons after all selection steps.

In Fig. 2 the Λ invariant mass distribution is finally shown, the $\bar{\Lambda}$ case being almost identical in shape. The low, remaining background has been evaluated with the sideband method, considering two equally wide intervals on the left and on the right of the mass peak. As a last step, the hyperons have been selected within $3\,\sigma$ from the peak, where $\sigma = 2.45$ MeV/c^2 is the width of the Gaussian function fitted to the mass distribution (in yellow in the Figure).

The final hyperon sample was constituted of almost 300 000 Λ and 150 000 $\bar{\Lambda}$ hyperons, a significant fraction of which are expected to originate from the strong decay of heavier hyperons. Using the event generator LEPTO based on the Lund string model [30], tuned to reproduce the experimental distributions, 37% of the Λ and 32% of the $\bar{\Lambda}$ hyperons in the COMPASS kinematic regime have been estimated to be produced in a mechanism different from the direct string fragmentation [31]. Such indirect contribution, not considered here as a source of systematic uncertainty, could dilute the polarization signal.

3. Polarization extraction and results

The transversity-induced $P_{\Lambda(\bar{\Lambda})}$ polarization has been measured along the spin direction of the fragmenting quark. For each event, the initial quark spin has been assumed aligned with the nucleon spin and thus vertical in the laboratory frame. After the interaction with the virtual photon γ^*, the quark spin direction, characterized by an azimuthal angle in the γ^*-nucleon system ϕ_S, has been reflected with respect to the normal to the lepton scattering plane, thus obtaining a reference axis along $\phi_{S'} = \pi - \phi_S$.

The unique three-cells configuration of the COMPASS target and the division of the data-taking into periods, each consisting of two sub-periods in which the polarization orientation in each target cell is reversed, allow for a minimization of systematic effects. The numbers $\mathcal{N}_i^{(')}$ of $\Lambda(\bar{\Lambda})$ hyperons emitting a proton (antiproton) in a given $\cos\theta$ range with a given target cell orientation i ($i = 1, 2$) in a given sub-period have been combined to form the double ratio,

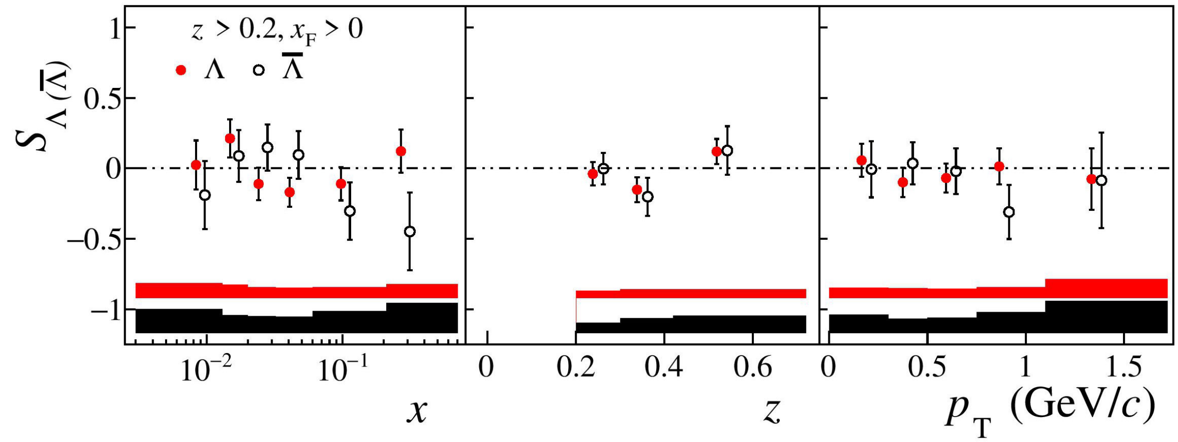

FIGURE 3. Spin transfer $S_{\Lambda(\bar{\Lambda})}$ for the current fragmentation region as a function of x, z and p_T . The bands show the systematic uncertainties, while the error bars represent statistical uncertainties. The values in x, z and p_T are staggered for clarity.

$$\varepsilon_{\Lambda(\bar{\Lambda})}(\cos\theta) = \frac{\mathcal{N}_{\Lambda(\bar{\Lambda}),1}(\cos\theta)\mathcal{N}'_{\Lambda(\bar{\Lambda}),2}(\cos\theta)}{\mathcal{N}'_{\Lambda(\bar{\Lambda}),1}(\cos\theta)\mathcal{N}_{\Lambda(\bar{\Lambda}),2}(\cos\theta)}, \qquad (3)$$

where, as described in Refs. [32, 33], in addition to all constant factors, also flux and acceptance terms cancel out provided the flux is equalized in all three target cells and under the reasonable assumption that the acceptance ratios for the target cells after polarization reversal are equal to those before. For small values of the $P_{\Lambda(\bar{\Lambda})}$ Eq. (3) reduces to:

$$\varepsilon_{\Lambda(\bar{\Lambda})}(\cos\theta) \approx 1 + 4\alpha_{\Lambda(\bar{\Lambda})}P_{\Lambda(\bar{\Lambda})}\cos\theta. \qquad (4)$$

In each kinematic bin in x, z or p_T (the hyperon transverse momentum with respect to the virtual photon), the data sample has been divided into eight $\cos\theta$ bins, from which $P_{\Lambda(\bar{\Lambda})}$ could be obtained with a linear fit. This procedure has been applied to the whole accessible phase-space and to several kinematic regions: current and target fragmentation regions, high and low x, high and low p_T. In particular, the current fragmentation region has been selected by requiring $z \geq 0.2$ and Feynman variable $x_F > 0$, and the target fragmentation regions as its complementary to the full phase-space. In the collinear approximation, no dependence on p_T is expected.

The presence of possible systematic biases has been investigated in all the aforementioned regions. Two sources of non-negligible systematic uncertainties have been found to be period compatibility and false polarizations. The former have been evaluated by comparing the results from the various periods; the latter by arranging the terms in Eq. (3) in such a way that $P_{\Lambda(\bar{\Lambda})}$-related terms cancel. A scale uncertainty of about 7.5% contributes to the overall systematics due to the uncertainty on the weak decay constant α and on the dilution and polarization factors f and P_T. In general, $\sigma_{\text{syst}} < 0.85\,\sigma_{\text{stat}}$.

In Fig. 3, the results for the current fragmentation region are presented in terms of the spin transfer

$$S_{\Lambda(\bar{\Lambda})} = \frac{P_{\Lambda(\bar{\Lambda})}}{f P_T D_{NN}} = \frac{\sum_q e_q^2 h_1^q H_{1,q}^{\Lambda(\bar{\Lambda})}}{\sum_q e_q^2 f_1^q D_{1,q}^{\Lambda(\bar{\Lambda})}}, \qquad (5)$$

by definition ranging from -1 to 1. The measured values of $S_{\Lambda(\bar{\Lambda})}$ have been found compatible with zero within the experimental uncertainties in all studied kinematic regions, in agreement with a recent measurement of the transverse spin transfer D_{TT} in polarized Drell-Yan [34]. The mean value of Q^2 in the current fragmentation region is $\langle Q^2\rangle \approx$ 4.1 (GeV/c)^2.

4. Interpretation

Some conclusions can be drawn from these results. Considering the case of $\bar{\Lambda}$ hyperons polarization, transversity appears coupled only to unfavoured fragmentation functions:

$$\sum_q e_q^2 h_1^q H_{1,q}^{\bar{\Lambda}} \propto 4h_1^u H_{1,u}^{\bar{\Lambda}} + h_1^d H_{1,d}^{\bar{\Lambda}}. \qquad (6)$$

Thus, the compatibility with zero of the measured polarization for $\bar{\Lambda}$ hyperons is in agreement with the expectations of small values for the unfavoured fragmentation functions [35], compared to the favoured cases. In the case of Λ hyperons, retaining only the favoured combinations in both numerator and denominator in Eq. (5) results in:

$$S_\Lambda = \frac{4h_1^u H_{1,u}^\Lambda + h_1^d H_{1,d}^\Lambda + h_1^s H_{1,s}^\Lambda}{4f_1^u D_{1,u}^\Lambda + f_1^d D_{1,d}^\Lambda + f_1^s D_{1,s}^\Lambda}. \qquad (7)$$

By isospin symmetry, $D_{1,d}^\Lambda = D_{1,u}^\Lambda$ and $H_{1,d}^\Lambda = H_{1,u}^\Lambda$. As for the s-quark fragmentation functions, $D_{1,s}^\Lambda$ can be assumed proportional to $D_{1,u}^\Lambda$ with a proportionality constant r [36, 37]. In Ref. [38] it is found that $1/r = 0.44$. With these simplifications, Eq. (7) turns into:

$$S_\Lambda = \frac{\left[4h_1^u + h_1^d\right] H_{1,u}^\Lambda + h_1^s H_{1,s}^\Lambda}{\left[4f_1^u + f_1^d + rf_1^s\right] D_{1,u}^\Lambda}. \qquad (8)$$

The following interpretation is based on three different scenarios. When needed, the CTEQ5D PDFs [39] have been used for f_1^q, while the values of h_1^u and h_1^d have been obtained from the fit presented in Ref. [12].

4.1. Transversity non-vanishing only for valence quarks in the nucleon

If transversity is assumed non-vanishing only for valence quarks, h_1^s can be safely neglected and the expression for the spin transfer to the Λ further simplifies to:

$$S_\Lambda = \frac{[4h_1^u + h_1^d]H_{1,u}^\Lambda}{[4f_1^u + f_1^d + rf_1^s]D_{1,u}^\Lambda}. \qquad (9)$$

Thus, the measurement of S_Λ as a function of x can be used to extract the ratio $\mathcal{R}$ of the z-integrated fragmentation functions $H_{1,u}^\Lambda$ and $D_{1,u}^\Lambda$:

$$\mathcal{R}(x) = \frac{4f_1^u(x) + f_1^d(x) + rf_1^s(x)}{4h_1^u(x) + h_1^d(x)} S_\Lambda(x), \qquad (10)$$

the mean value of which, $\langle\mathcal{R}\rangle = -0.27 \pm 0.56$, shows a weak dependence on r.

4.2. Λ polarization carried by the s quark only

If instead the polarization is entirely carried by the s quark, as in the SU(3) non-relativistic quark model, $H_{1,u}^\Lambda$ can be neglected, yielding:

$$S_\Lambda = \frac{h_1^s\, H_{1,s}^\Lambda}{\left[4f_1^u + f_1^d + rf_1^s\right] \frac{1}{r} D_{1,s}^\Lambda} \approx \frac{r\, h_1^s}{4f_1^u + f_1^d + rf_1^s}, \qquad (11)$$

where $H_{1,s}^\Lambda$ has been substituted with $D_{1,s}^\Lambda$: a reasonable approximation for $z > 0.2$ [40]. The s-quark transversity h_1^s can thus be extracted: in Fig. 4 the quantity $xh_1^s(x)$ is given for various choices of r and compared to the fitted value and accuracy of the $xh_1^u(x)$ distribution [12]. Again, only a weak dependence on r is observed. The data slightly favour a negative sign of $h_1^s(x)$, but they are not precise enough to accurately determine $h_1^s(x)$.

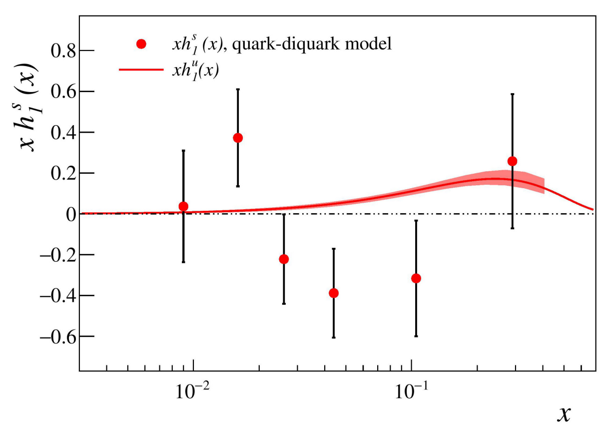

FIGURE 4. Extracted values of $xh_1^s(x)$ for the three options $r = 2, 3, 4$. The u quark transversity curve from Ref. [12] is given for comparison. Only statistical uncertainties are shown and the x values are staggered for clarity.

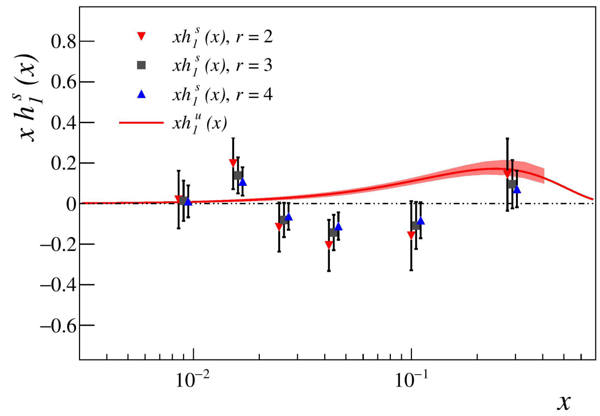

FIGURE 5. Extracted values of $xh_1^s(x)$ according to a quark-diquark model [40, 41]. The u quark transversity curve from Ref. [12] is given for comparison. Only statistical uncertainties are shown.

4.3. Polarized Λ production described by a quark-diquark fragmentation model

In the context of the quark-diquark model [40, 41], the fragmentation of a valence quark into a final-state hadron is accompanied by the emission of a diquark D, which can be in a scalar (S) or vector (V) spin configuration. The probabilities associated to these two configurations, for either unpolarized and polarized quarks, are calculated in the model and enter the definition of the quark fragmentation function, which are modelled by introducing the flavour structure ratios $F_D^{(u/s)}(z)$ and the spin-structure ratios $\hat{W}_D^q(z)$. The transversity-induced polarization can thus be written as:

$$S_\Lambda = \frac{\left(h_1^u + \frac{1}{4}h_1^d\right)\left(\hat{W}_S^{(u)} F_S^{(u/s)} - \hat{W}_V^{(u)} F_M^{(u/s)}\right) + h_1^s \hat{W}_S^{(s)}}{\left(f_1^u + \frac{1}{4}f_1^d\right)\left(F_S^{(u/s)} + 3F_M^{(u/s)}\right) + f_1^s}, \qquad (12)$$

where the x and z dependences have been omitted for clarity. Information on h_1^s can be obtained by integrating Eq. (12) over z in each x bin. The values of $xh_1^s(x)$, as predicted by the quark-diquark model and based on the measured polarization, are shown in Fig. 5. The dependence of the final results on the mass of the diquark (containing or not the s quark) has been found negligible. Once again, the data suggest a negative sign of $h_1^s(x)$, but statistical uncertainties are even larger in this case.

5. Summary and perspectives

The transversity-induced Λ and $\bar{\Lambda}$ polarization has been measured at COMPASS along the spin axis of the struck quark: the results are compatible with zero in all the considered kinematic regions. The statistical uncertainty affecting the results is large; nevertheless, some information could be deduced. Under the hypothesis that transversity is non-vanishing only for valence quarks, the data have been used to investigate the ratio of z-integrated polarized to unpolarized fragmentation functions. If instead a non-relativistic SU(3) quark model or a quark-diquark model is considered, some information can be derived on the transversity distribution for the s quark. In both cases, there is a slight indication for a negative s-quark transversity h_1^s. The results expected from the upcoming COMPASS run in 2022, when SIDIS data will be collected with a transversely polarized deuteron target, will be of great importance in further improving our knowledge on transversity.

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