

Measurement of polarization observables of the associated strangeness production in proton proton interactions

The COSY-TOF Collaboration

F. Hauenstein^{1,4}, E. Borodina¹, H. Clement^{5,6}, E. Doroshkevich^{5,6a}, R. Dzhygadlo^{1b}, K. Ehrhardt^{5,6}, W. Eyrich⁴, W. Gast¹, A. Gillitzer¹, D. Grzonka¹, S. Jowzaee^{1,7}, P. Klaja^{1,4}, L. Kober⁴, K. Kilian¹, M. Krapp⁴, M. Mertens^{1c}, P. Moskal⁷, J. Ritman^{1,2,8}, E. Roderburg^{1d}, M. Röder^{1e}, W. Schroeder⁹, T. Sefzick¹, J. Smyrski⁷, P. Wintz¹, and P. Wüstner³

¹ Institut für Kernphysik, Forschungszentrum Jülich, 52428 Jülich, Germany

² Jülich Aachen Research Alliance, Forces and Matter Experiments (JARA-FAME)

³ Zentralinstitut für Engineering, Elektronik und Analytik, 52428 Jülich, Germany

⁴ Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

⁵ Physikalisches Institut der Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

⁶ Kepler Center for Astro and Particle Physics, University of Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

⁷ Institute of Physics, Jagellonian University, PL-30-348 Cracow, Poland

⁸ Experimentalphysik I, Ruhr-Universität Bochum, 44780 Bochum, Germany

⁹ Corporate Development, Forschungszentrum Jülich, 52428 Jülich, Germany

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Abstract. The Λ polarization, the analyzing power, and the Λ spin transfer coefficient of the reaction $pp \rightarrow pK^+\Lambda$ were measured at beam momenta of 2.70 GeV/c and 2.95 GeV/c corresponding to excess energies of 122 MeV and 204 MeV. While the analyzing power and the spin transfer coefficient do not change significantly with the excess energy, the Λ polarization varies strongly and changes its sign. As this is the first measurement of polarization observables below an excess energy of 200 MeV, the change of the sign of the Λ polarization was not observed before. The high statistics of the data (≈ 200 k events for each momentum) enables detailed studies of the dependence of the Λ polarization and the analyzing power on the center of mass momentum of the particles. The results of the spin transfer coefficient are in qualitative agreement with the DISTO experiment. The Λ polarization data of 2.95 GeV/c are only conform with the DISTO experiment, while both the 2.70 GeV/c and 2.95 GeV/c data differ strongly from all previous measurements, whether exclusive or inclusive.

1 Introduction

In this paper the results concerning the polarization observables of recent COSY-TOF measurements of $pp \rightarrow pK^+\Lambda$ are presented. Angular distributions, Dalitz plots, and invariant masses were discussed in a previous paper [1]. Due to the nearly 4π acceptance of the COSY-TOF detector for this reaction it is possible to measure the Λ polarization, the analyzing power determined with the final state particles, and the Λ spin transfer coefficient for

the whole kinematic range. For measurements of the analyzing power and the spin transfer coefficient the experiment made use of the polarized extracted proton beam from the COSY accelerator, with polarization up to 90%

Since the first observation that Λ 's exhibit a polarization, even being produced with an unpolarized beam [2], many experiments examined the dependence of this polarization on different kinematic variables. These experiments were performed with high beam momenta. No consistent behavior of the Λ polarization emerged from these measurements. Closer to threshold only inclusive data from HADES ($p_b = 4.34$ GeV/c) [3] and exclusive data from DISTO ($p_b = 3.67$ GeV/c) [4] exist. The COSY-TOF data discussed in this paper are the first to give information of the Λ polarization as close as $\epsilon = 122$ MeV above threshold. They exhibit a strong dependence of the Λ polarization on the excess energy, which was not observed before.

^a current address: Institute for Nuclear Research Moscow 117312, Russia

^b current address: Hadron Physics I, GSI Helmholtzzentrum für Schwerionenforschung GmbH

^c current address: Universität Duisburg-Essen 45141 Essen, Germany

^d corresponding author e.roderburg@fz-juelich.de

^e current address: Corporate Development, Forschungszentrum Jülich, 52428 Jülich, Germany

The analyzing power measured with the final state particles provides information on the angular momenta involved in the process in addition to the information that can be gained from the angular distributions. The measured distributions should help to determine parameters of a partial wave analysis, which is in preparation [5]. As most of the previous measurements were inclusive and high acceptance is needed for measurements of the analyzing power, the existing data are very scarce and partly still preliminary. As the COSY-TOF data cover the full accessible phase space, they can be described with Legendre polynomials. The dependence of the Legendre coefficients on the particle momenta is examined.

The measurement of the spin transfer coefficient combines information on the Λ polarization with the analyzing power by an event to event analysis. Apart from three measurements at high momenta, which were restricted in the kinematic range [6,7,8], the only exclusive measurements were published by the DISTO experiment [9]. The COSY-TOF data allow for the first time a comparison of this observable between independent measurements.

2 Experimental setup and analysis

The data were taken with the COSY-TOF spectrometer, which was situated at an external beam of the accelerator COSY/Jülich. The COSY-TOF detector is a non mag-

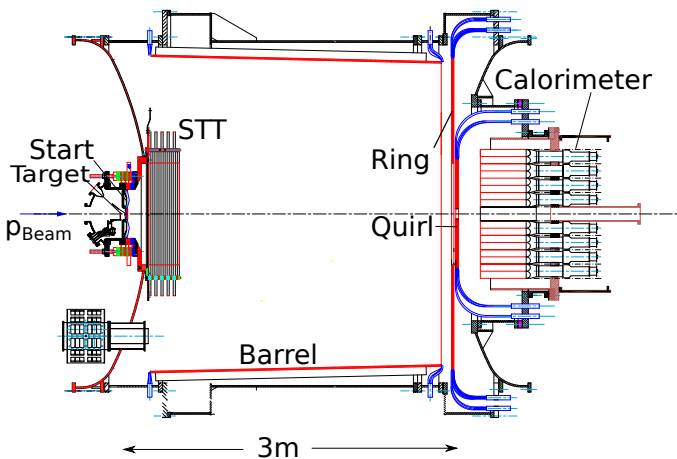


Fig. 1. Side view of the COSY-TOF spectrometer. In beam direction the start counter (Start), the straw tube tracker (STT) the barrel scintillators, the inner ring (Quirl), the outer ring (Ring) and the Calorimeter are shown. All detectors and the liquid hydrogen target are located inside the vacuum vessel.

netic spectrometer built as a cylindrical vacuum vessel, with 3.5 m length and 3 m diameter (see fig.1). The inner walls are covered with segmented scintillation counters, which are used for trigger signal generation. The main components are the miniaturized liquid hydrogen target in cylinder form with 6 mm diameter and 4 mm length

and the straw tube tracker, from which precise information of the vertices and track directions are obtained. The detector is described in detail in [1].

The analysis of the $pK^+\Lambda$ final state examines events which are triggered by four or more hits in the scintillator hodoscopes. These events are fitted by a two vertices hypothesis: a primary vertex of pK^+ and a secondary vertex of the Λ decay. Events for which this fit converges are submitted to a kinematic fit procedure, which applies momentum and energy conservation and the masses of the involved particles. The assignment of the proton and kaon masses to the primary tracks is done by applying the kinematic fit for each possibility, and the result with the lowest χ^2 is chosen [10,11]. For the definition of a $pK\Lambda$ event the following criteria are applied: The χ^2/NDF of the kinematic fit has to be less than 5, the decay length in the rest system of the Λ has to be larger than 2 cm and the angle of the decay proton to the Λ direction has to be larger than 2.5° .

The background introduced by multi-pion events is determined to be less than 5% by comparing the measured Λ decay length distribution to the expected distribution [1]. Special care has to be taken for the admixture of Λ 's from $pp \rightarrow pK(\Sigma^0 \rightarrow \gamma\Lambda)$, which dilutes the measured Λ polarization and introduces unknown errors to the spin transfer coefficient and to the analyzing power. The suppression of the Σ^0 events by the χ^2 threshold for the kinematic fit is studied with a Monte Carlo sample of $pK(\Sigma^0 \rightarrow \gamma\Lambda)$ events. Including the cross section ratios, the contamination of Σ^0 events is less than 5% for the 2.95 GeV/c data [1] and less than 1% for the 2.70 GeV/c data [10]. From the Monte Carlo simulations it is known that the $pp \rightarrow pK(\Sigma^0 \rightarrow \gamma\Lambda)$ events are shifted by the kinematic fit, which assumes a $pp \rightarrow pK\Lambda$ reaction, to backward kaon directions. Therefore, the 2.95 GeV/c data are analyzed in addition with a selection on the kaon angle of $|\cos\theta_K^{\text{cm}}| < 0.9$ and compared with the results without this restriction. Apart from statistical fluctuations, no differences are found in the distributions of all polarization observables.

In order to determine the beam polarization, a sample of elastic scattering events is recorded by a trigger which requires at least two charged tracks. With cuts on the coplanarity and on the missing energy elastic scattered events are determined with a background of less than 1% [10]. By evaluating the left-right asymmetry of the elastic scattered protons and by comparing this distribution with the analyzing power determined with the partial wave analysis SAID [12] the averaged transverse beam polarization is determined. For the 2.70 GeV/c data it is $(79.0 \pm 1.1)\%$ [10]. The 2.95 GeV/c data were acquired in two different runs, the first with 54,000 events had a polarization of $(61.0 \pm 1.7)\%$ [13] and the second with 121,000 events had a polarization of $(87.5 \pm 2.0)\%$ [11]. Both runs are analyzed together by assuming a weighted mean beam polarization of $(79.3 \pm 2.0)\%$. For the data taking the direction of the beam polarization was changed by switching the polarization in the H^- ion source [14] with every spill, which has a typical length of 100 s.

The systematic errors due to instrumental asymmetries are studied by comparing the results of the observables obtained by different methods: in case of the Λ polarization these are the integral method, which is applied in this analysis (see eq. 2), and the weighted sum method, which is described in [15]. In case of the analyzing power these are the double difference method (eq. 9 of reference [16]), and the method described in eq. 6. The comparison of both methods indicates that the deviations are within the range of their statistical error. Therefore, we assume that the systematic errors are less than or equal to the statistical errors. For the spin transfer measurement we assume the same systematic error due to instrumental asymmetries as in the former observables. The effect of admixtures of $pK(\Sigma^0 \rightarrow \gamma\Lambda)$ events is expected to introduce the same amount of systematic errors. With these assumptions the mean absolute systematic error for the Λ polarization is 0.04. For the measurement of the analyzing power and the spin transfer coefficient the uncertainty of the beam polarization has to be added to the systematic errors, the mean value of these systematic errors is 0.05 (absolute value).

3 Λ polarization P_N

3.1 Results

The Λ polarization is given by the equation:

$$I(\theta^*) = I_0 \cdot (1 + P_N \alpha \cos(\theta^*)) \quad (1)$$

θ^* is the angle between the direction of the decay proton (in the Λ rest frame) and the normal vector to the plane which is spanned by the beam proton and the Λ direction. α is the hyperon decay asymmetry parameter:

$$\alpha(\Lambda \rightarrow p\pi^-) = 0.642 \pm 0.013 \quad [17]$$

From eq. 1 the Λ polarization is calculated by applying the difference of the count rates with $\cos(\theta^*) > 0$ (N_A) and $\cos(\theta^*) < 0$ (N_B):

$$P_N = \frac{2 N_A - N_B}{\alpha N_A + N_B} \quad (2)$$

For the beam momentum of 2.70 GeV/c 227,000 events and for the beam momentum of 2.95 GeV/c 206,000 events are analyzed, including runs without beam polarization. The Λ polarization is shown in fig. 2 as a function of the scattering angle, of Feynman x_F ¹, and of the transverse momentum. The initial system consists of two identical particles², therefore, the Λ polarization has to change its sign between the backward Λ region and the forward Λ region:

¹ Feynman x_F is defined as the ratio of the longitudinal cm momentum to its maximum possible value

² this is exactly true only for an unpolarized beam, the polarization of the beam proton violates this symmetry. But the Λ polarization is evaluated by taking the average of the up and down polarization runs. The integrated luminosities with up and down polarization are almost the same.

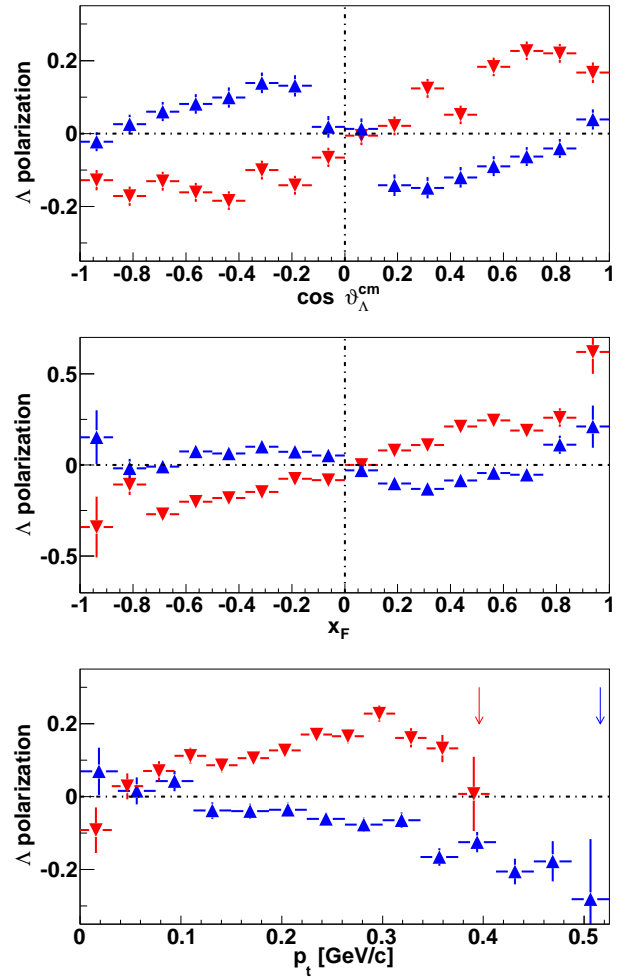


Fig. 2. The Λ polarization is shown for two beam momenta: 2.70 GeV/c (red triangles down) and 2.95 GeV/c (blue triangles up). Top: dependence on the Λ cm scattering angle. Middle: dependence on Feynman x_F . Bottom: dependence on the Λ transverse momentum. For each beam momentum the maximum of the transverse momentum is indicated with arrows in the upper part of the bottom panel.

$$P_{\Lambda}(\cos(\vartheta_{\Lambda}^{cm})) = -P_{\Lambda}(-\cos(\vartheta_{\Lambda}^{cm})) \quad (3)$$

$$P_{\Lambda}(x_F) = -P_{\Lambda}(-x_F) \quad (4)$$

As the evaluation of the dependence on the transverse momentum averages the Λ polarization of the forward and backward region of the Λ , the resulting polarization would be zero. Therefore, by evaluating the dependence on the transverse momenta, the sign of the polarization for events in the backward region is reversed. The same holds for the dependence on the invariant masses.

The measured Λ polarization is shown in fig. 2 as function of the three kinematic variables. In this and all following figures the error bars indicate the statistical errors. The striking feature of the data is the change of the sign of the polarization between the two beam momen-

tum settings, which is seen in all figures. In the Λ backward region the Λ polarization is negative for the beam momentum of 2.70 GeV/c and positive for the beam momentum of 2.95 GeV/c. In the forward range the signs are exchanged. This phenomenon has not been observed before. Both curves exhibit within their errors the expected point symmetry for $\cos\theta^{cm} = 0$ and $x_F = 0$. In addition to the difference in sign, the absolute values of the Λ polarization are significantly different between the two data sets.

As the variables Feynman x_F and transverse momentum are not independent, restricted efficiency in one of these variables will affect the value of the Λ polarization in the other variable. For the transverse Λ momentum the COSY-TOF efficiency (acceptance \cdot reconstruction efficiency) is nearly constant, the variation is less than $\pm 10\%$. For the Feynman x_F variable the acceptance drops in the range of $|x_F| > 0.8$ from 50% of the maximum acceptance to zero at $|x_F| = 1$. But the range of $|x_F| > 0.8$ corresponds to less than 2.8% of the total phase space volume. Therefore, the small fraction of events lying in this range can be neglected for the p_t distribution.

3.2 Comparison with existing data

In a first COSY-TOF publication [18] the Λ polarization was given as a function of the Λ transversal momentum. But here the change of sign between the Λ backward and forward region as given in equation 3 was not taken into account. Therefore, these values cannot be compared with the new results.

The full kinematic range of the Λ polarization can only be compared with measurements of DISTO and HADES, which covered a large fraction of the available phase space. The results of these measurements are shown together with the COSY-TOF results in fig. 3. The references are given in table 1. Apart from one data point at $x_F \sim 0.55$ the DISTO data³ agree with the COSY-TOF data of 2.95 GeV/c. In dependence on the transverse momentum the HADES data exhibit a negative Λ polarization similar to the 2.95 GeV/c COSY-TOF results.

As there are conjectures in the literature (see for instance [30]) that the Λ polarization may be independent of the beam momentum and target material, the COSY-TOF results are compared with measurements with beam momenta ranging from near threshold up to 1 TeV/c and with measurements on different target materials. These experiments cover only a small part of the available phase space. The range of x_F and p_t , for which the Λ polarization is specified, is plotted by lines in fig. 4. The labels of the different experiments in the legends of figs. 3, 4 are referenced in table 1.

Most of these measurements are inclusive, and thus the separation of directly produced Λ from $\Sigma^0 \rightarrow \gamma\Lambda$ decay is not possible. The first determination of the Σ^0 polarization [31] yields a value of $\approx 30\%$ with opposite sign

³ These data are quoted to be preliminary, they are scanned from fig. 8 of reference [4].

Table 1. Denotation of $pX \rightarrow \Lambda X$ measurements given in figs. 3,4. The reaction types and the proton beam momenta (for collider experiments the invariant masses) are given.

| | reference | reaction and beam momentum |
|---------------------|-----------|---|
| FNAL 1978 | [19] | $p+\text{Be} \rightarrow \Lambda+X$ 400.9 GeV/c |
| KEK 1986 | [20] | $p+\text{Be} (\text{Cu,W}) \rightarrow \Lambda+X$ 12.9 GeV/c |
| CERN ISR 1987 | [21] | $p+p \rightarrow \Lambda+X$ $\sqrt{s} = 3\text{--}61$ GeV |
| AGS 1988 13.5 GeV/c | [7] | $p+\text{Be} \rightarrow \Lambda+X$ 13.5 GeV/c |
| AGS 1988 18.5 GeV/c | [7] | $p+\text{Be} \rightarrow \Lambda+X$ 18.5 GeV/c |
| AGS 1996 | [22,23] | $p+p \rightarrow pK^+\Lambda N(\pi^+\pi^-)$ 27.5 GeV/c |
| FNAL 1989 | [24] | $p+\text{Be} (\text{Cu,Pb}) \rightarrow \Lambda+X$ 400.9 GeV/c |
| FNAL 1991 | [25] | $p+p \rightarrow pK^+\Lambda$ 800.9 GeV/c |
| FNAL 1994 | [26] | $p+\text{Be} \rightarrow \Lambda+X$ 800.9 GeV/c |
| DISTO 1998 | [4] | $p+p \rightarrow pK^+\Lambda$ 3.67 GeV/c |
| CERN NA48 1999 | [27] | $p+\text{Be} \rightarrow \Lambda+X$ $\sqrt{s} = 61$ GeV |
| HERA-B 2006 | [28] | $p+C(\text{W}) \rightarrow \Lambda+X$ 920.9 GeV/c |
| HADES 2014 | [3] | $p+\text{Nb} \rightarrow \Lambda+X$ 4.34 GeV/c |
| ATLAS 2015 | [29] | $p+p \rightarrow \Lambda+X$ $\sqrt{s} = 7$ TeV |

compared to the Λ polarization. Therefore, the inclusive measurements are expected to reveal a Λ polarization that is lower than the polarization of the directly produced Λ . The ratio of directly produced Λ to those from the Σ^0 decay is dependent on the beam momentum and may be dependent on the kinematical regions of the measurements. The first exclusive measurement of the Λ polarization of the reaction $pp \rightarrow pK^+\Lambda$ at CERN [32] yielded values up to 60%, which are significantly larger than the results obtained by the inclusive measurements. The high polarization values were confirmed by an exclusive measurement at FNAL [25].

In order to incorporate the restricted ranges of the measurements given in fig. 4, the results of COSY-TOF are recalculated for 4 ranges in x_F and compared with values of the literature that are inside these ranges (see fig. 5).

For each interval in x_F a linear fit is applied to the COSY-TOF data. The results are given in table 2. The slope of the 2.70 GeV/c data fit is positive for all x_F intervals and rises with x_F . The slope of the 2.95 GeV/c data fit is negative and within the errors the same in the first three x_F intervals. For the extreme Λ forward and backward range ($|x_F| > 0.7$) it is compatible with zero. No systematic agreement with the data from the literature

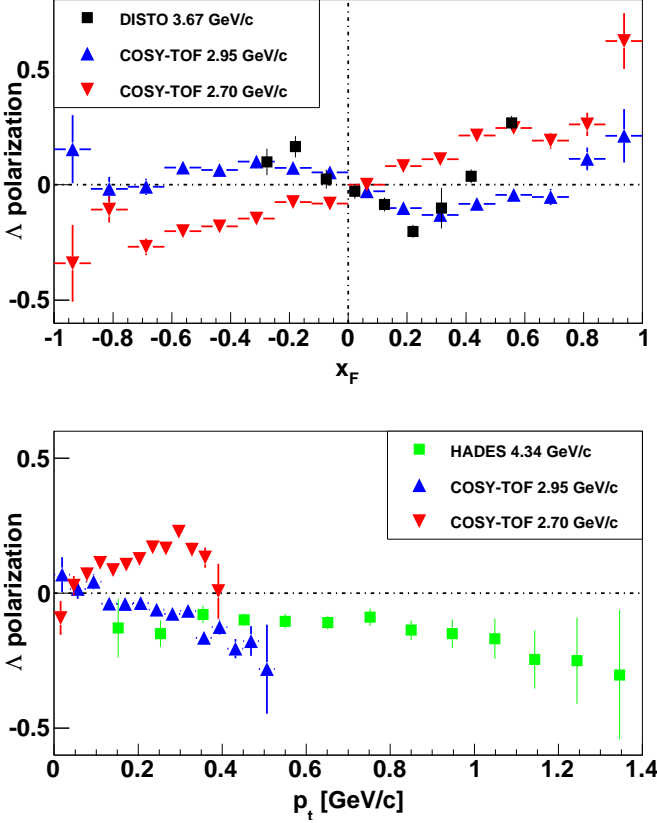


Fig. 3. Upper frame: the Λ polarization as a function of Feynman x_F in comparison to the results of the DISTO experiment. Bottom frame: the Λ polarization as a function of the transverse momentum in comparison to the results of the HADES experiment. The error bars of the HADES data include statistical plus systematic errors. The references for the DISTO and HADES data are given in table 1.

can be detected. Nearly all measurements of the literature show a negative Λ polarization. Apart from the data of one experiment [25] below $p_t = 0.6$ GeV/c the COSY-TOF 2.70 GeV/c data are the only ones with a positive polarization for all intervals.

Table 2. The results from the linear fit in fig. 5 ($P_N = a_1 \cdot p_t [\text{GeV}/c]$)

| data range $ x_F $ | $a_1 [(\text{GeV}/c)^{-1}]$ | |
|-----------------------|-----------------------------|--------------------|
| | $p_b = 2.70$ GeV/c | $p_b = 2.95$ GeV/c |
| 0.0–0.3 | 0.33 ± 0.04 | -0.33 ± 0.04 |
| 0.3–0.5 | 0.87 ± 0.06 | -0.43 ± 0.05 |
| 0.5–0.7 | 1.23 ± 0.08 | -0.34 ± 0.07 |
| 0.7–1.0 | 1.59 ± 0.18 | 0.20 ± 0.15 |

The dependence of the Λ polarization on the kaon- Λ invariant mass is given by the experiments BNL E766 and FNAL E690 [25, 33, 34]. These data are compared with the data of COSY-TOF in fig. 6. Because the data of BNL and

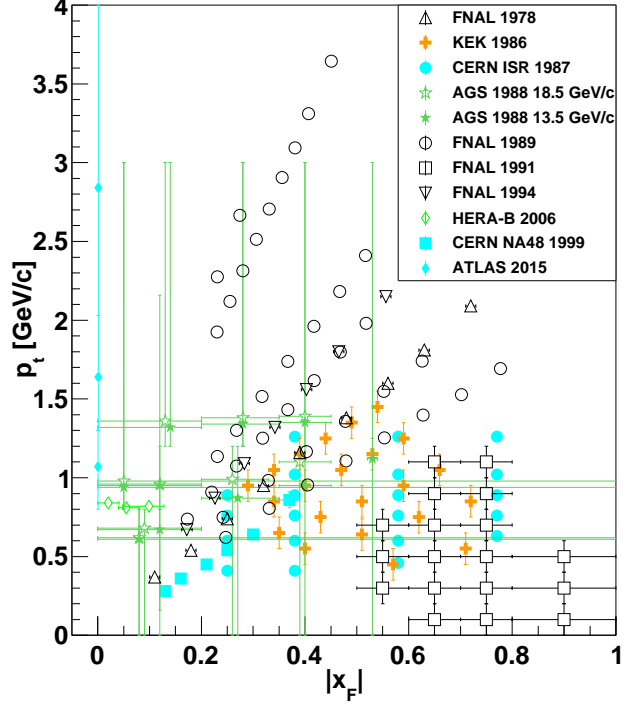


Fig. 4. Kinematic regions of Λ polarization measurements, for which the dependence of the Λ polarization on the transverse momentum and on Feynman x_F are explicitly given. The bin width of the measurements is indicated by error bars. The references for the measurements are given in table 1.

FNAL are restricted to Feynman x_F region of $|x_F| > 0.4$, we apply the same restriction to the COSY-TOF data. The BNL data set varies by including $\pi^+\pi^-$ pairs to the $pK\Lambda$ final state. Only the data with 2 and 4 pions are shown in fig. 6. No obvious similarities between these data sets and the COSY-TOF data can be found. For the sake of completeness the Λ polarization is plotted as a function of the $p\Lambda$ invariant mass in the lower part of fig. 6. No data in the literature are existing for comparison.

3.3 Dependence of the Λ polarization on the cm momentum

In order to characterize the variation of the Λ polarization with $\cos\vartheta_{\Lambda}^{\text{cm}}$ by only two parameters, the Λ polarization is multiplied by the differential cross section and fitted with the sum of the associated Legendre polynomials L_2^1 and L_4^1 :

$$P_N(\cos\vartheta_{\Lambda}^{\text{cm}}) \cdot \frac{d\sigma_0}{d\Omega} = b_2 L_2^1(\cos\vartheta_{\Lambda}^{\text{cm}}) + b_4 L_4^1(\cos\vartheta_{\Lambda}^{\text{cm}}) \quad (5)$$

$d\sigma_0/d\Omega$ is the spin averaged differential cross section determined as described in sec. 4.3. These polynomials are

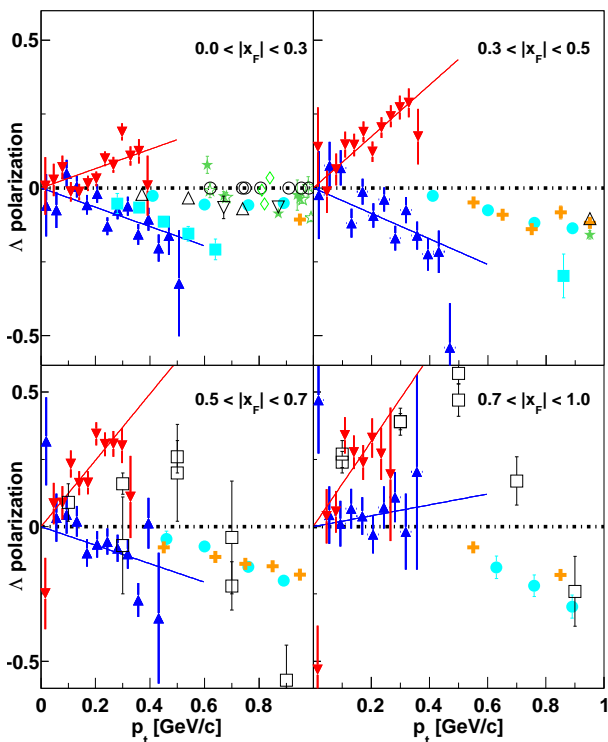


Fig. 5. Comparison of the COSY-TOF data (blue, filled triangles up for 2.95 GeV/c and red, filled triangles down for 2.70 GeV/c) with data from the literature, the symbols are the same as in fig. 4. For better visibility error bars of the abscissa are not plotted. The range of Feynman x_F is indicated in the plots. The COSY-TOF data have been fit with a straight line, the fit parameters are given in table 2.

chosen as they have the required roots and point symmetry. L_2^1 describes the data with a structure of one maximum/minimum each in the forward and backward region, while the polynomial L_4^1 has two maxima/minima in each region. The data are divided into six bins of the Λ cm momentum as shown by the error bars at the abscissa in fig. 7 and fit according to eq. 5. The fit results do not improve by adding the $l = 6$ Legendre polynomial, which would add structures with three maxima/minima in each region. The variation of the coefficients b_2 and b_4 with the cm momentum are shown in fig. 7 for both beam momenta.

For the 2.70 GeV/c data the coefficient b_4 is within the error bars constant and close to zero, while the magnitude of the coefficient b_2 increases nearly linearly with the Λ cm momentum. For the 2.95 GeV/c data the magnitudes of both coefficients rise with the momentum. The distribution and fit for each momentum bin is shown in the appendix A in figs. 15, 16.

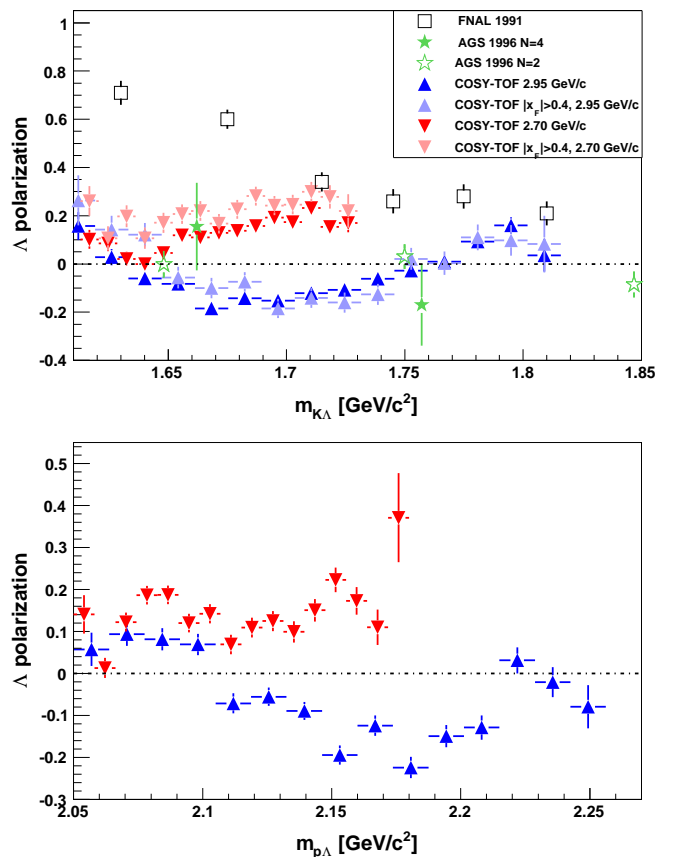


Fig. 6. Top: comparison of the Λ polarization as a function of the $K\Lambda$ invariant mass. In order to show the effect of the restriction of the data to the range of Feynman x_F as in the literature data, the COSY-TOF data are plotted with and without this restriction. In the legend of the AGS data N gives the number of $\pi^+\pi^-$ pairs which are evaluated together with $pK\Lambda$. Bottom: COSY-TOF data of the Λ polarization as a function of the $p\Lambda$ invariant mass.

4 Analyzing power A_N

4.1 Results

The analyzing power A_N describes the left-right asymmetry of the final state particles induced by the vertical beam polarization. The analyzing power is determined by applying the equation:

$$A_N = \frac{1}{P_B \cdot \cos(\varphi)} \cdot \frac{N^\uparrow(\varphi) - N^\downarrow(\varphi)}{N^\uparrow(\varphi) + N^\downarrow(\varphi)} \quad (6)$$

φ is the azimuth angle, N denotes the count rates, and \uparrow , \downarrow indicate the direction of the beam polarization. P_B is the absolute value of the beam polarization. Three beam proton analyzing powers can be determined: $A_N(\varphi^p)$, $A_N(\varphi^K)$, and $A_N(\varphi^\Lambda)$ depending on which final state particle is considered.

In contrast to the Λ polarization the symmetry of the initial system is broken because the beam proton is po-

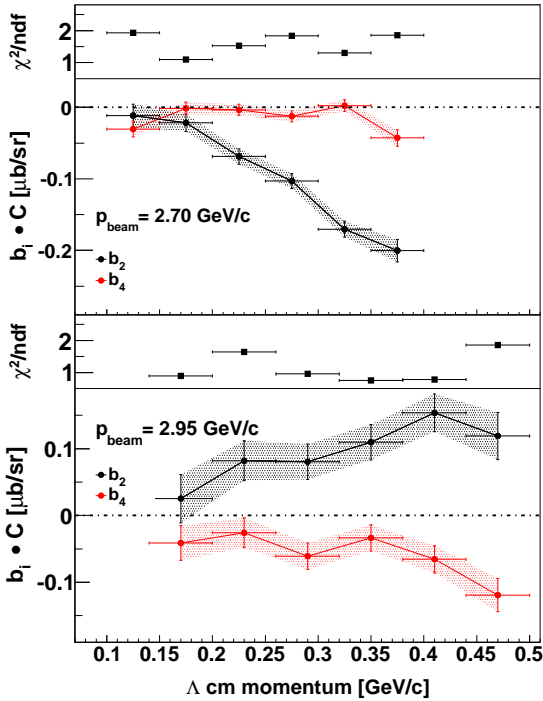


Fig. 7. The variation of the Legendre coefficients b_2 (black) and b_4 (red) as defined in eq. 5 with the cm Λ momentum. The upper panel contains the data of 2.70 GeV/c beam momentum, the lower one contains the 2.95 GeV/c data. Above each plot the reduced χ^2 of the fit is plotted.

larized. Therefore, no symmetry in the functional dependence on the scattering angle and on the Feynman x_F are expected. The following boundary conditions are given: $A_N(|\cos(\vartheta^{cm})| = 1) = 0$ and $A_N(|x_F| = 1) = 0$. As the minimum of the transverse momentum corresponds to $|\cos(\vartheta^{cm})| = 1$, the analyzing power at $p_t = 0$ GeV/c must also be zero.

The results of the analyzing power measured by the proton, kaon, and Λ asymmetries are shown in fig. 8. The analyzing powers are given as a function of the cm scattering angle, the Feynman x_F , and the transverse momentum of the corresponding final state particle.

While the analyzing power generating the p and K^+ asymmetries does not change significantly with the beam momentum, larger differences are found for the analyzing power from the Λ asymmetry. The analyzing power of the proton and of the Λ asymmetry are mainly negative, while the analyzing power of the kaon asymmetry is essentially positive. For transverse momenta below 0.25 GeV/c the analyzing power of the proton asymmetry is nearly zero and decreases linearly to -0.2 above this momentum. The analyzing power of the kaon asymmetry shows an inverse behavior: for momenta below 0.25 GeV/c it increases nearly linearly from 0 to 0.10 and it is constant above this momentum.

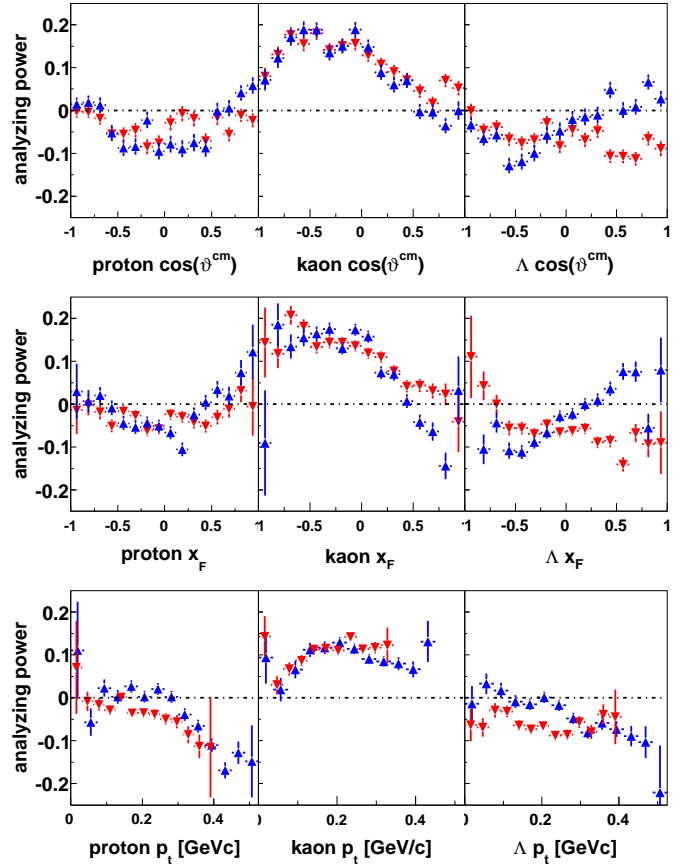


Fig. 8. The analyzing power is shown for two beam momenta: 2.70 GeV/c (red triangles down) and 2.95 GeV/c (blue triangles up). Top: dependence on the cm scattering angle. Middle: dependence on the Feynman x_F . Bottom: dependence on the transverse momentum.

4.2 Comparison with existing data

The analyzing power has only been measured exclusively for the associated strangeness production by DISTO and COSY-TOF. The DISTO data were measured at beam momenta of 3.67 GeV/c, 3.31 GeV/c, and 2.94 GeV/c [35, 36]. The analyzing power determined with the Λ asymmetry of the 2.94 GeV/c data⁴ are compared in fig. 9 with the COSY-TOF data of 2.95 GeV/c as a function of the scattering angle, Feynman x_F , and the transverse momentum. While the dependence on the transverse momentum of both data sets exhibits a similar behavior, discrepancies are seen in $\cos\vartheta^{cm}$ and x_F : for the forward range the DISTO data yield a negative analyzing power, the COSY-TOF data have positive values.

A subset of the COSY-TOF data, which had been measured in 2010, was evaluated in [13] for the determination of the spin triplet $p\Lambda$ scattering length. The comparison of the analyzing power of the kaon asymmetry is given

⁴ The data are scanned from fig. 4 of reference [35], they are quoted to be preliminary.

in the last plot of fig. 9. Both analyses exhibit consistent characteristics of this analyzing power.

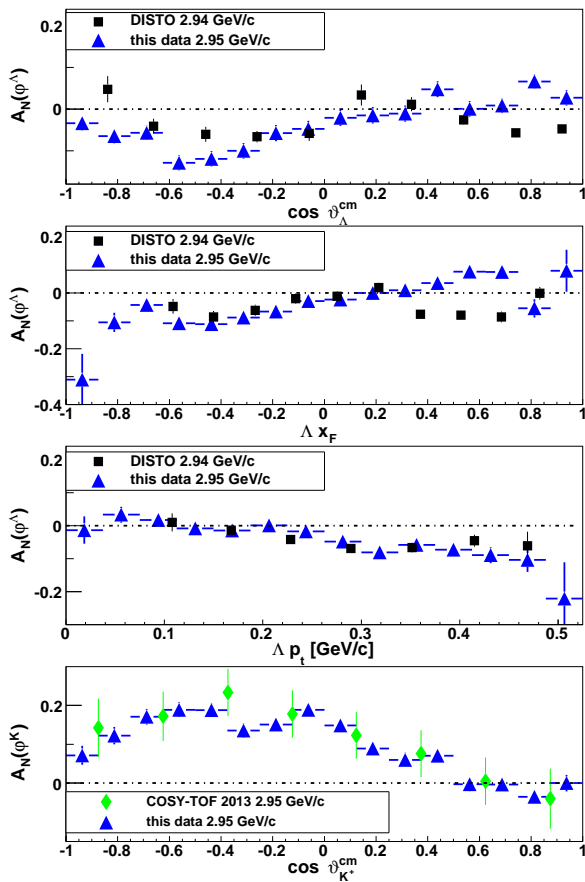


Fig. 9. In the top panels the analyzing power measured at 2.95 GeV/c is compared with data from DISTO, which were measured at 2.94 GeV/c [35]. The bottom panel compares the analyzing power of the kaon asymmetry at 2.95 GeV/c with a previous analysis including only 20% of the COSY-TOF data [13].

4.3 Description with Legendre polynomials:

The differential cross section of proton-proton interactions with a beam polarization P_B in the $\pm y$ direction and an unpolarized target is given by ([37,38]):

$$\frac{d\sigma(\cos\vartheta^*)}{d\Omega} = \frac{d\sigma_0(\cos\vartheta^*)}{d\Omega} + P_B \frac{d\sigma_y(\cos\vartheta^*)}{d\Omega} \quad (7)$$

$d\sigma_0(\cos\vartheta^*)/d\Omega$ is the spin averaged differential cross section and $d\sigma_y(\cos\vartheta^*)/d\Omega$ is the spin dependent cross section. The analyzing power A_N is given by

$$A_N = \frac{d\sigma_y(\cos\vartheta^*)/d\Omega}{d\sigma_0(\cos\vartheta^*)/d\Omega} \quad (8)$$

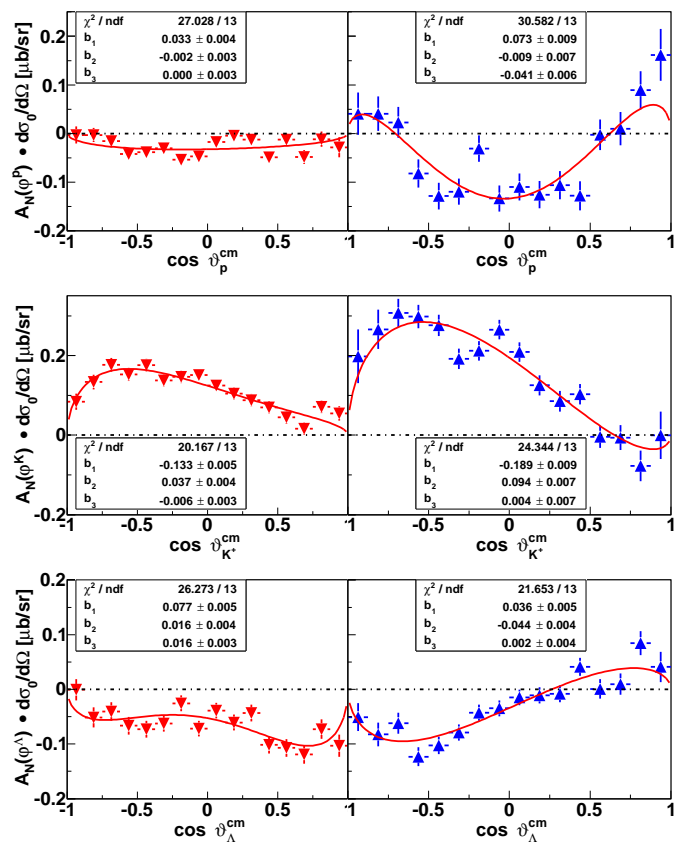


Fig. 10. The product of the analyzing power and the unpolarized cross section $A_N \cdot d\sigma_0/d\Omega$ for the three final state particles is shown by the triangles, left column for 2.70 GeV/c beam momentum, right column for 2.95 GeV/c beam momentum. The fit results for the sum of the Legendre polynomials are shown by the red lines. The values of the coefficients b_i are given in the plots.

The differential cross sections can be expressed by a sum of Legendre polynomials:

$$\begin{aligned} d\sigma_0(\cos\vartheta^*)/d\Omega &= \frac{1}{4\pi} \sum_n a_n L_n^0 \\ d\sigma_y(\cos\vartheta^*)/d\Omega &= \frac{1}{4\pi} \sum_n b_n L_n^1 \end{aligned} \quad (9)$$

L_n^0 (L_n^1) are the associated Legendre functions of order 0 (1). a_n are the related coefficients of order 0, $n = 0, 1, 2, \dots$ and b_n , $n = 1, 2, 3, \dots$ are the related coefficients of order 1. In order to determine the coefficients b_n , the product of the analyzing power and the unpolarized cross section $A_N \cdot d\sigma_0/d\Omega$ is fit with the $n = 1, 2, 3$ associated Legendre functions. The unpolarized cross section $d\sigma_0/d\Omega$ is determined by fitting the angular distribution (see fig. 3 in reference [1]) with associated Legendre functions of order 0 up to the degree of $n = 2$. The fit results of $A_N \cdot d\sigma_0/d\Omega$ are shown in fig. 10.

In contrast to proton-proton reactions with two particles in the final state – e.g. $pp \rightarrow d\pi^+$ – no direct conclu-

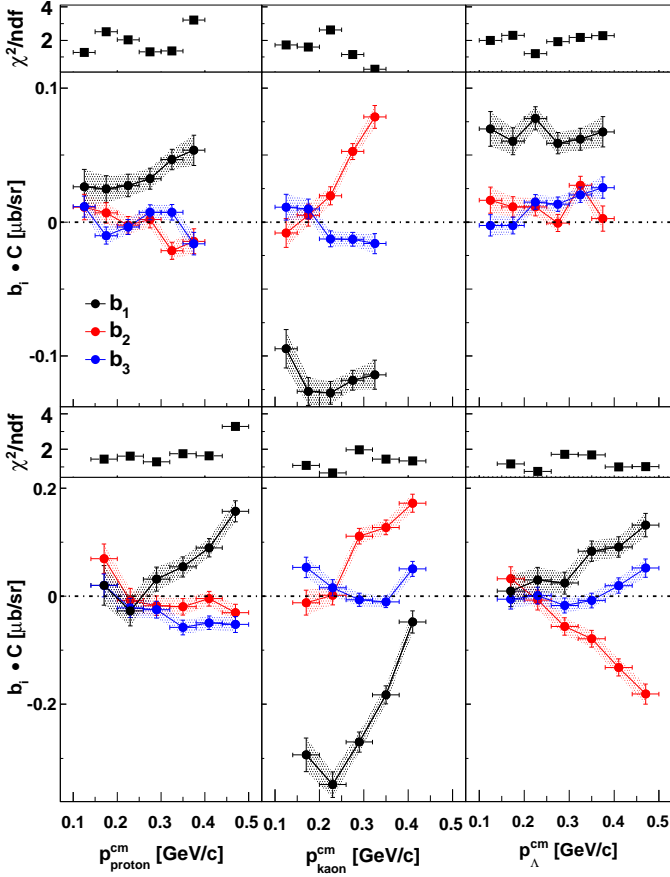


Fig. 11. Legendre coefficients obtained by fitting the analyzing power plotted as a function of the cm momenta. The coefficients are distinguished by the color code: black: b_1 , red: b_2 , and blue: b_3 . The values are plotted for 2.70 GeV/c (top row) and 2.95 GeV/c (bottom row). The reduced χ^2 values of the fits are shown above each plot.

sions on the partial waves can be drawn from the composition of the Legendre coefficients.

4.4 Dependence of the Legendre Coefficients on the particle momenta

In order to determine the dependence of the Legendre coefficients on the particle cm momentum, the data are divided into six bins of the particle momentum. The analyzing power distribution is calculated for each bin and fit with the Legendre polynomials L_n^1 ($n = 1, 2, 3$). The distributions of the analyzing power and the fit in each bin are shown in the appendix A in figs. 17 - 22. The range of the momentum of each bin is indicated in the plots. The momentum dependence of the coefficients is shown in fig. 11.

By omitting the coefficients b_2 , b_3 or both in the fit and by comparing the reduced χ^2 of these fits it is observed that below cm momenta of 200–300 MeV/c the analyzing power can be described with the first Legendre polynomial alone. Above this momentum the analyzing power of the

proton asymmetry needs the third Legendre polynomial and the analyzing powers of the Λ and kaon asymmetry need the second Legendre polynomial.

The spin triplet part of the p- Λ scattering length can be derived from the kaon cm momentum distribution and the analyzing power [39]. This method is based on the variation of the coefficient b_1 (see eq. 9) with the kaon cm momentum in the range of the highest kaon momenta (fig. 11, second column). At 2.95 GeV/c (lower row of fig. 11) the coefficient b_1 is for the highest kaon momenta close to zero (-0.05 ± 0.02), thus the spin triplet part of the Λ -p scattering length can not be determined with the required precision [13]. But for the 2.70 GeV/c data this coefficient is -0.12 ± 0.01 for the higher kaon momenta (upper row of fig. 11), enabling this determination. The results of the scattering length from the 2.70 GeV/c data are discussed in a separate paper [40].

5 Spin transfer coefficient: D_{NN}

5.1 Results

The transfer of the beam-proton polarization to the hyperon is quantified by the spin transfer coefficient D_{NN} . The common definition (see for instance [7]) implies that it is positive if the polarization of the hyperon is aligned with the beam polarization, negative if the hyperon polarization is oriented opposite to the beam polarization, and zero if the hyperon polarization is independent of the beam polarization.

The spin transfer coefficient is calculated with the following formula:

$$D_{NN}(\vartheta^*) = \frac{4}{\alpha P_B} \epsilon_D(\vartheta^*) \quad (10)$$

α is the Λ decay asymmetry parameter, P_B the magnitude of the beam polarization, and $\epsilon_D(\vartheta^*)$ is calculated from the differences of count rates depending on the orientation of the beam polarization, the Λ polarization, and the hemisphere of the detector. For a detailed discussion see ref. [41].

The spin transfer coefficient D_{NN} is shown in fig. 12 as a function of the Λ scattering angle, Feynman x_F , and the transverse momentum of the Λ . The measurements show that the coefficient D_{NN} is negative for nearly all regions, thus the hyperon polarization is opposite to the beam polarization. It is mainly constant as a function of the scattering angle and of Feynman x_F within the interval of $x_F = [-0.4, +1.0]$. For the 2.70 GeV/c data D_{NN} increases linearly with the transverse momentum with a slope of $(1.3 \pm 0.2) (\text{GeV}/c)^{-1}$ starting with -0.6 at $p_t = 0 \text{ GeV}/c$. This behavior is not repeated for the data of 2.95 GeV/c beam momentum, where the fit gives a gradient consistent with zero.

5.2 Comparison with existing data

The first measurement of the spin transfer coefficient of $pp \rightarrow \Lambda X$ was performed in 1975 at a beam momentum

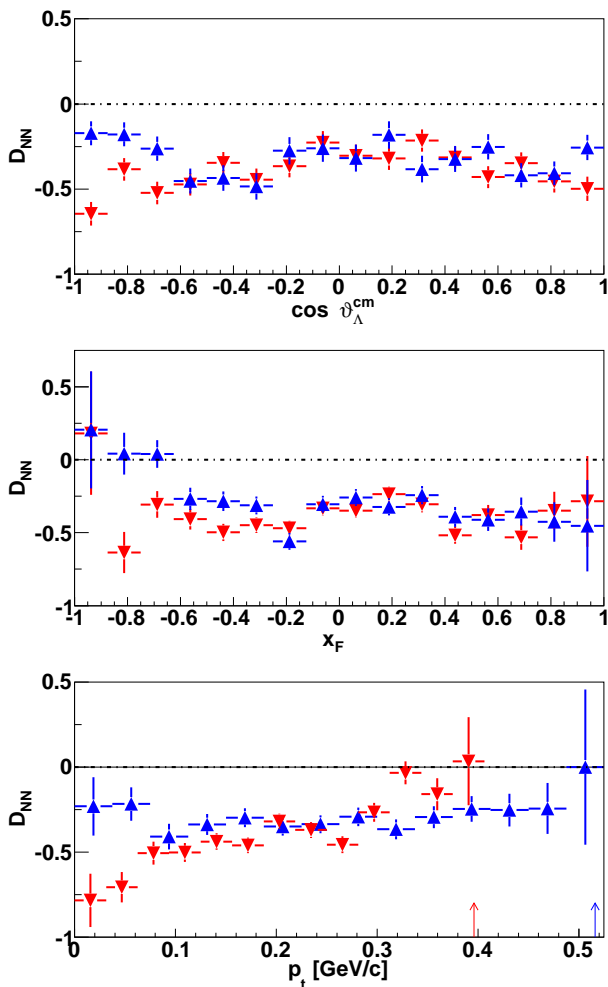


Fig. 12. Spin transfer coefficient for 2.70 GeV/c (red triangles down) and 2.95 GeV/c (blue triangles up). Top: dependence on the Λ cm scattering angle. Middle: dependence on the Λ Feynman x_F . Bottom: dependence on the Λ transverse momentum. For both beam momenta the maxima of the transverse momenta are indicated with arrows in the lower part of the plot.

of 6 GeV/c [42]. D_{NN} was measured to be ≈ 0 for Feynman $x_F < 0.6$ and for $x_F > 0.6$ to be ≈ -0.5 . The range of the corresponding transverse momentum is not given in the paper and the contamination with Λ 's of the Σ^0 decay is not discussed. In 1988 D_{NN} was measured at beam momenta of 13.3 GeV/c and 18.5 GeV/c with a beryllium target [7]. The measurements covered transverse momenta from 0 to 3 GeV/c with Feynman x_F mainly in the forward range. The ratio of Λ from the Σ^0 decay to direct production was estimated to be 40%. No significant deviations of D_{NN} from zero were found. A third measurement with a beam momentum of 200 GeV/c and a liquid hydrogen target covered the forward range of x_F [8]. The fraction of Λ 's from Σ^0 decay is not discussed in the paper. D_{NN} was measured to be compatible with zero for $0.1 \text{ GeV/c} < p_t < 0.6 \text{ GeV/c}$, and for $0.6 \text{ GeV/c} < p_t < 1.5 \text{ GeV/c}$ D_{NN} is positive and in the range of 0.3–0.4.

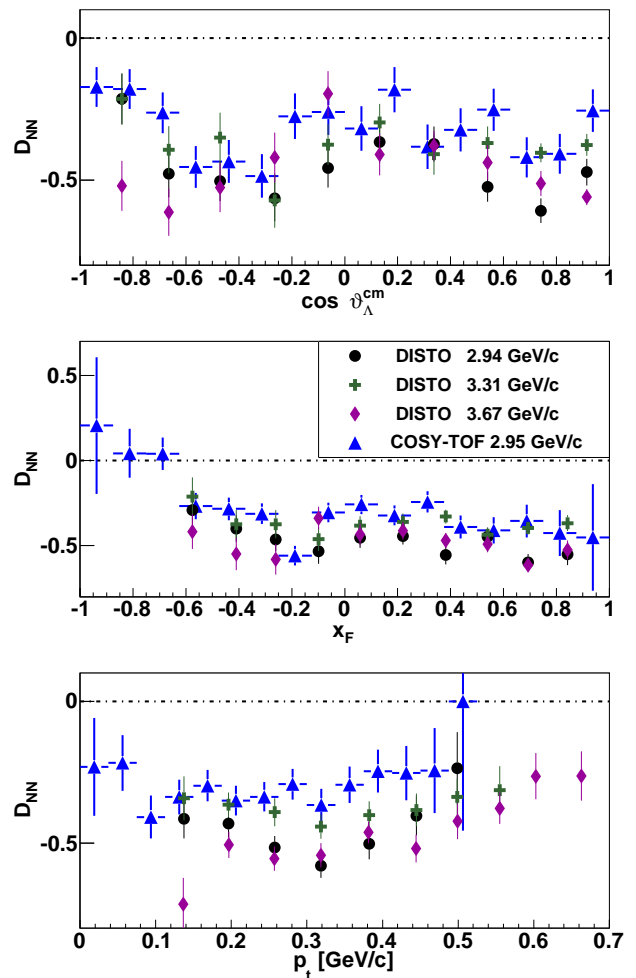


Fig. 13. The spin transfer coefficient is shown for the DISTO data [35] and the 2.95 GeV/c COSY-TOF data. For a better clarity, the 2.70 GeV/c data of COSY-TOF are omitted. Top: dependence on the Λ cm scattering angle. Middle: dependence on the Λ Feynman x_F . Bottom: dependence on the Λ transverse momentum.

The results of these measurements are not in agreement with the present data and they exhibit no consistent dependence on Feynman x_F . Therefore, it cannot be determined how strongly the polarization transfer depends on the beam momentum. The first exclusive measurements of the polarization transfer were performed by the DISTO experiment [35]. Here $pK\Lambda$ and $pK\Sigma^0$ events are identified in the pK missing mass spectrum. For the beam momentum of 3.67 GeV/c the admixture of Λ from Σ^0 decay was measured to be lower than 30% [9]. These data are compared with the COSY-TOF results of $p_b = 2.95 \text{ GeV/c}$ in fig. 13. Both data sets exhibit a negative D_{NN} , which is approximately constant. The magnitude of D_{NN} measured by COSY-TOF is smaller compared with the DISTO data. The mean value of the COSY-TOF data in the x_F range of $[-0.5, +1.0]$ is -0.37 ± 0.02 , the corresponding mean value of the DISTO data is -0.46 ± 0.01 . The mean values of each measurement are given in table 3.

Table 3. Mean values of D_{NN} for $x_F = [-0.5, +1.0]$

| data set | $\overline{D_{NN}}$ |
|---------------------|---------------------|
| DISTO 2.94 GeV/c | -0.50 ± 0.02 |
| DISTO 3.31 GeV/c | -0.38 ± 0.02 |
| DISTO 3.67 GeV/c | -0.50 ± 0.02 |
| COSY-TOF 2.70 GeV/c | -0.39 ± 0.02 |
| COSY-TOF 2.95 GeV/c | -0.34 ± 0.02 |

The indication that D_{NN} changes to positive values for $x_F < -0.6$ cannot be confirmed by the DISTO data, as the acceptance of this detector for that range is too small [43].

5.3 Comparison with model calculations

As developed by Laget [44] the dependence of the spin transfer coefficient on the Feynman x_F can be characterized by assuming pion or kaon exchange mechanism for the associated strangeness production. For pion exchange the upper vertex in the Feynman diagram of fig. 14 is $p + \pi \rightarrow K^+ + \Lambda$. Both sides of this vertex have negative parity, if angular momenta are 0. For a polarized beam proton, the Λ spin will have the same direction as the proton spin ($D_{NN} = +1$). In case of a kaon exchange the

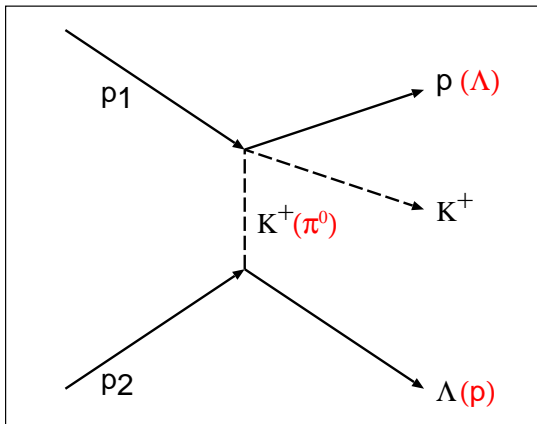


Fig. 14. Feynman graph of the associated strangeness production, with either kaon exchange or pion exchange (red symbols in brackets). $p_{1,2}$ are the beam and target proton, their order can be exchanged.

lower vertex in the Feynman diagram is given by $p \rightarrow K^+ + \Lambda$. Here the parity changes, and therefore, the Λ spin has to be opposite compared to the beam proton polarization direction ($D_{NN} = -1$). For backward Λ regions the Λ is essentially produced on the unpolarized target proton. Thus, in this region D_{NN} is expected to be zero.

As for $x_F > 0$ the data exhibit $D_{NN} \approx -0.3$, the conclusion from the Laget model indicates the existence of a mixture of kaon and pion exchange mechanism. The backward region exhibits the same value for D_{NN} , only for $x_F < -0.6$ the 2.95 GeV/c data give values of D_{NN} which

are compatible with zero. A later calculation [45] considers in addition the exchange of a ρ meson. It is shown that D_{NN} can have negative values without assuming a kaon exchange. D_{NN} is given as a function of the ratio of the π exchange amplitude (D_π) to the ρ exchange amplitude (B_ρ). For $D_{NN} = -0.3$ there are two solutions: $D_\pi/B_\rho = 0.3$ and $D_\pi/B_\rho = 1.5$ (fig. 3 of ref. [45]). In addition, this calculation gives the ratio of the total cross sections $R = (pn \rightarrow nK^+\Lambda) / (pp \rightarrow pK^+\Lambda)$ as a function of D_π/B_ρ . The value of $D_{NN} = -0.3$ implies the ratio $R = 4$ and $R = 6$. This ratio will be examined by a future publication, where results from COSY-TOF of $pn \rightarrow pK^0\Lambda$ at a beam momentum of 2.95 GeV/c will be presented.

6 Summary

The Λ polarization, the analyzing power determined by the asymmetry of the final state particles, and the Λ spin transfer coefficient are measured exclusively in the reaction $pp \rightarrow pK^+\Lambda$ at beam momenta of 2.70 GeV/c and 2.95 GeV/c.

It is shown that the Λ polarization changes significantly in its magnitude and sign with the beam momentum. This is the first time that this effect is observed. In contrast to all existing data the 2.70 GeV/c COSY-TOF data exhibit a positive Λ polarization in forward direction. The 2.95 GeV/c data are in agreement with the measurements of DISTO and HADES. Comparisons of the Λ polarization of both beam momenta with data from high beam momentum experiments do not yield similar characteristics.

In contrast to the Λ polarization the analyzing power does not change significantly with the beam momentum, only the analyzing power measured with the Λ asymmetry differs for these beam momenta. The results at 2.95 GeV/c beam momentum are in agreement with a measurement of DISTO at a beam momentum of 2.94 GeV/c. Apart from the DISTO data no other data exist for comparison. The dependence of the Legendre coefficients on the particle cm momenta yield different behavior between the two beam momenta, especially for the analyzing power measured with the kaon asymmetry.

The measurement of the spin transfer coefficient D_{NN} yields a negative value of about -0.3 . Apart from the backward region ($x_F < -0.6$) this value does not significantly vary with the beam momentum. The comparison with data from the DISTO experiment yields an agreement of the sign, but the magnitude of D_{NN} measured with DISTO is about 25% larger compared with the COSY-TOF data. A model calculation, which compares ρ and π exchange, connects the value of D_{NN} with the ratio of the cross sections associated strangeness production in pp and pn reactions. The measured value of D_{NN} implies that this ratio is 4 or 6. This ratio will be determined with existing COSY-TOF data.

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7 Appendix A

This appendix contains the individual fits of the observables as a function of the cm angle, which are separated into bins of the cm momentum. Inside each figure the fit results and the range of the cm momentum are given.

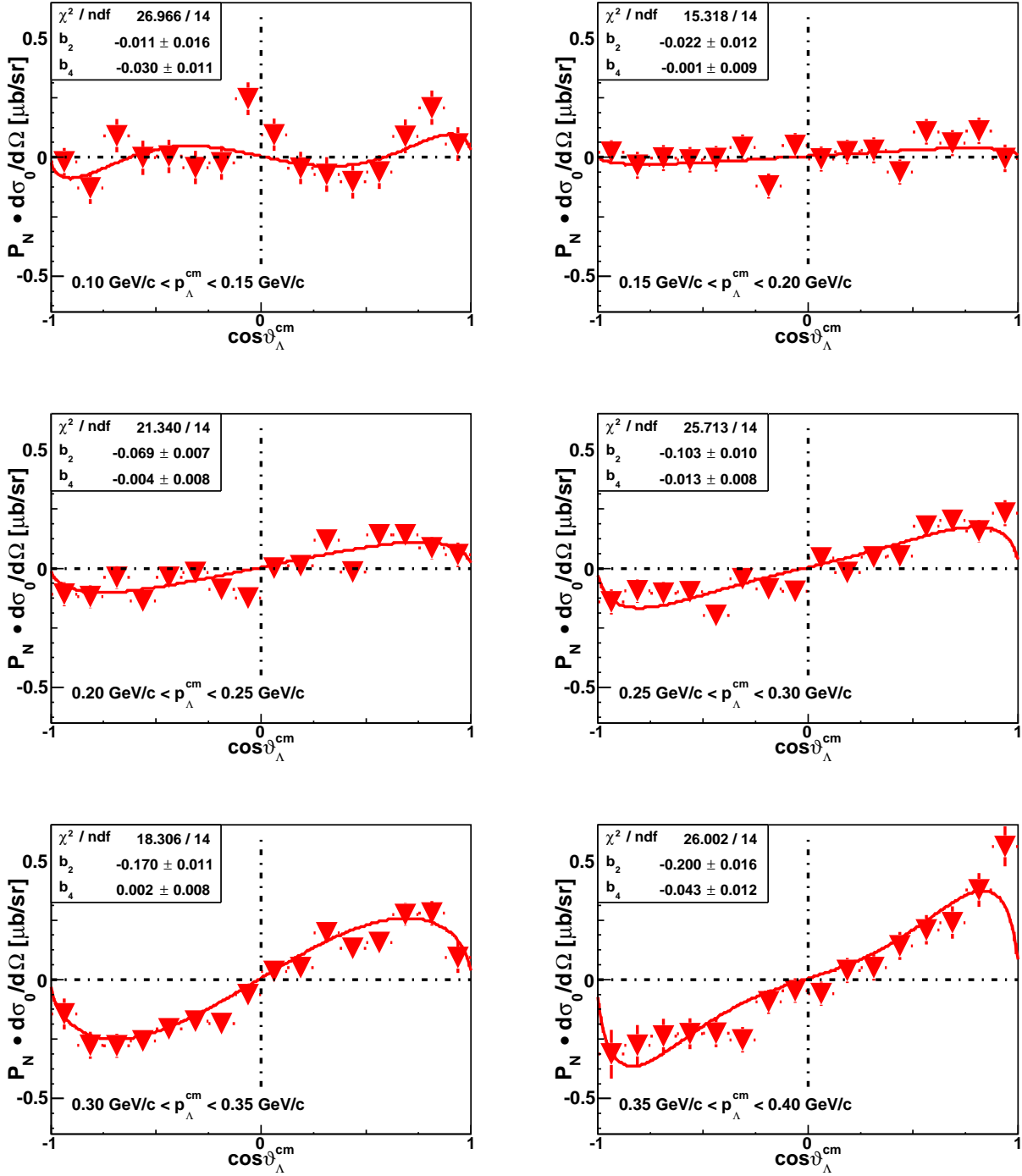


Fig. 15. The Λ polarization multiplied with the differential cross section of the 2.70 GeV/c data is shown for different ranges of the Λ cm momentum. The distributions have been fit with Legendre polynomials according to eq. 5. The fit results and the limits of the Λ cm momenta are given in each panel.

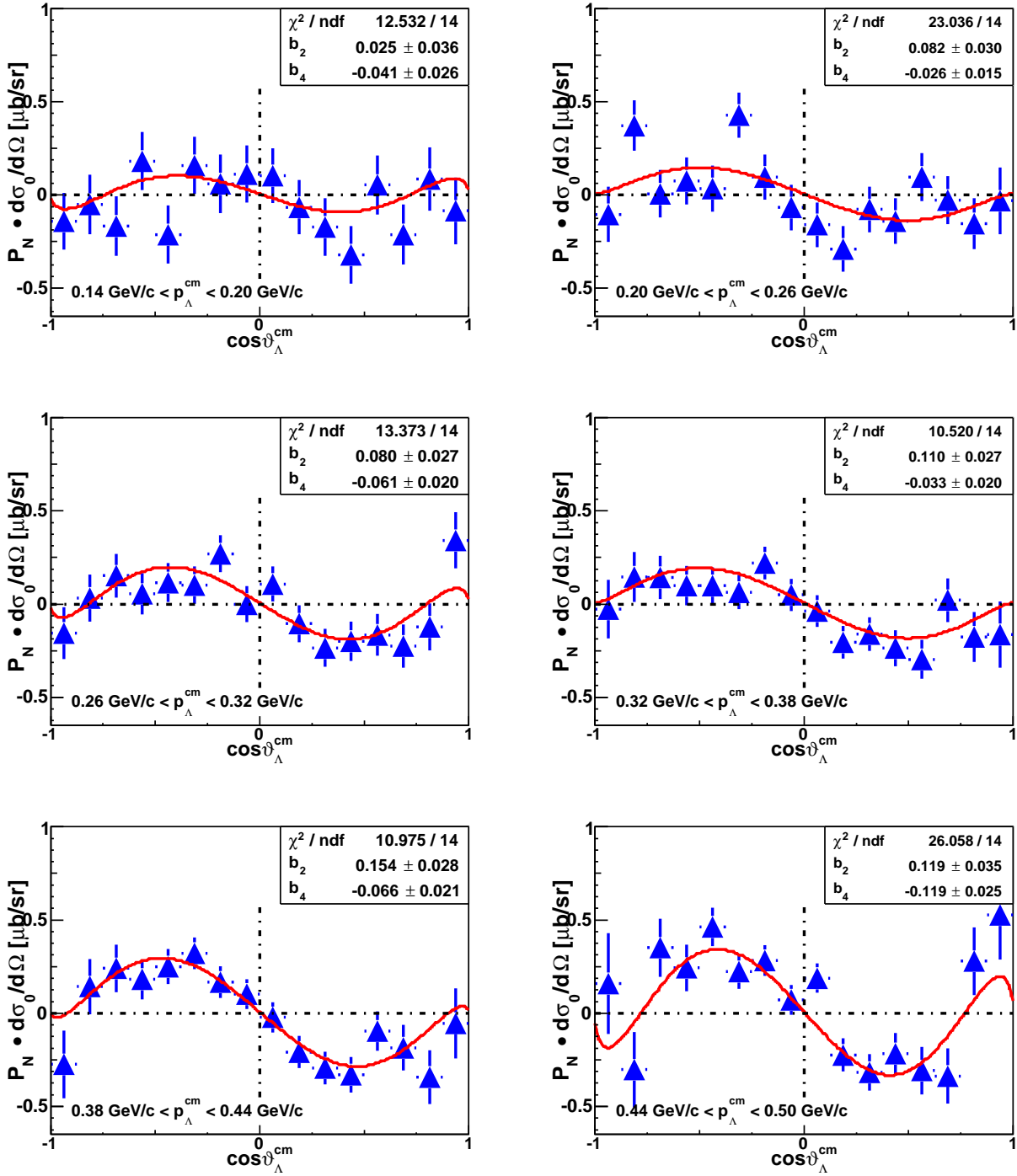


Fig. 16. The Λ polarization multiplied with the differential cross section of the 2.95 GeV/c data is shown for different ranges of the Λ cm momentum. The distributions have been fit with Legendre polynomials according to eq. 5. The fit results and the limits of the Λ cm momenta are given in each panel.

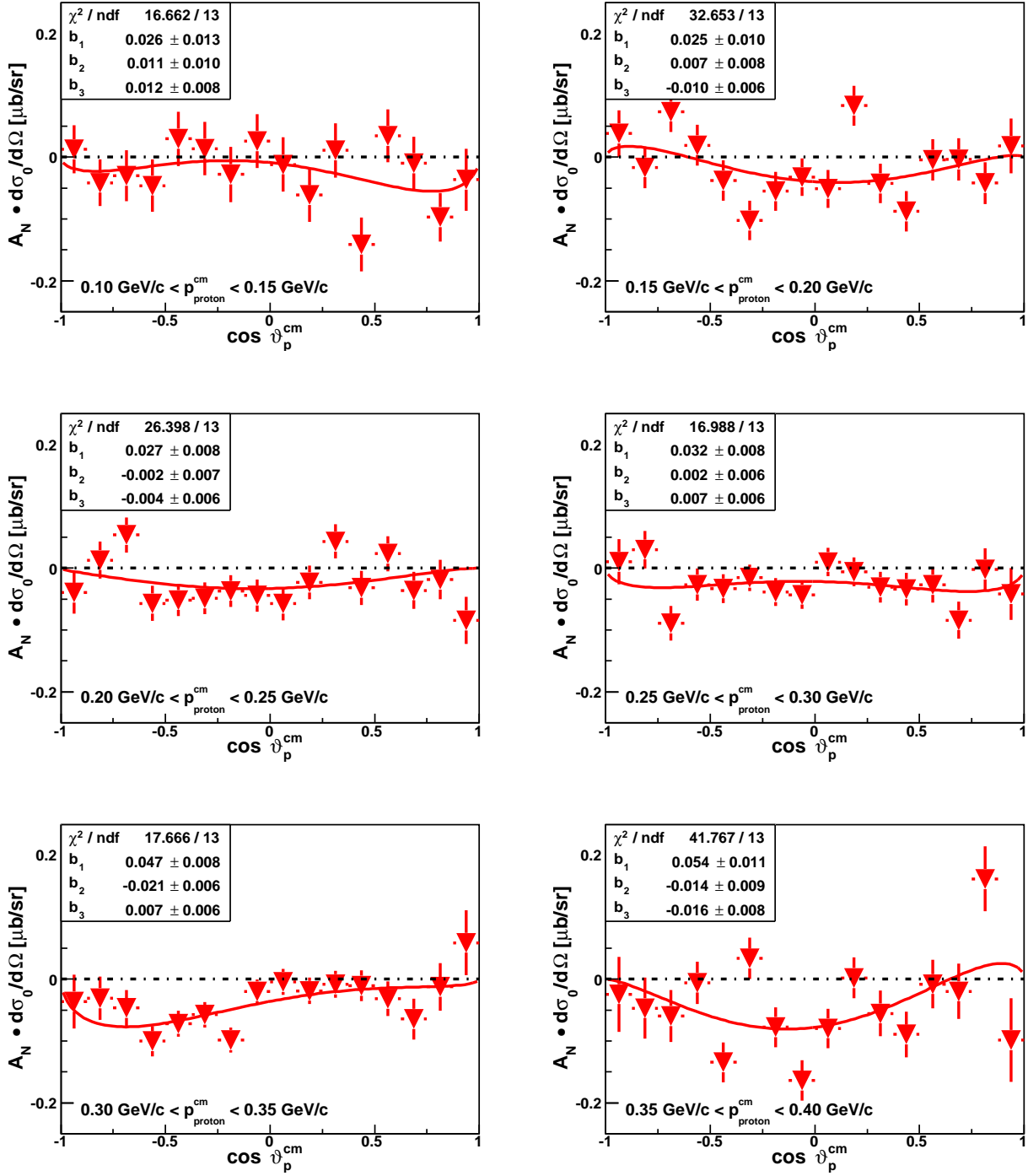


Fig. 17. The proton analyzing power multiplied with the differential cross section is shown for different ranges of the proton cm momentum for the 2.70 GeV/c data. The distributions have been fit with Legendre polynomials according to eq. 9. The fit results and the limits of the proton cm momenta are given in each panel.

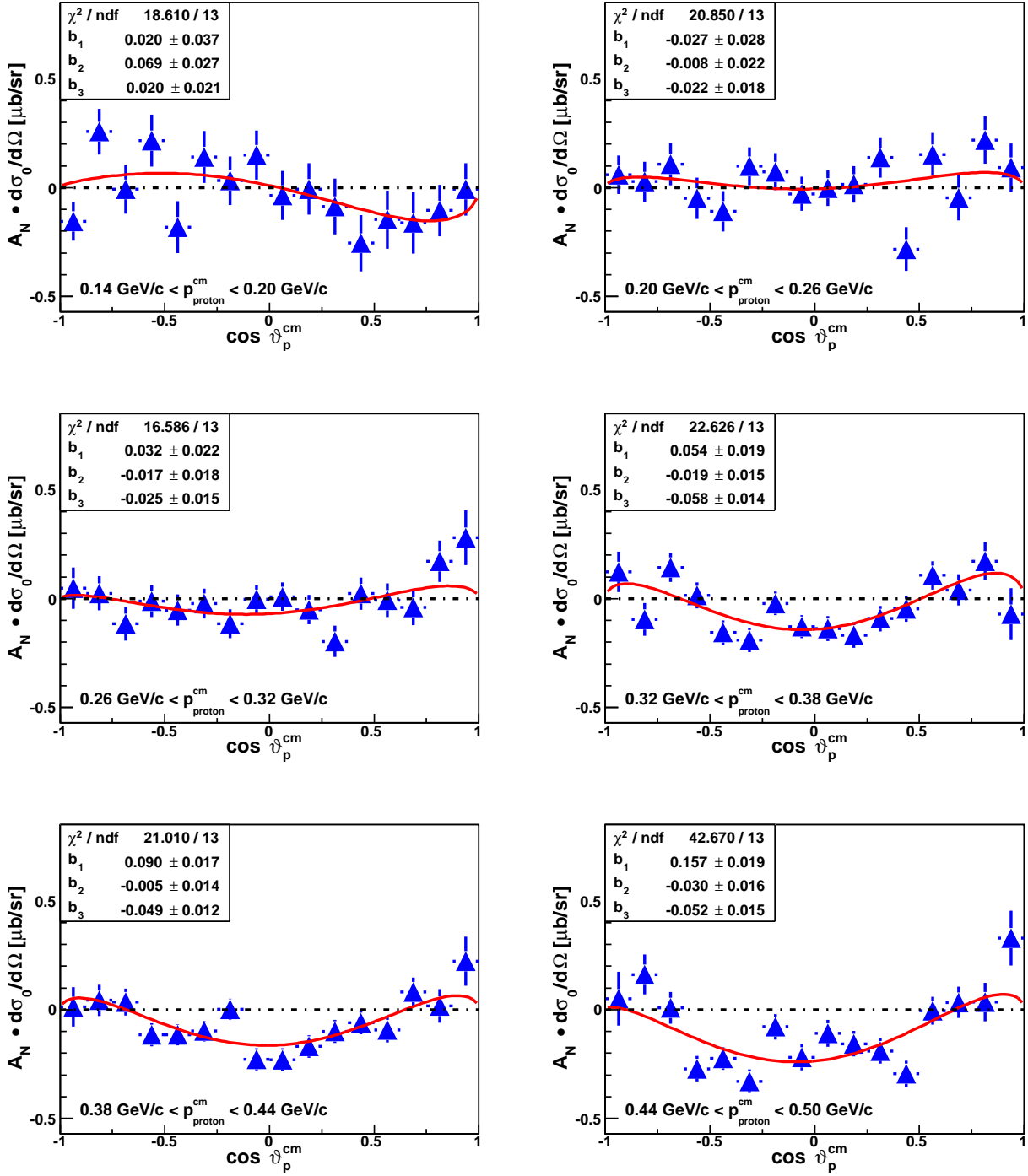


Fig. 18. The proton analyzing power multiplied with the differential cross section is shown for different ranges of the proton cm momentum for the 2.95 GeV/c data. The distributions have been fit with Legendre polynomials according to eq. 9. The fit results and the limits of the proton cm momenta are given in each panel.

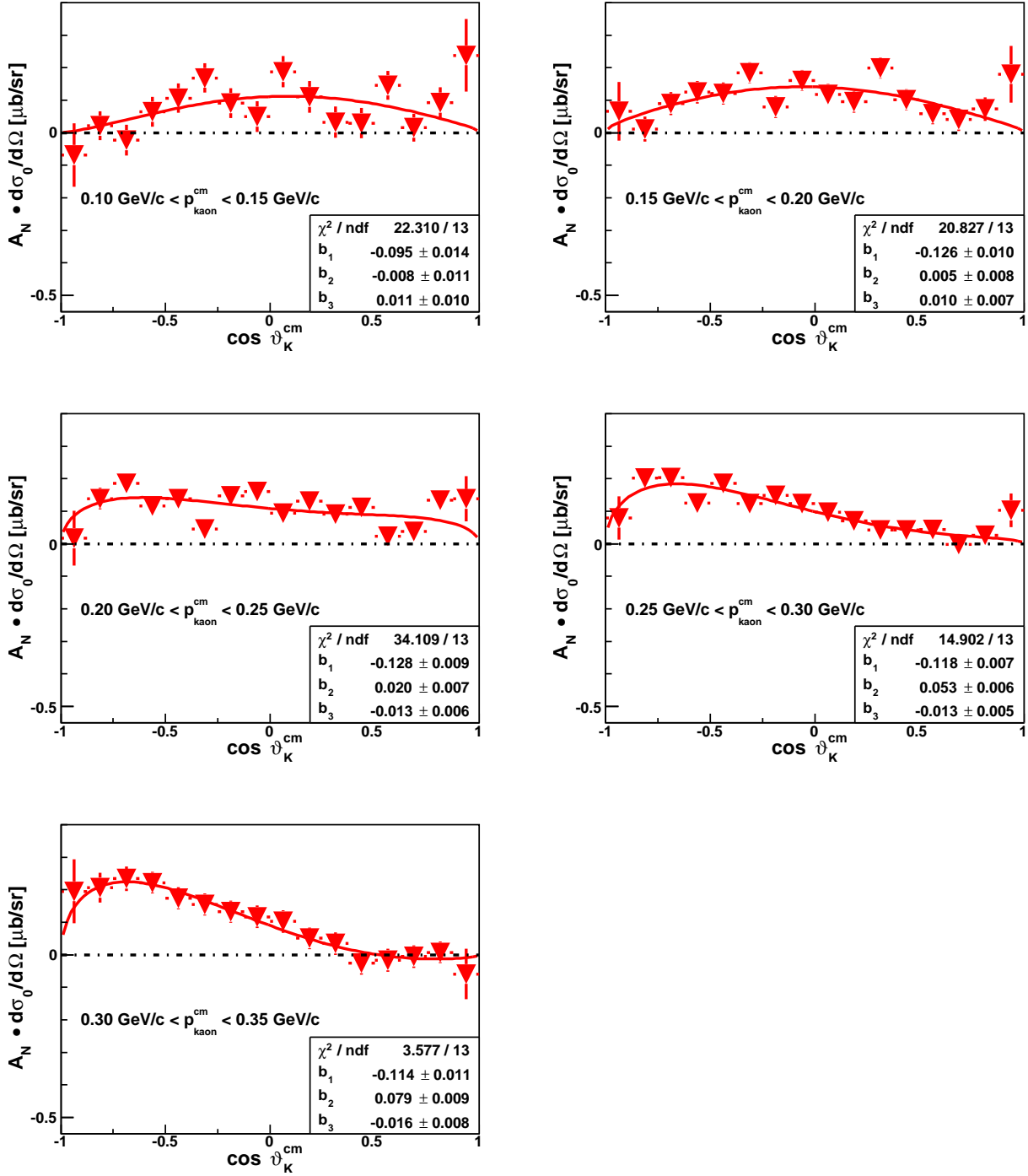


Fig. 19. The kaon analyzing power multiplied with the differential cross section is shown for different ranges of the kaon cm momentum for the 2.70 GeV/c data. The distributions have been fit with Legendre polynomials according to eq. 9. The fit results and the limits of the kaon cm momenta are given in each panel.

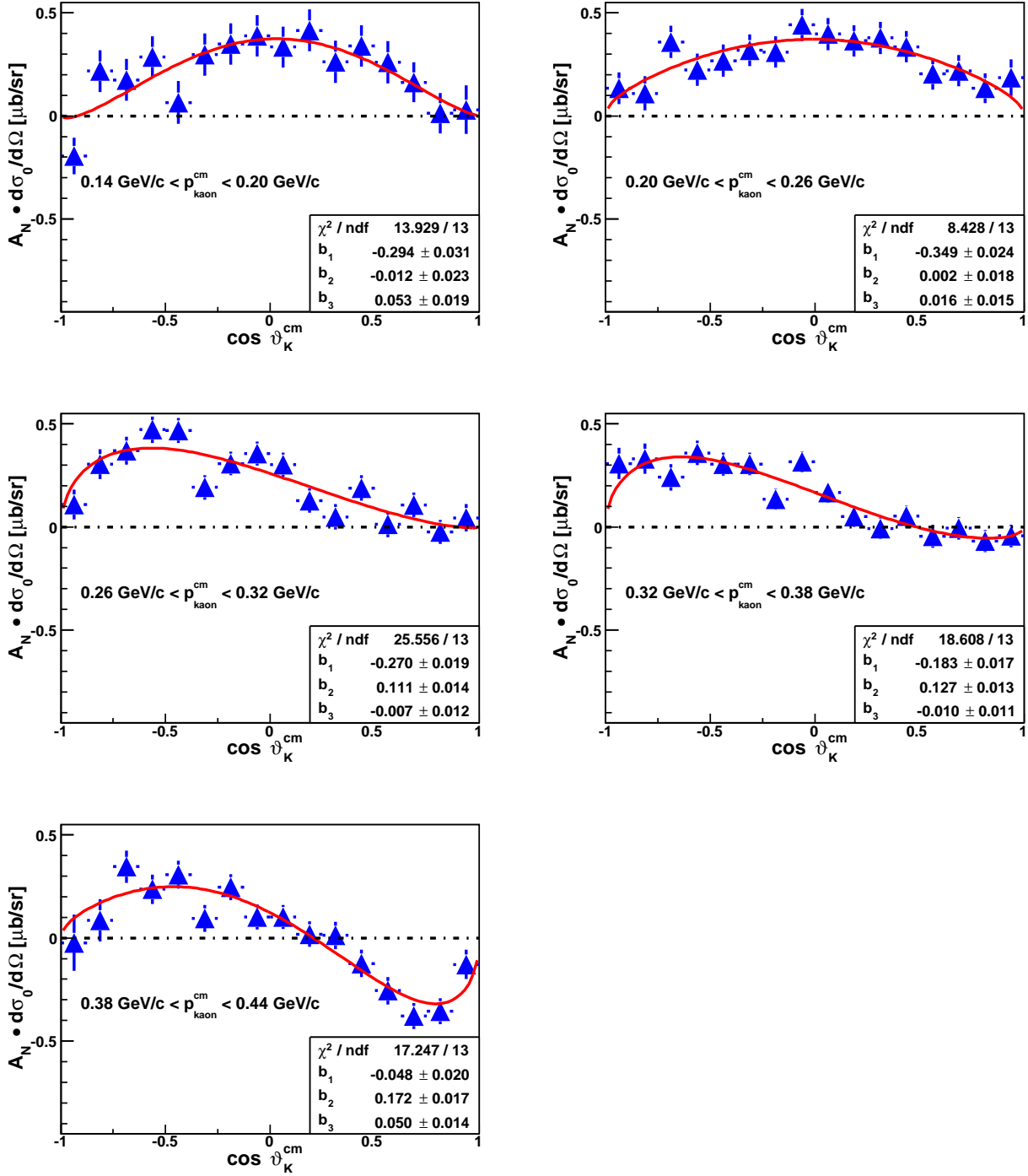


Fig. 20. The kaon analyzing power multiplied with the differential cross section is shown for different ranges of the kaon center-of-mass momentum for the 2.95 GeV/c data. The distributions have been fit with Legendre polynomials according to eq. 9. The fit results and the limits of the kaon center-of-mass momenta are given in each panel.

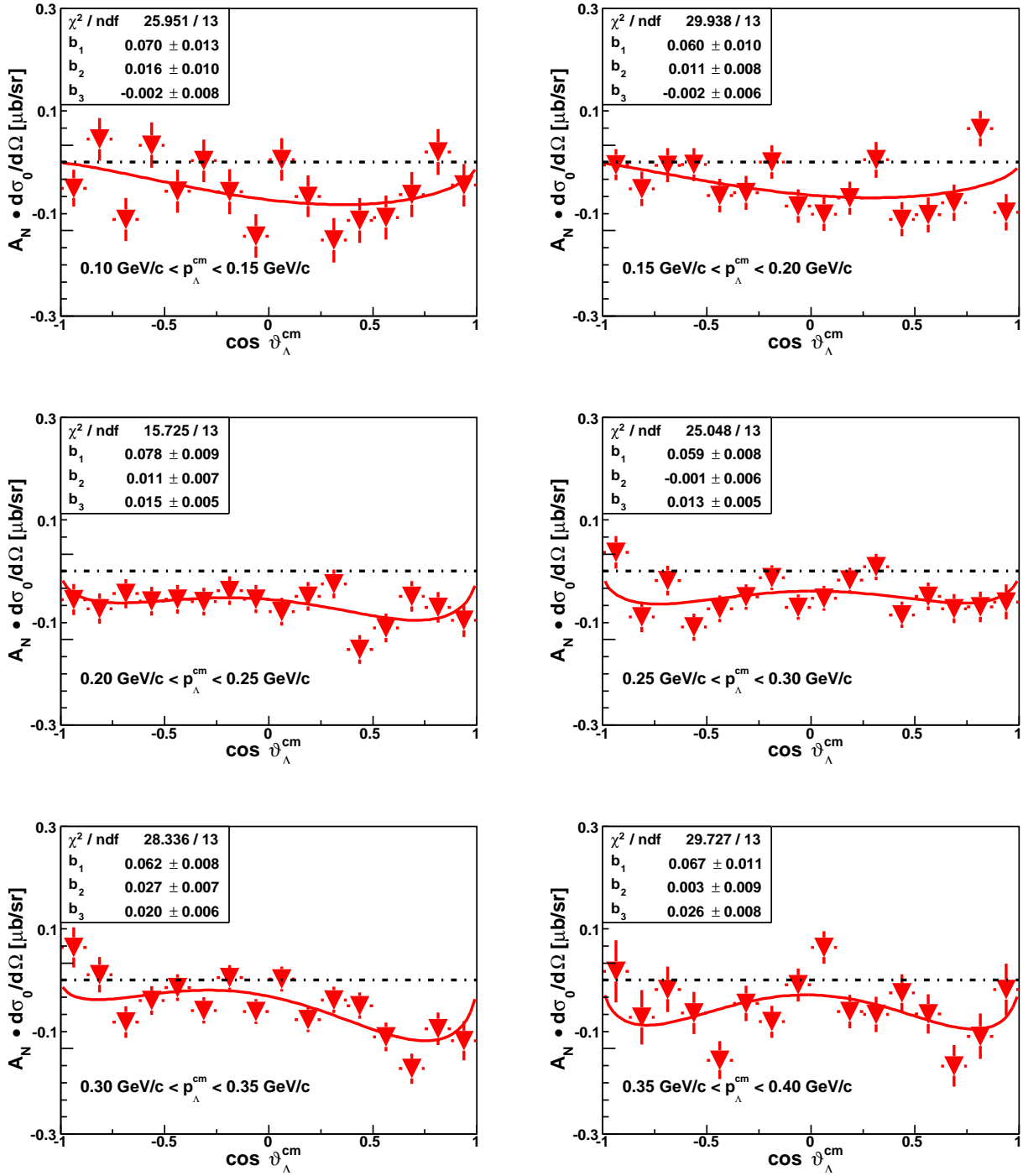


Fig. 21. The Λ analyzing power multiplied with the differential cross section is shown for different ranges of the Λ cm momentum for the 2.70 GeV/c data. The distributions have been fit with Legendre polynomials according to eq. 9. The fit results and the limits of the Λ cm momenta are given in each panel.

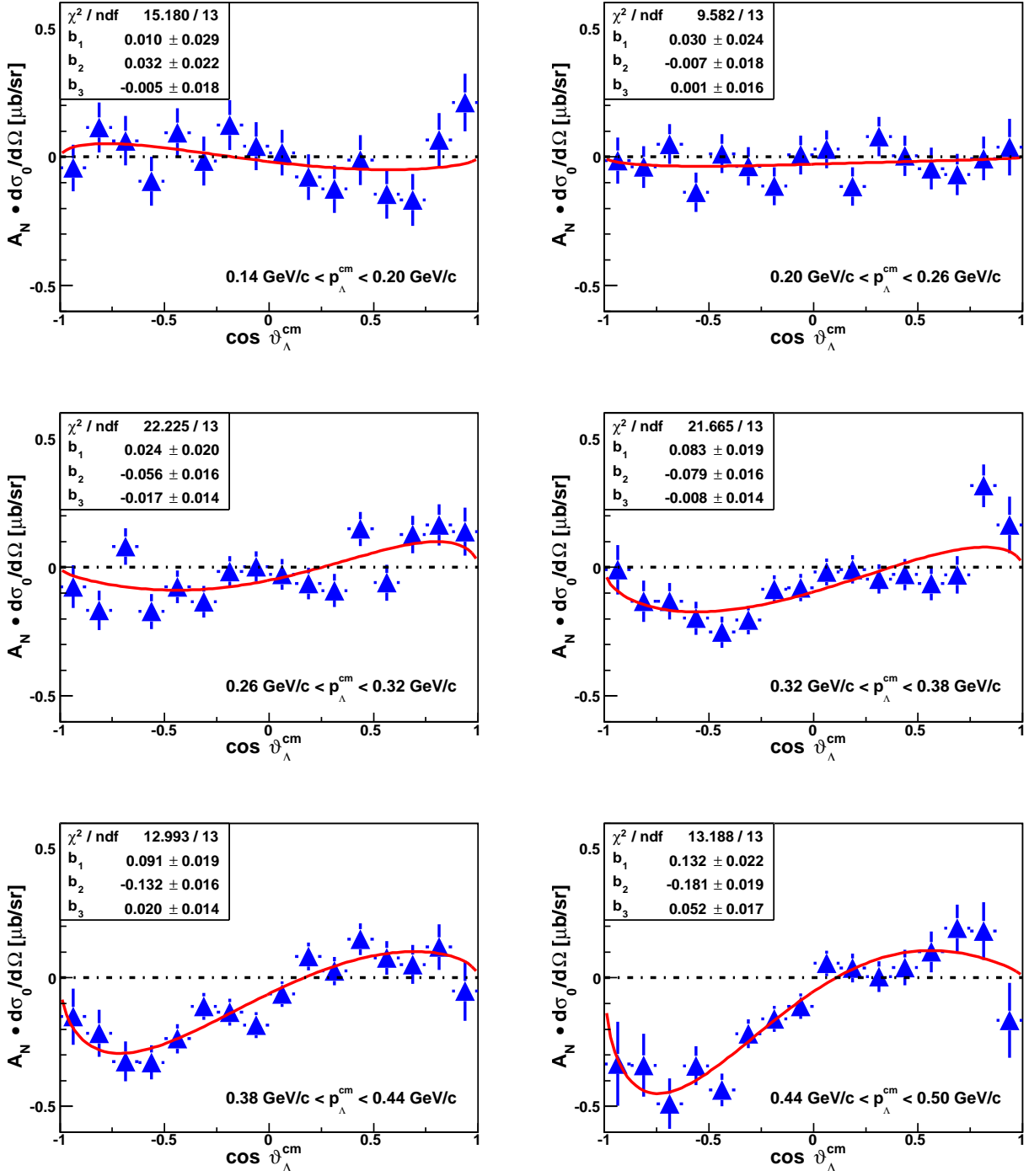


Fig. 22. The Λ analyzing power multiplied with the differential cross section is shown for different ranges of the Λ cm momentum for the 2.95 GeV/c data. The distributions have been fit with Legendre polynomials according to eq. 9. The fit results and the limits of the Λ cm momenta are given in each panel.

8 Appendix B

This appendix contains data tables with the measured quantities corresponding to figs. 2, 8, and 12.

Table 4. Λ polarization, dependence on Λ cm scattering angle

| $\cos\theta_{\Lambda}^*$ | $p_b = 2.70 \text{ GeV}/c$ | | $p_b = 2.95 \text{ GeV}/c$ | |
|--------------------------|----------------------------|-------|----------------------------|-------|
| | polarization | \pm | polarization | \pm |
| -0.9375 | -0.128 | 0.028 | -0.023 | 0.026 |
| -0.8125 | -0.172 | 0.027 | 0.026 | 0.026 |
| -0.6875 | -0.130 | 0.026 | 0.060 | 0.026 |
| -0.5625 | -0.161 | 0.026 | 0.081 | 0.027 |
| -0.4375 | -0.184 | 0.026 | 0.098 | 0.028 |
| -0.3125 | -0.100 | 0.026 | 0.139 | 0.028 |
| -0.1875 | -0.142 | 0.026 | 0.131 | 0.029 |
| -0.0625 | -0.066 | 0.026 | 0.018 | 0.030 |
| 0.0625 | -0.005 | 0.026 | 0.012 | 0.029 |
| 0.1875 | 0.021 | 0.026 | -0.142 | 0.029 |
| 0.3125 | 0.124 | 0.026 | -0.149 | 0.029 |
| 0.4375 | 0.051 | 0.025 | -0.120 | 0.028 |
| 0.5625 | 0.183 | 0.025 | -0.090 | 0.027 |
| 0.6875 | 0.227 | 0.025 | -0.063 | 0.026 |
| 0.8125 | 0.220 | 0.026 | -0.041 | 0.026 |
| 0.9375 | 0.167 | 0.028 | 0.039 | 0.028 |

Table 5. Λ polarization, dependence on Feynman x_F

| x_F | $p_b = 2.70 \text{ GeV}/c$ | | $p_b = 2.95 \text{ GeV}/c$ | |
|---------|----------------------------|-------|----------------------------|-------|
| | polarization | \pm | polarization | \pm |
| -0.9375 | -0.340 | 0.166 | 0.153 | 0.147 |
| -0.8125 | -0.108 | 0.056 | -0.019 | 0.053 |
| -0.6875 | -0.269 | 0.036 | -0.010 | 0.035 |
| -0.5625 | -0.202 | 0.028 | 0.074 | 0.028 |
| -0.4375 | -0.180 | 0.023 | 0.063 | 0.024 |
| -0.3125 | -0.147 | 0.021 | 0.100 | 0.022 |
| -0.1875 | -0.076 | 0.020 | 0.073 | 0.021 |
| -0.0625 | -0.082 | 0.019 | 0.053 | 0.021 |
| 0.0625 | -0.000 | 0.019 | -0.029 | 0.021 |
| 0.1875 | 0.080 | 0.020 | -0.101 | 0.022 |
| 0.3125 | 0.110 | 0.021 | -0.131 | 0.023 |
| 0.4375 | 0.212 | 0.024 | -0.084 | 0.025 |
| 0.5625 | 0.245 | 0.027 | -0.044 | 0.029 |
| 0.6875 | 0.190 | 0.034 | -0.054 | 0.036 |
| 0.8125 | 0.260 | 0.051 | 0.111 | 0.050 |
| 0.9375 | 0.621 | 0.121 | 0.211 | 0.115 |

Table 6. Λ polarization, dependence on the transversal momentum

| p_t [GeV/c] | $p_b = 2.70 \text{ GeV}/c$ | | $p_b = 2.95 \text{ GeV}/c$ | | |
|---------------|----------------------------|-------|----------------------------|--------|-------|
| | polarization | \pm | polarization | \pm | |
| 0.016 | -0.092 | 0.063 | 0.019 | 0.069 | 0.065 |
| 0.047 | 0.028 | 0.035 | 0.056 | 0.015 | 0.037 |
| 0.078 | 0.070 | 0.027 | 0.094 | 0.042 | 0.028 |
| 0.109 | 0.112 | 0.022 | 0.131 | -0.038 | 0.023 |
| 0.141 | 0.086 | 0.019 | 0.169 | -0.040 | 0.020 |
| 0.172 | 0.106 | 0.018 | 0.206 | -0.036 | 0.019 |
| 0.203 | 0.127 | 0.018 | 0.244 | -0.062 | 0.019 |
| 0.234 | 0.170 | 0.018 | 0.281 | -0.077 | 0.020 |
| 0.266 | 0.166 | 0.020 | 0.319 | -0.065 | 0.021 |
| 0.297 | 0.227 | 0.022 | 0.356 | -0.166 | 0.024 |
| 0.328 | 0.161 | 0.027 | 0.394 | -0.125 | 0.028 |
| 0.359 | 0.132 | 0.037 | 0.431 | -0.206 | 0.035 |
| 0.391 | 0.008 | 0.102 | 0.469 | -0.178 | 0.055 |
| - | - | - | 0.506 | -0.281 | 0.165 |

Table 7. Analyzing power, 2.70 GeV/c data dependence on the cm scattering angle

| $\cos(\vartheta^*)$ | $A_N(\varphi^P)$ | \pm | $A_N(\varphi^K)$ | \pm | $A_N(\varphi^\Lambda)$ | \pm |
|---------------------|------------------|-------|------------------|-------|------------------------|-------|
| -0.9375 | -0.002 | 0.014 | 0.080 | 0.019 | -0.001 | 0.017 |
| -0.8125 | -0.003 | 0.014 | 0.131 | 0.018 | -0.046 | 0.016 |
| -0.6875 | -0.018 | 0.015 | 0.177 | 0.017 | -0.038 | 0.016 |
| -0.5625 | -0.055 | 0.016 | 0.155 | 0.017 | -0.066 | 0.016 |
| -0.4375 | -0.055 | 0.016 | 0.181 | 0.016 | -0.076 | 0.016 |
| -0.3125 | -0.046 | 0.017 | 0.141 | 0.016 | -0.069 | 0.016 |
| -0.1875 | -0.085 | 0.017 | 0.151 | 0.016 | -0.029 | 0.016 |
| -0.0625 | -0.076 | 0.018 | 0.156 | 0.016 | -0.083 | 0.017 |
| 0.0625 | -0.029 | 0.018 | 0.129 | 0.016 | -0.045 | 0.016 |
| 0.1875 | -0.007 | 0.018 | 0.107 | 0.016 | -0.069 | 0.017 |
| 0.3125 | -0.019 | 0.018 | 0.090 | 0.016 | -0.047 | 0.017 |
| 0.4375 | -0.071 | 0.018 | 0.071 | 0.016 | -0.107 | 0.016 |
| 0.5625 | -0.016 | 0.017 | 0.046 | 0.016 | -0.107 | 0.016 |
| 0.6875 | -0.056 | 0.016 | 0.016 | 0.016 | -0.112 | 0.016 |
| 0.8125 | -0.011 | 0.015 | 0.070 | 0.016 | -0.065 | 0.016 |
| 0.9375 | -0.023 | 0.016 | 0.052 | 0.017 | -0.089 | 0.017 |

Table 8. Analyzing power, 2.95 GeV/c data dependence on the cm scattering angle

| $\cos(\vartheta^*)$ | $A_N(\varphi^P)$ | \pm | $A_N(\varphi^K)$ | \pm | $A_N(\varphi^\Lambda)$ | \pm |
|---------------------|------------------|-------|------------------|-------|------------------------|-------|
| -0.9375 | 0.015 | 0.016 | 0.071 | 0.024 | -0.034 | 0.017 |
| -0.8125 | 0.019 | 0.016 | 0.122 | 0.023 | -0.065 | 0.017 |
| -0.6875 | 0.013 | 0.018 | 0.171 | 0.020 | -0.057 | 0.017 |
| -0.5625 | -0.052 | 0.018 | 0.189 | 0.019 | -0.129 | 0.018 |
| -0.4375 | -0.088 | 0.019 | 0.188 | 0.018 | -0.119 | 0.019 |
| -0.3125 | -0.084 | 0.019 | 0.135 | 0.018 | -0.100 | 0.019 |
| -0.1875 | -0.022 | 0.019 | 0.150 | 0.018 | -0.057 | 0.020 |
| -0.0625 | -0.095 | 0.019 | 0.189 | 0.018 | -0.048 | 0.020 |
| 0.0625 | -0.078 | 0.020 | 0.149 | 0.018 | -0.020 | 0.019 |
| 0.1875 | -0.089 | 0.020 | 0.089 | 0.018 | -0.015 | 0.020 |
| 0.3125 | -0.075 | 0.020 | 0.060 | 0.018 | -0.011 | 0.019 |
| 0.4375 | -0.087 | 0.020 | 0.070 | 0.018 | 0.048 | 0.019 |
| 0.5625 | -0.002 | 0.020 | -0.003 | 0.018 | 0.001 | 0.019 |
| 0.6875 | 0.005 | 0.019 | -0.003 | 0.018 | 0.009 | 0.018 |
| 0.8125 | 0.041 | 0.018 | -0.035 | 0.018 | 0.066 | 0.017 |
| 0.9375 | 0.058 | 0.019 | -0.000 | 0.022 | 0.027 | 0.018 |

Table 9. Analyzing power, 2.70 GeV/c data dependence on Feynman x_F

| x_F | $A_N(\varphi^P)$ | \pm | $A_N(\varphi^K)$ | \pm | $A_N(\varphi^\Lambda)$ | \pm |
|---------|------------------|-------|------------------|-------|------------------------|-------|
| -0.9375 | -0.014 | 0.056 | 0.144 | 0.081 | 0.110 | 0.096 |
| -0.8125 | -0.002 | 0.024 | 0.118 | 0.033 | 0.043 | 0.034 |
| -0.6875 | -0.018 | 0.017 | 0.207 | 0.022 | -0.000 | 0.022 |
| -0.5625 | -0.051 | 0.015 | 0.181 | 0.017 | -0.056 | 0.017 |
| -0.4375 | -0.016 | 0.014 | 0.133 | 0.015 | -0.056 | 0.015 |
| -0.3125 | -0.026 | 0.013 | 0.144 | 0.014 | -0.069 | 0.013 |
| -0.1875 | -0.062 | 0.013 | 0.143 | 0.013 | -0.047 | 0.012 |
| -0.0625 | -0.057 | 0.013 | 0.136 | 0.013 | -0.065 | 0.012 |
| 0.0625 | -0.024 | 0.013 | 0.119 | 0.013 | -0.062 | 0.012 |
| 0.1875 | -0.030 | 0.014 | 0.110 | 0.013 | -0.057 | 0.013 |
| 0.3125 | -0.042 | 0.015 | 0.077 | 0.014 | -0.089 | 0.014 |
| 0.4375 | -0.051 | 0.015 | 0.042 | 0.014 | -0.085 | 0.015 |
| 0.5625 | -0.031 | 0.017 | 0.044 | 0.015 | -0.141 | 0.017 |
| 0.6875 | -0.011 | 0.020 | 0.031 | 0.018 | -0.067 | 0.021 |
| 0.8125 | 0.031 | 0.027 | 0.023 | 0.026 | -0.093 | 0.031 |
| 0.9375 | -0.005 | 0.068 | -0.041 | 0.071 | -0.090 | 0.073 |

Table 10. Analyzing power, 2.95 GeV/c data dependence on Feynman x_F

| x_F | $A_N(\varphi^P)$ | \pm | $A_N(\varphi^K)$ | \pm | $A_N(\varphi^\Lambda)$ | \pm |
|---------|------------------|-------|------------------|-------|------------------------|-------|
| -0.9375 | 0.030 | 0.064 | -0.091 | 0.123 | -0.311 | 0.093 |
| -0.8125 | 0.007 | 0.026 | 0.185 | 0.050 | -0.105 | 0.035 |
| -0.6875 | 0.021 | 0.019 | 0.134 | 0.028 | -0.043 | 0.023 |
| -0.5625 | -0.009 | 0.017 | 0.155 | 0.020 | -0.108 | 0.019 |
| -0.4375 | -0.044 | 0.016 | 0.164 | 0.017 | -0.112 | 0.016 |
| -0.3125 | -0.054 | 0.015 | 0.175 | 0.015 | -0.089 | 0.015 |
| -0.1875 | -0.043 | 0.015 | 0.130 | 0.014 | -0.066 | 0.014 |
| -0.0625 | -0.051 | 0.015 | 0.173 | 0.014 | -0.029 | 0.014 |
| 0.0625 | -0.067 | 0.015 | 0.157 | 0.014 | -0.023 | 0.014 |
| 0.1875 | -0.105 | 0.016 | 0.073 | 0.015 | -0.000 | 0.015 |
| 0.3125 | -0.025 | 0.017 | 0.070 | 0.015 | 0.009 | 0.016 |
| 0.4375 | 0.004 | 0.018 | 0.007 | 0.016 | 0.036 | 0.017 |
| 0.5625 | 0.035 | 0.020 | -0.042 | 0.018 | 0.076 | 0.019 |
| 0.6875 | 0.019 | 0.022 | -0.064 | 0.021 | 0.076 | 0.024 |
| 0.8125 | 0.073 | 0.029 | -0.144 | 0.031 | -0.055 | 0.033 |
| 0.9375 | 0.122 | 0.063 | 0.032 | 0.079 | 0.080 | 0.075 |

Table 11. Analyzing power, 2.70 GeV/c data dependence on transversal momentum

| p_t [GeV/c] | $A_N(\varphi^P)$ | \pm | $A_N(\varphi^K)$ | \pm | $A_N(\varphi^\Lambda)$ | \pm |
|---------------|------------------|-------|------------------|-------|------------------------|-------|
| 0.016 | 0.071 | 0.108 | 0.143 | 0.048 | -0.064 | 0.038 |
| 0.047 | -0.008 | 0.022 | 0.030 | 0.020 | -0.069 | 0.022 |
| 0.078 | -0.016 | 0.014 | 0.067 | 0.015 | -0.029 | 0.017 |
| 0.109 | -0.028 | 0.012 | 0.087 | 0.013 | -0.032 | 0.014 |
| 0.141 | 0.002 | 0.011 | 0.113 | 0.012 | -0.064 | 0.012 |
| 0.172 | -0.035 | 0.011 | 0.116 | 0.011 | -0.073 | 0.011 |
| 0.203 | -0.035 | 0.011 | 0.110 | 0.011 | -0.066 | 0.011 |
| 0.234 | -0.038 | 0.012 | 0.142 | 0.011 | -0.088 | 0.011 |
| 0.266 | -0.049 | 0.013 | 0.114 | 0.011 | -0.086 | 0.012 |
| 0.297 | -0.056 | 0.016 | 0.117 | 0.013 | -0.057 | 0.014 |
| 0.328 | -0.086 | 0.020 | 0.122 | 0.042 | -0.080 | 0.017 |
| 0.359 | -0.113 | 0.027 | - | - | -0.039 | 0.023 |
| 0.391 | -0.115 | 0.117 | - | - | -0.045 | 0.064 |

Table 12. Analyzing power, 2.95 GeV/c data dependence on transversal momentum

| p_t [GeV/c] | $A_N(\varphi^P)$ | \pm | $A_N(\varphi^K)$ | \pm | $A_N(\varphi^\Lambda)$ | \pm |
|---------------|------------------|-------|------------------|-------|------------------------|-------|
| 0.019 | 0.111 | 0.113 | 0.094 | 0.061 | -0.014 | 0.041 |
| 0.056 | -0.057 | 0.032 | 0.019 | 0.027 | 0.033 | 0.024 |
| 0.094 | 0.023 | 0.020 | 0.066 | 0.020 | 0.017 | 0.018 |
| 0.131 | 0.002 | 0.016 | 0.112 | 0.017 | -0.009 | 0.015 |
| 0.169 | 0.026 | 0.014 | 0.117 | 0.015 | -0.015 | 0.014 |
| 0.206 | 0.002 | 0.014 | 0.129 | 0.013 | 0.001 | 0.013 |
| 0.244 | 0.020 | 0.014 | 0.114 | 0.012 | -0.018 | 0.013 |
| 0.281 | 0.002 | 0.014 | 0.091 | 0.012 | -0.048 | 0.013 |
| 0.319 | -0.039 | 0.014 | 0.085 | 0.012 | -0.081 | 0.014 |
| 0.356 | -0.066 | 0.015 | 0.080 | 0.015 | -0.059 | 0.016 |
| 0.394 | -0.111 | 0.016 | 0.067 | 0.019 | -0.073 | 0.019 |
| 0.431 | -0.169 | 0.019 | 0.131 | 0.048 | -0.089 | 0.024 |
| 0.469 | -0.128 | 0.026 | - | - | -0.103 | 0.037 |
| 0.506 | -0.148 | 0.084 | - | - | -0.221 | 0.110 |

Table 13. D_{NN} , dependence on Λ cm scattering angle

| $\cos\vartheta_{\Lambda}^*$ | $p_b = 2.70 \text{ GeV}/c$ | | $p_b = 2.95 \text{ GeV}/c$ | |
|-----------------------------|----------------------------|-------|----------------------------|-------|
| | D_{NN} | \pm | D_{NN} | \pm |
| -0.9375 | -0.645 | 0.070 | -0.172 | 0.070 |
| -0.8125 | -0.384 | 0.067 | -0.179 | 0.070 |
| -0.6875 | -0.523 | 0.066 | -0.263 | 0.072 |
| -0.5625 | -0.473 | 0.065 | -0.453 | 0.074 |
| -0.4375 | -0.347 | 0.065 | -0.435 | 0.076 |
| -0.3125 | -0.445 | 0.065 | -0.485 | 0.077 |
| -0.1875 | -0.365 | 0.066 | -0.275 | 0.080 |
| -0.0625 | -0.226 | 0.067 | -0.260 | 0.080 |
| 0.0625 | -0.305 | 0.066 | -0.318 | 0.079 |
| 0.1875 | -0.321 | 0.066 | -0.182 | 0.080 |
| 0.3125 | -0.215 | 0.066 | -0.383 | 0.078 |
| 0.4375 | -0.315 | 0.064 | -0.323 | 0.076 |
| 0.5625 | -0.430 | 0.064 | -0.252 | 0.075 |
| 0.6875 | -0.349 | 0.065 | -0.420 | 0.071 |
| 0.8125 | -0.455 | 0.065 | -0.407 | 0.070 |
| 0.9375 | -0.498 | 0.072 | -0.256 | 0.075 |

Table 14. D_{NN} , dependence on Feynman x_F

| x_F | $p_b = 2.70 \text{ GeV}/c$ | | $p_b = 2.95 \text{ GeV}/c$ | |
|---------|----------------------------|-------|----------------------------|-------|
| | D_{NN} | \pm | D_{NN} | \pm |
| -0.9375 | 0.181 | 0.422 | 0.206 | 0.401 |
| -0.8125 | -0.636 | 0.140 | 0.042 | 0.144 |
| -0.6875 | -0.306 | 0.091 | 0.040 | 0.096 |
| -0.5625 | -0.407 | 0.070 | -0.268 | 0.076 |
| -0.4375 | -0.497 | 0.059 | -0.284 | 0.066 |
| -0.3125 | -0.447 | 0.054 | -0.313 | 0.061 |
| -0.1875 | -0.469 | 0.050 | -0.559 | 0.058 |
| -0.0625 | -0.333 | 0.049 | -0.305 | 0.057 |
| 0.0625 | -0.349 | 0.049 | -0.259 | 0.057 |
| 0.1875 | -0.235 | 0.050 | -0.323 | 0.059 |
| 0.3125 | -0.306 | 0.054 | -0.243 | 0.062 |
| 0.4375 | -0.517 | 0.060 | -0.391 | 0.068 |
| 0.5625 | -0.379 | 0.069 | -0.410 | 0.078 |
| 0.6875 | -0.530 | 0.086 | -0.355 | 0.096 |
| 0.8125 | -0.348 | 0.128 | -0.426 | 0.134 |
| 0.9375 | -0.285 | 0.312 | -0.452 | 0.313 |

Table 15. D_{NN} , dependence on the transversal momentum

| p_t [GeV/c] | $p_b = 2.70 \text{ GeV}/c$ | | | $p_b = 2.95 \text{ GeV}/c$ | | |
|---------------|----------------------------|-------|--|----------------------------|--------|-------|
| | D_{NN} | \pm | | D_{NN} | \pm | |
| 0.016 | -0.784 | 0.157 | | 0.019 | -0.231 | 0.172 |
| 0.047 | -0.707 | 0.089 | | 0.056 | -0.217 | 0.098 |
| 0.078 | -0.505 | 0.068 | | 0.094 | -0.408 | 0.075 |
| 0.109 | -0.503 | 0.056 | | 0.131 | -0.338 | 0.061 |
| 0.141 | -0.438 | 0.048 | | 0.169 | -0.298 | 0.055 |
| 0.172 | -0.460 | 0.045 | | 0.206 | -0.350 | 0.053 |
| 0.203 | -0.319 | 0.045 | | 0.244 | -0.337 | 0.052 |
| 0.234 | -0.370 | 0.046 | | 0.281 | -0.292 | 0.054 |
| 0.266 | -0.457 | 0.050 | | 0.319 | -0.366 | 0.058 |
| 0.297 | -0.266 | 0.056 | | 0.356 | -0.294 | 0.064 |
| 0.328 | -0.034 | 0.067 | | 0.394 | -0.246 | 0.076 |
| 0.359 | -0.160 | 0.094 | | 0.431 | -0.253 | 0.096 |
| 0.391 | 0.034 | 0.258 | | 0.469 | -0.244 | 0.150 |
| - | - | - | | 0.506 | 0.000 | 0.456 |

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