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Transverse Λ and $\overline{\Lambda}$ polarization with a transversely polarized proton target at COMPASS

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Abstract. The transverse Λ and $\overline{\Lambda}$ polarizations have been studied in deep-inelastic scattering at the COMPASS experiment. New data on the hyperon polarization in semi-inclusive deep inelastic scattering have been collected by the COMPASS collaboration at CERN in 2007, using a beam of 160 GeV/c polarized μ^+ scattering off a NH_3 target that is transversely polarized. We present the preliminary results on the transverse Λ and $\overline{\Lambda}$ polarization as a function of x_{Bj} and z. Λ and $\overline{\Lambda}$ are within the errors unpolarized and have no dependence on x_{Bj} as well as z.

1 Introduction

The transversely polarized quark distributions $\Delta_T q(x)$, being chiral-odd objects and also called transversity distribution functions, in the nucleon and the transversely polarized fragmentation function $\Delta_T D_q^{\Lambda}(z)$ are the interesting topics of modern high energy physics. Recently many efforts have been made to access these distributions. The transversity distribution functions are accessible in Semi-Inclusive Deep Inelastic lepton-nucleon Scattering (SIDIS) or in hadron-hadron collisions. Promising channels for the measurement of the transversity distributions in SIDIS are the Collins effect by measuring the azimuthal asymmetries in single hadron production [1] and the azimuthal asymmetries in two hadrons production [2]. Another channel suggested to measure transversity distribution functions [3–6] is the measurement of the transverse polarization of Λ hyperons produced in SIDIS on a transversely polarized target with respect to the direction of beam momentum. When a lepton interacts with one of the valence quarks of a transversely polarized nucleon, the scattered quark leaves the nucleon in a polarization state that is determined by its transverse spin distribution function inside the nucleon. The outgoing quark has a certain probability to fragment into a Λ hyperon and to transfer part of its polarization in this process. Therefore, a measurement of the transverse Λ polarization, being the spin correlation between the transversely polarized quark and the Λ , can provide useful information about these unknown functions.

The COMPASS experiment offers an excellent opportunity to measure the transverse Λ and $\overline{\Lambda}$ polarization in the reaction $\mu N^{\uparrow} \rightarrow \mu' \Lambda^{\uparrow} X$, using the 160 GeV muon beam and a polarized deuteron or proton target. If the struck quark fragments into a Λ hyperon in this reaction, the corresponding polarization is given by [7]

$$P_{\Lambda}(x,y,z) = \frac{d\sigma^{lN^{\uparrow}\rightarrow l'\Lambda^{\uparrow}X} - d\sigma^{lN^{\uparrow}\rightarrow l'\Lambda^{\downarrow}X}}{d\sigma^{lN^{\uparrow}\rightarrow l'\Lambda^{\uparrow}X} + d\sigma^{lN^{\uparrow}\rightarrow l'\Lambda^{\downarrow}X}} = f P_T D_{NN}(y) \frac{\sum_q e_q^2\, \Delta_T q(x) \Delta_T D_q^{\Lambda}(z)}{\sum_q e_q^2\, q(x) D_q^{\Lambda}(z)}, \quad (1)$$

where the T-axis is the polarization vector of the initial struck quark, P_T and f are the target polarization and dilution factor, respectively. The quark polarization is reduced by the so-called virtual photon depolarization factor, originating from the lepton-photon QED vertex and given

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by $D_{NN}(y) = 2(1-y)/(1+(1-y)^2)$, where y is the fraction of the incoming lepton energy carried by the exchanged virtual photon. The transversity distribution $\Delta_T q(x)$ appears coupled to the chiral-odd transversity fragmentation functions $\Delta_T D_q^{\Lambda}(z)$, which are so far completely unknown. In the hypothesis that part of the quark spin is transferred to the final state hadron in the fragmentation process (i.e., $\Delta_T D_q^{\Lambda}(z) \neq 0$), then the measurement of the transverse Λ polarization allows either to access the transversity distributions by modeling $\Delta_T D_q^{\Lambda}(z)$, or to obtain separate information on $\Delta_T q(x)$ and $\Delta_T D_q^{\Lambda}(z)$ by studying the x_{Bj} and z dependence of transverse Λ polarization [6].

2 Extraction of the polarization

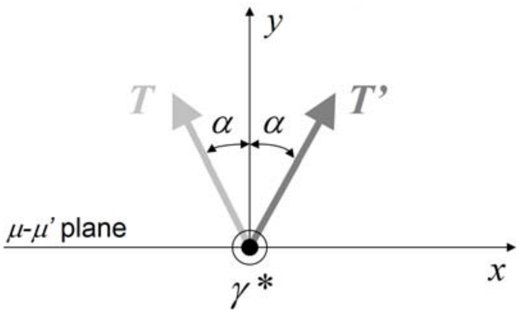

Fig. 1. Definition of the reference frame: The initial and final quark transverse spin-polarization vector is defined by T and T' in the $\mu - \mu'$ scattering plane. The γ^* moves along the positive z-axis. T and T' is symmetric with respect to the y'-axis [8].

To determine the Λ polarization, the reference axis T' is defined by using the target polarization T along the transverse direction of the virtual photon momentum and the $\mu - \mu'$ scattering plane [8]. The schematic diagram of the reference system in Λ production is given in Fig. 1. The transverse polarization is measured along the direction obtained by reflecting the target polarization axis with respect to the normal to the lepton scattering plane.

As this direction is completely uncorrelated with the normal to the production plane $\hat{n} = \gamma^* \times \Lambda$, no contribution of the spontaneous polarization is expected. All directions of defined axes are unaffected by Lorentz transformation. Finally, the Λ polarization P_T^{Λ} with respect to analyzer T' reveals itself in it's angular distribution of the parity violating weak decay in the Λ rest frame. The spin observable is then given by

$$\frac{dN}{d\cos\theta_{T'}} = \frac{N}{2}(1 + \alpha P_T^{\Lambda} \cos\theta_{T'}), \tag{2}$$

where N is the total number of produced Λ hyperon, $\theta_{T'}$ is the decay angle of proton with respect to the defined polarization axis T', $\alpha = \pm\ 0.642 \pm 0.013$ is the analyzing power of the parity violating Λ and $\overline{\Lambda}$ decay. The number of hyperons in each cos$\theta_{T'}$ bins are determined by fitting the invariant mass distributions. In general, the transverse polarization P_T^{Λ} cannot be directly extracted from the experimental data due to the distortion by the apparatus acceptance. However, this distortion can be corrected by exploiting the symmetries of the apparatus. The technique is based on the combination of two data taking periods in the same experimental conditions, but with opposite polarized target cells, so that the acceptance terms are canceled out in the raw asymmetry and only the term proportional to the pure Λ polarization remains. The polarization P_T^{Λ} was extracted from the acceptance corrected counting rate asymmetry $\epsilon_T(\theta_{T'})$ by combining the cos$\theta_{T'}$ bins with two target spin orientations and two periods. It can be readily shown that the geometric symmetry of target polarization leads to the relation [9]

$$\epsilon_T(\theta_{T'}) = \alpha P_T^{\Lambda} \cos\theta_{T'} \tag{3}$$

and the Λ polarization can be extracted from the slope of the $\epsilon_T(\theta_{T'})$ distribution. If only two bins in the angle distributions of decay proton are considered due to limited statistics, this formula can be simplified to $\epsilon_T(\theta_{T'}) = 2\alpha P_T^{\Lambda}$.

3 Event Selection

The analysis is based on the data sample recorded during the 2007 run with transversely polarized proton target by the COMPASS experiment at CERN. For a detailed description of the COMPASS apparatus, as well as a complete list of references, can be found in Ref. [10]. The events are selected by requiring of an incoming μ, a scattered $\mu^{'}$, a position of primary vertex in the NH_3 target material, together with at least two hadron tracks forming a secondary vertex. The decay vertex has a V^0 shape, and the decay particles are bent into opposite directions by the spectrometer magnets. The kinematic cuts $Q^2 > 1$ (GeV/c)^2 and $0.1 < y < 0.9$ have been applied in order to select the DIS events. The reconstructed position of the primary interaction vertex must be within the geometrical volume occupied by the target material. To ensure an equal beam flux in the target cells, the extrapolated beam trajectory must not intersect the cylindrical surfaces of the target volumes in target. The sources of background in the sample come from K^0 decays, photon conversion, and fake vertices from combinatorial track associations. However, the background is reduced when a cut on the collinearity angle between the reconstructed Λ momentum and the direction from the primary to the decay vertex is applied. The angle between the two vectors must be smaller than 10 mrad. If the distance of the Λ decay vertex to the primary vertex is not large enough, Λ particles cannot be properly reconstructed. Therefore, we select Λ with a decay length 7 times larger than the error of the decay length.

Fig. 2 shows the Armenteros-Podolanski plot of the all V^0 decays. The transverse momentum p_T of one of decay particles relative to the V^0 momentum is plotted versus the asymmetry of longitudinal momenta of both decay particles. The contamination of e^+e^- pairs from photon conversions is significantly reduced by requiring a minimal transverse momentum $p_T \geq 23$ MeV/c of the decay particle with respect to the reconstructed V^0 momentum. The Λ and $\overline{\Lambda}$ are visible on a non-vanishing background decay. As the Λ hyperons are reconstructed from their

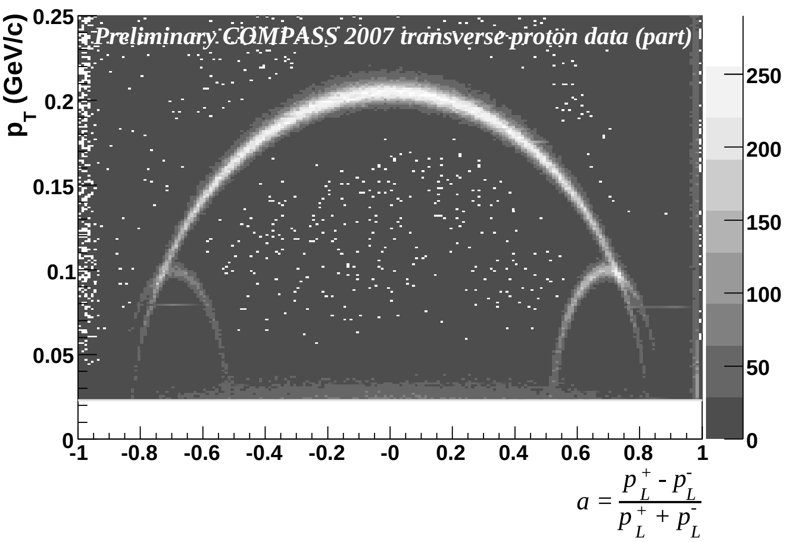

Fig. 2. Armenteros-Podolanski plot of the V^0 sample before application of RICH cut in the COMPASS 2007 transverse proton data.

charged decay $\Lambda \to p\pi^-$ ($\overline{\Lambda} \to \bar{p}\pi^+$), Λ and $\overline{\Lambda}$ are distributed oppositely in a. The $K^0 \to \pi^+\pi^-$ contribute mainly to the background.

Finally, the information from the RICH detector is further employed to reduce the remaining background. Due to the high momentum threshold of the RICH, a selection of the proton is limiting the statistics too much to be applied in this analysis. Thus, the Λ selection relies purely on rejection of non-protons. The RICH is used to reject $e^+(e^-)$, $\pi^+(\pi^-)$, and $K^+(K^-)$ particles from the proton (anti-proton) candidates in the Λ ($\overline{\Lambda}$) decay. The non-proton rejection using the RICH detector is based on a likelihood method. In the Fig. 3 the invariant mass distribution of Λ and $\overline{\Lambda}$ are shown after applying the RICH cuts. In addition, the Armenteros-Podolanski plots with corresponding Λ and $\overline{\Lambda}$ are shown in the right panel, separately. The K^0 decay is clearly reduced at the region of overlap where Λ and K^0 cannot be distinguished kinematically. The ratio of the signal to background is significantly improved by a factor 5 with applying the RICH and the number of Λ is maintained without losing signal. Therefore statistical errors are reduced by applying RICH when the transverse Λ polarizations are extracted. The invariant mass distributions, that are subtracted by reference value of particle data group, are fitted with a Gaussian peak superimposed to a 3rd degree polynomial background parameterization in the final event sample used for the polarization calculation. The overall number of detected Λ decays in the sample used in the presented analysis, corresponding to the 50% of transversely polarized proton data collected in the year of 2007, is about 28,000 for Λ and 14,000 for $\overline{\Lambda}$. The measurement of transverse Λ and $\overline{\Lambda}$ polarization is only valid in the case that the Λ originates from the scattered quark i.e., current fragmentation region. The mean value of the z variable is $< z > = 0.28$, indicating that most of the events in the sample belong to the so-called current fragmentation region. Here, the reconstructed Λ sample contains also a fraction of Λs originating from the fragmentation of the target remnants. Nevertheless, the small acceptance of the COMPASS spectrometer for events at $x_F < 0$ and $z < 0.05$ naturally suppresses the contamination of Λ produced in the target fragmentation. The measured $< x_{Bj} >$ is about 0.04, indicating that the

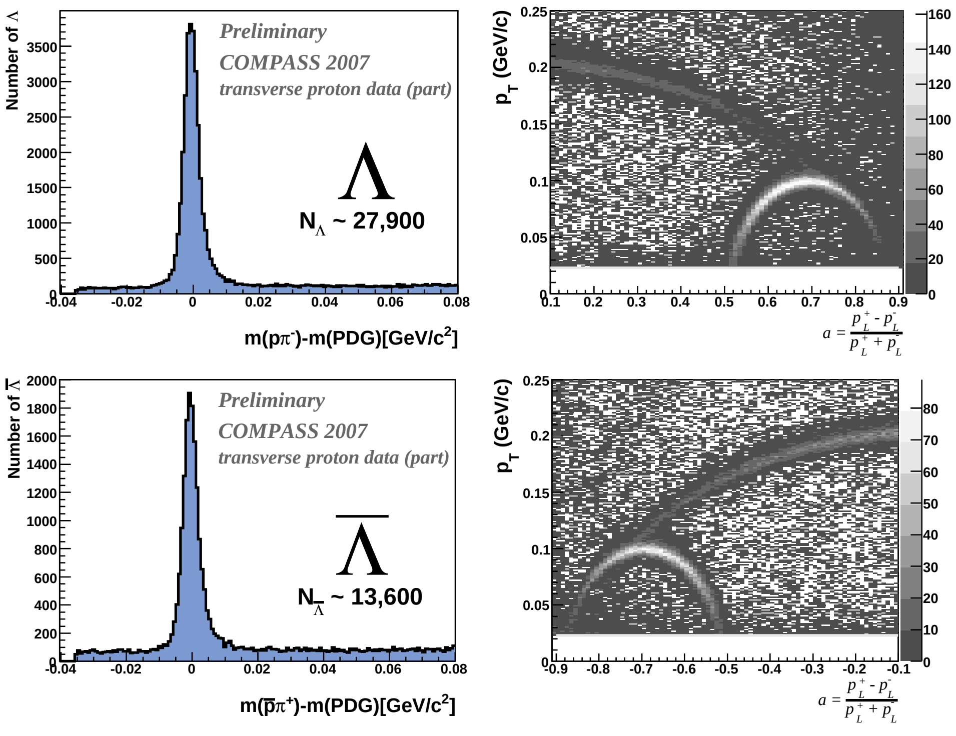

Fig. 3. Invariant Mass distribution and corresponding Armenteros-Podolanski plots for Λ and $\overline{\Lambda}$ after applying RICH cuts.

Λ production is dominated by the sea quark. The multiplicative factors appearing on the right side of Eq. 1 contribute to reduce the polarization that is measured experimentally. In the case of COMPASS 2007 run, the average target polarization is about 85% and the dilution factor is about 0.17. The factor $D_{NN}(y)$ depends on the scattering muon kinematics, the average value of y in the event sample used in this analysis is $< y > = 0.44$, giving a mean depolarization factor of $< D_{NN}(y) > = 0.85$. That means that the experimentally measurable polarization is not significantly reduced by the acceptance of COMPASS spectrometer. For $\overline{\Lambda}$ the mean values of kinematic variables are similar to the ones of Λ, indicating that the acceptances for Λ and $\overline{\Lambda}$ hyperons are practically the same.

4 Result

The statistics available in the present sample allowed not only to extract the overall transverse polarization, but also to investigate its dependence on x_{Bj} as well as on z. The measured P_T^{Λ} as a function of x_{Bj} and z is shown in Fig. 4. The x_{Bj} and z dependence is studied by subdividing the sample into bins in x_{Bj} and z, independently. Here 5 subsamples were chosen with the statistics in the bins roughly equal. The distributions show no significant deviation from zero for both hyperons in the whole explored x_{Bj} and z range. Thus, no dependence on x_{Bj} or z is observed. The shaded bands give the size of the corresponding systematic errors. The systematic errors are mainly due to the uncertainty of the subtraction method, the variation of selection cuts, and the influence of the target spin orientation and target geometry. To estimate the systematic uncertainties, the compatibility with statistical fluctuations of the measured points in the sample has been tested by looking at the pulls distribution. The upper limit of systematic errors is estimated in the unit of the statistical error. The observed systematic error is below 60% of the statistical one for Λ and 40% for $\overline{\Lambda}$. In addition the K^0s, being spinless and having a similar decay topology as the Λ and $\overline{\Lambda}$, are used to verify that the polarization analysis is free of biases. It was found that the polarization of kaons are close to zero with and without applying RICH cuts in the same kinematic range. The results for K^0 polarization gives a confidence, that possible apparatus effects are quite small and the acceptance correction is working properly.

5 Discussion

The transverse Λ and $\overline{\Lambda}$ polarization measured by COMPASS in the $\mu p^{\uparrow} \to \mu' \Lambda^{\uparrow} X$ reaction are compatible with 0. Λ and $\overline{\Lambda}$ have neither dependence of the transverse polarization on x_{Bj} nor z. That means that the production mechanism of $\overline{\Lambda}$ is similar to Λ in all the accessible x_{Bj} and z ranges. The Λ and $\overline{\Lambda}$ polarization observed in the SIDIS production data might therefore indicate that the transversity distributions are absent for the Λ and $\overline{\Lambda}$ production in the presented kinematic range. Recent parameterizations of the transversity distribution functions with experimental data from Belle, HERMES, and COMPASS predicts opposite transversity distribution for u and d quark [11]. Since u quarks dominate in the proton, one may expect the transverse Λ polarization should be differ from the Λ production with a transversely polarized deuteron target. COMPASS already measured the transverse Λ and $\overline{\Lambda}$ polarizations with a transversely polarized deuteron target in the DIS region [12]. Taking into account the limited statistics the transverse Λ and $\overline{\Lambda}$ polarizations exhibited the behavior very similar to that of the presented proton data. Thus, the naive expectation of transverse Λ and $\overline{\Lambda}$ polarization seems to be not suitable to explain the present data. One of reasons is that the COMPASS data cover only a x_{Bj} range upto 0.1. The data at $x_{Bj} > 0.1$, where the transversity distribution function is expected to be different, still needs improvement in statistics. Another important feature of the transverse Λ and $\overline{\Lambda}$ polarization is the coupling of the transversity to $\Delta_T D_q^{\Lambda}(z)$. If the $\Delta_T D_q^{\Lambda}(z)$ is too small, it may lead to small polarization although the transversity is a considerable quantity. In this case, there is no analyzing power to access the transversity. Anselmino *et al* [13] proposed a phenomenological approach to calculate the transverse Λ polarization with

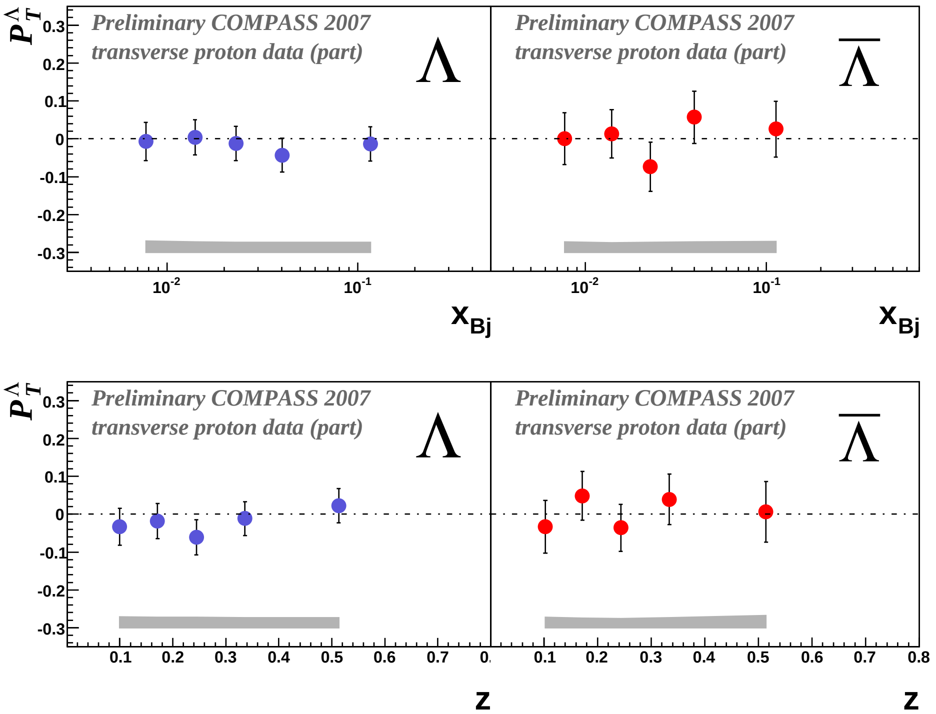

Fig. 4. Transverse Λ and $\overline{\Lambda}$ polarizations as a function of x_{Bj} and z for $Q^2 > 1$ (GeV/c)^2 in the 2007 transverse proton data. The lower band shows the upper limit of the systematic error.

numerical parameterization of the $\Delta_T D_q^\Lambda(z)$. The calculation showed that the transverse Λ and $\overline{\Lambda}$ polarizations are increased when z is increased. A non-zero polarization is expected at $z > 0.4$. Due to the limited statistic the interesting x_{Bj} and z region is currently not accessible, therefore no conclusion can be drawn on the transverse Λ and $\overline{\Lambda}$ polarizations yet. However, we have already accumulated a factor of 2 more data during 2007 run. The analysis of the full 2007 data sample will allow to extend the x_{Bj} and z range and further obtain novel information about $\Delta_T q(x)$ and $\Delta_T D_q^\Lambda(z)$.

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