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# The measurement of the transverse polarization of $\Lambda$ hyperons produced in $nC$ reactions in the EXCHARM experiment

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**Abstract.** New precise data of the $\Lambda^0$ polarization are obtained in the EXCHARM experiment at the Serpukhov accelerator. The $\Lambda^0$s have been produced in $nC$ interactions in the neutron energy interval 40–70 GeV and detected in the kinematic range of $0.1 \lesssim x_F \lesssim 0.6$ and $0.2 \leq p_t \leq 1.2$ GeV/$c$. The obtained results are compared with other measurements in the $pp$ and $pA$ interactions.

## 1 Introduction

It has been observed more than 15 years ago (see e.g., [1]) that the $\Lambda^0$s produced inclusively by unpolarized protons have a significant polarization. The polarization has been investigated over a wide range of reaction energies and at various $\Lambda^0$ production angles. The absolute value of the polarization has been found to grow approximately linearly with $\Lambda^0$ transverse momentum $p_t$ in the region of $p_t < 1$ GeV/$c$. Some theoretical models attempt to describe the experimental data on the polarization [6–8], but the polarization mechanism is still not well understood.

Most of the experiments have been carried out in proton beams. Up to now, only one experiment has been performed in the neutron beam [9] which indicated a rather higher polarization of the $\Lambda^0$s than the ones in the proton beam at different energies. In this paper new results of $\Lambda^0$ polarization measured in the $nC$ reaction are presented. The experiment is performed at the Serpukhov accelerator with the EXCHARM spectrometer located in the neutral channel 5N.

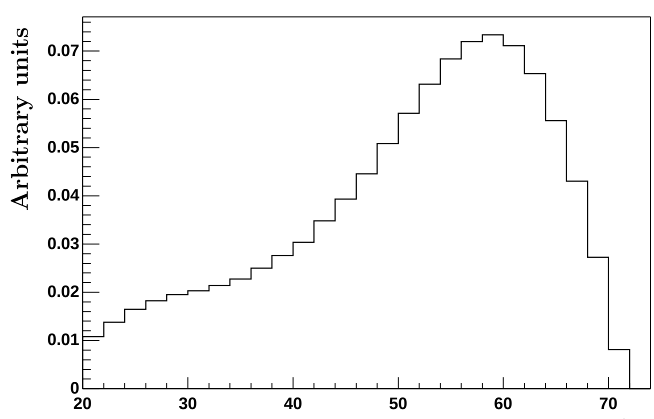

**Fig. 1.** Neutron beam energy spectrum

## 2 Experimental set-up and data taking

Neutrons were produced on a 3 mm in diameter and 3 cm long inner beryllium target by 70 GeV primary protons. The target is followed by a set of collimators located at an angle of $\approx 0°$ with respect to the incident protons. The neutral channel 5N of $\approx$ 110 m long includes the set of collimators and a 20 cm lead filter for $\gamma$ rejection. Charged particles were swept out by the accelerator magnets and a

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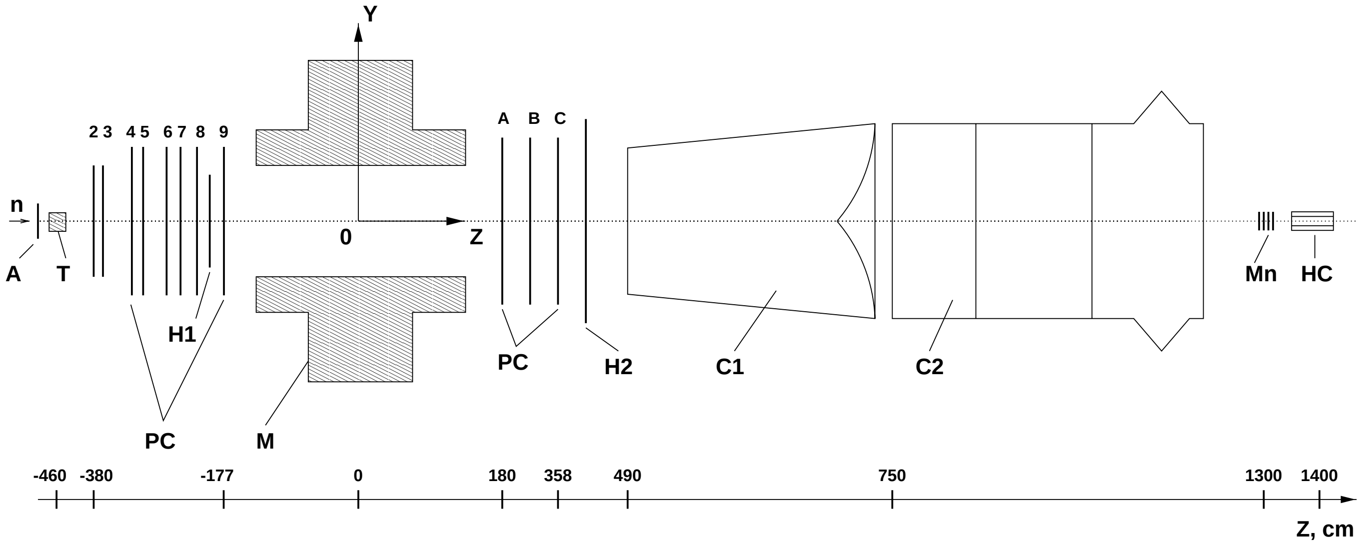


**Fig. 2.** Set-up of EXCHARM spectrometer (schematic)

special sweeping magnet, $SP-129$, installed at the exit of the final collimator. The neutron beam energy spectrum has a maximum at $\approx 58$ GeV and a width of $\approx 12$ GeV (Fig. 1).

The lay-out of the EXCHARM set-up is presented in Fig. 2. The detector is described in a right handed orthogonal coordinate system with the OZ axis directed along the beam (n). The center of the coordinate system coincides with the center of the analyzing magnet M. The magnet has an aperture of $274 \times 4\,\text{cm}^2$ with a maximum field of $\approx 0.79$ T. The magnetic field was directed vertically along the 0Y axis. The polarity of the magnetic field was alternated every 5–6 h during data taking. The neutron beam was interacting with the $1.3\,\text{g/cm}^2$ (1.5 cm) long carbon target $T$ located in front of the spectrometer. The particles produced were detected by 11 proportional chambers (PC) with 0.2 cm wire spacing (25 coordinate planes in total). The PC dimensions are up to $100 \times 60\,\text{cm}^2$ (before the magnet) and $200 \times 100\,\text{cm}^2$ (after the magnet). The two scintillator hodoscopes $H1$ and $H2$ consist of 15 and 60 counters, respectively. The two Čerenkov counters $C1$ and $C2$, filled with air and freon, respectively, are intended to distinguish protons, $K$ and $\pi$ mesons. In the present analysis $C1$ and $C2$ were not used. The set-up geometry is symmetric with respect to the horizontal plane X0Z.

The trigger was designed as a coincidence logic of signals from $H1$, $H2$, three hodoscopes of the PC planes, and a charge anti-counter A as a veto. The trigger condition required at least four charged particles passed through the spectrometer.

A more detailed description of the apparatus can be found elsewhere [10].

## 3 Event selection

The presented results are based on the analysis of $1.72 \times 10^8$ nC interactions recorded under the mentioned conditions. $\Lambda^0$s have been selected by their decay

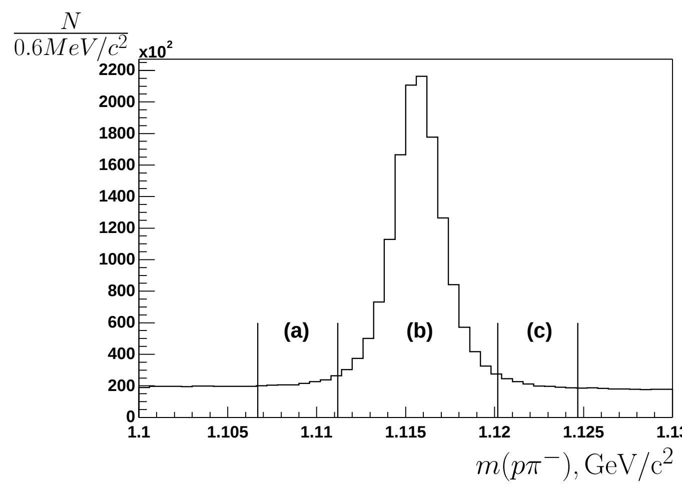


**Fig. 3.** Effective mass spectrum of $p\pi^-$. Events in region **b** are selected as $\Lambda^0$ while events in regions **a** and **c** are treated as the background

$$\Lambda^0 \to p\pi^- \tag{1}$$

which corresponds to the so-called "$V^0$" topology. $V^0$ is a pair of reconstructed tracks of positive and negative particles. These tracks have to meet within 0.4 cm (closest distance of approach: CDA) which corresponds to 3 times of the experimental resolution on this parameter. To reduce the background caused by interactions in the target and chamber media it was required that the Z coordinate of the $\Lambda^0$ decay vertex occupy a region from 5 cm downstream from the target to the first PC. The $\Lambda^0$ production point (event vertex) was reconstructed as a point of CDA of all particles detected in the event. A cut was applied on the event vertex quality: the distance between the CDA point and each track used for the vertex reconstruction should not exceed $3 \cdot \sigma$ where $\sigma \approx 0.1$ cm is the experimental resolution on this parameter. The event vertex

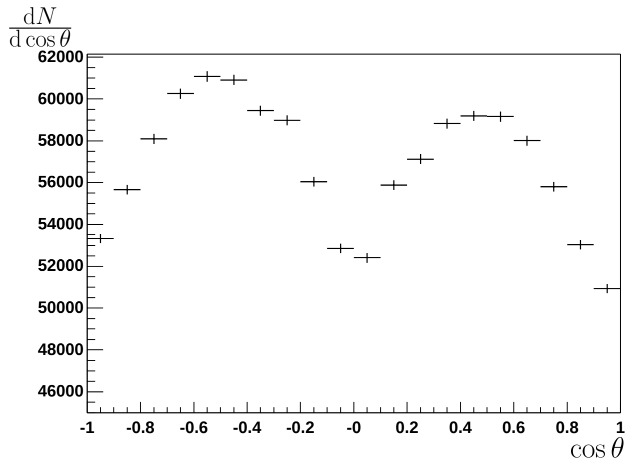

**Fig. 4.** Experimental angular distribution of $\Lambda^0$ decay proton

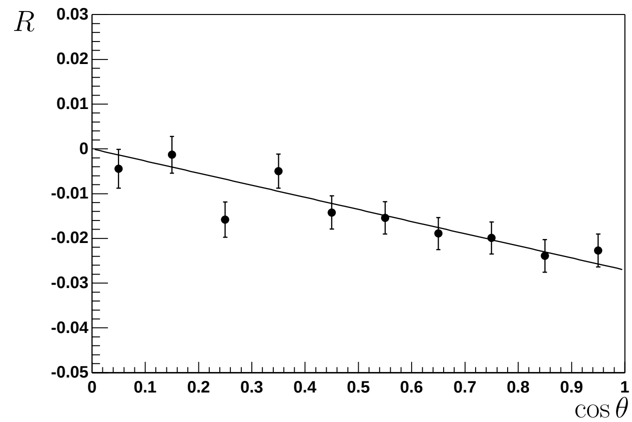

**Fig. 5.** Distribution of $R$ (4) for all selected $\Lambda^0$

should not be further than 3 cm from the target $T$ nominal position, which corresponds to the target thickness taking into account the event vertex resolution.

The $p\pi^-$ effective mass, $m(p\pi^-)$, spectrum for selected $V^0$s is shown in Fig. 3. Events have been identified as (1) decays if the $m(p\pi^-)$was within $3\sigma_m$ of the $\Lambda^0$ nominal mass ($\sigma_m \approx 1.5$ MeV is the experimental resolution on the $m(p\pi^-)$). The integrated number of $\Lambda^0$ decays in the signal is $\approx 1.1 \times 10^6$ and the signal to background ratio is $\approx 3.3$. These values were estimated by the approximation of the spectrum by the sum of the Gaussian function for the signal and a constant value for the background. Background distributions for all subsequent analyses were estimated using sidebands (marked as (a) and (c) in Fig. 3) of the signal mass region and subtracted.

## 4 Polarization measurement

According to the parity conservation in strong interactions, any non-vanishing polarization must be transverse to the production plane defined as $\mathbf{n}_{\text{prod}} = \mathbf{k_n} \times \mathbf{k_\Lambda}$, where $\mathbf{k_n}$ and $\mathbf{k_\Lambda}$ are the direction vectors of the neutron beam and $\Lambda^0$, respectively. The vector $\mathbf{k_n}$ was reconstructed as a vector pointing from the inner target center to the reconstructed event vertex. The $\Lambda^0$ polarization ($\mathcal{P}$) is determined by the angular distribution of the decay proton in the $\Lambda^0$ rest frame,

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} = A(\cos\theta)(1 + \alpha\mathcal{P}\cdot\cos\theta) \tag{2}$$

where $\cos\theta = \mathbf{n}_{\text{prod}} \cdot \mathbf{k_p}$, ( $\mathbf{k_p}$ is the direction vector of the decay proton), $\alpha = 0.642$ is the $\Lambda^0$ decay asymmetry parameter [11], and $A(\cos\theta)$ is the acceptance which depends on $\cos\theta$ and the set of kinematic variables. The experimental distribution of (2) is shown in Fig. 4 and indicates rather clearly the significant influence of the acceptance.

To measure the $\Lambda^0$ polarization the so-called bias canceling technique was applied, similar to the one used in [12,13]. The applied method exploits the symmetry of the set-up with respect to the horizontal Z0X plane (the magnetic field is directed vertically). The two distributions (2) were plotted separately for each of the azimuthal sectors of the $\Lambda$ production direction: upstream ("Up") and downstream ("Down") the Z0X plane; these are related with the $\mathcal{P}$ in the following way:

$$U(\cos\theta) \equiv \frac{\mathrm{d}N_U}{\mathrm{d}\cos\theta} = A_U(\cos\theta)(1 + \alpha\mathcal{P}\cdot\cos\theta),$$

$$D(\cos\theta) \equiv \frac{\mathrm{d}N_D}{\mathrm{d}\cos\theta} = A_D(\cos\theta)(1 + \alpha\mathcal{P}\cdot\cos\theta),$$

where $N_U$ and $N_D$ are the numbers of $\Lambda^0$ produced in the "Up" and "Down" sectors, respectively. In the estimation of $U(\cos\theta)$ and $D(\cos\theta)$ the background events have been subtracted. If the upper and lower parts of the detector are symmetric versus X0Z plane, then

$$A_U(\cos\theta) = A_D(-\cos\theta), \tag{3}$$

for $-1 < \cos\theta < 1$, and thus the ratio

$$R \equiv \frac{\sqrt{U(\cos\theta)D(\cos\theta)} - \sqrt{U(-\cos\theta)D(-\cos\theta)}}{\sqrt{U(\cos\theta)D(\cos\theta)} + \sqrt{U(-\cos\theta)D(-\cos\theta)}}, \tag{4}$$

defined in the region of $0 < \cos\theta < 1$, is not biased by the acceptances and is related to $\mathcal{P}$ by

$$R = \alpha\mathcal{P}\cdot\cos\theta. \tag{5}$$

The obtained distribution of $R$ over $\cos\theta$ for all selected $\Lambda^0$s is presented in Fig. 5 as well as its fit by the expression (5). The obtained $\Lambda^0$ polarization is

$$\mathcal{P} = (-4.2 \pm 0.3)\%.$$

The obtained value of $\chi^2/N\mathrm{d}f = 8.8/9$ indicates that the hypothesis (3) is reasonable and the applied procedure can be implemented.

The polarization has been measured as a function of the $\Lambda^0$ transverse momentum $p_{\text{t}}$ and the Feynman variable $x_{\text{F}}$.

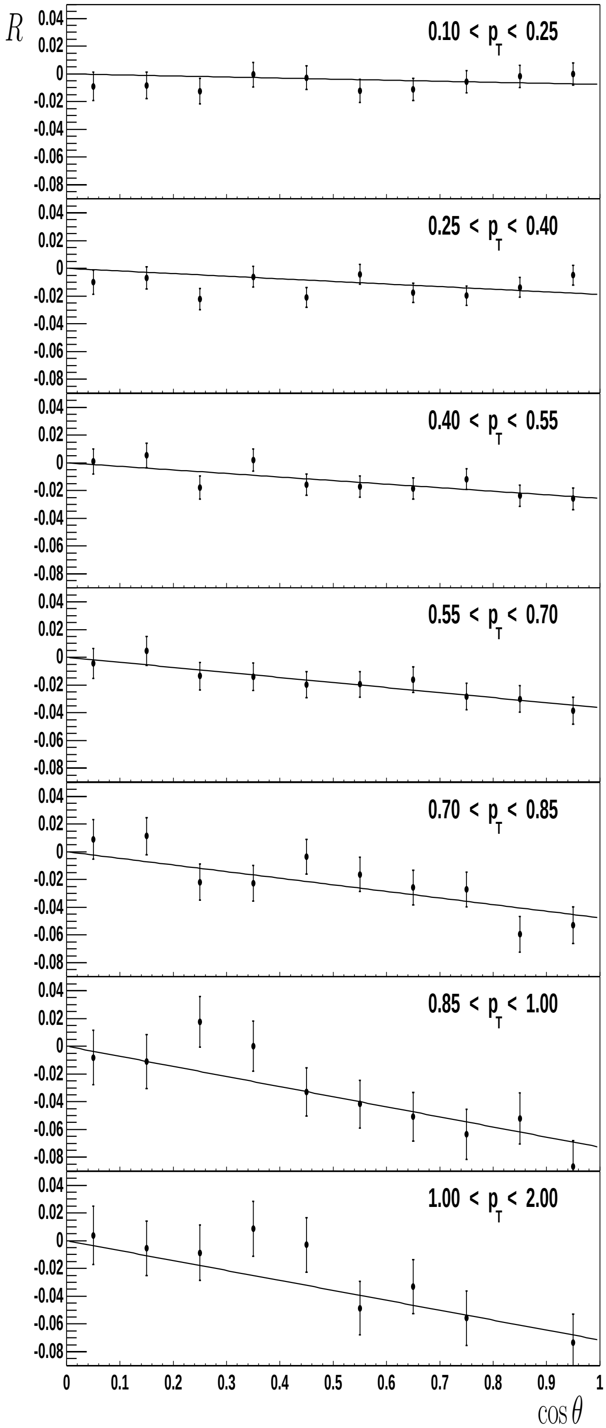


**Fig. 6.** Distributions of $R$ (4) obtained in seven $p_t$ intervals

Figure 6 shows the distributions of $R$ over $\cos\theta$ and its fit by (5) for the different $p_t$ ranges for all accepted $\Lambda^0$s which are characterized by $\langle x_F\rangle = 0.34^{+0.19}_{-0.23}$. The results of the fit are presented in Table 1. The data show a reasonable agreement with the assumption (3) for all intervals of $p_t$.

Since the initial neutron momentum is not known in each of the detected events, the $x_F$ regions have been determined by a selection of three intervals of $\Lambda^0$ longitudinal momentum $p_L$. A significant correlation between $x_F$ and $p_L$ was obtained from a Monte Carlo simulation (Fig. 7). The arrows in Fig. 7 indicate three chosen $p_L$ intervals which correspond to a particular $x_F$ region. The polarization measured in each of the three chosen $x_F$ regions and in all $p_t$ intervals are listed in Table 2. Figure 8 shows $\mathcal{P}$ as a function of $p_t$ separately for each of three $x_F$ regions. Our results reveal a nearly linear dependence of the polarization versus $p_t$ at fixed $x_F$. The $\Lambda^0$ polarization as a function of $x_f$ is also listed in Table 2 and is plotted in Fig. 9. The polarization was found to increase roughly linearly with $x_F$. The errors quoted in Table 2 and in Figs. 8 and 9 are statistical only.

**Table 1.** $\Lambda^0$ polarization as a function of $p_t$ obtained at $\langle x_F\rangle = 0.34^{+0.19}_{-0.23}$. The $\chi^2/Ndf$ column refers to the hypothesis (3)

| $p_t$ interval, GeV/$c$ | $\langle p_t\rangle$, GeV/$c$ | $\mathcal{P}$, % | $\chi^2/Ndf$ |
|---|---|---|---|
| $0.10 \div 0.25$ | 0.20 | $-1.2 \pm 0.7$ | 5.4/9 |
| $0.25 \div 0.40$ | 0.32 | $-2.9 \pm 0.6$ | 15.0/9 |
| $0.40 \div 0.55$ | 0.48 | $-4.0 \pm 0.7$ | 6.4/9 |
| $0.55 \div 0.70$ | 0.61 | $-5.7 \pm 0.8$ | 2.2/9 |
| $0.70 \div 0.85$ | 0.77 | $-7.4 \pm 1.1$ | 9.2/9 |
| $0.85 \div 1.00$ | 0.91 | $-11.3 \pm 1.6$ | 7.4/9 |
| $1.00 \div 2.00$ | 1.18 | $-11.2 \pm 1.7$ | 9.0/9 |

**Table 2.** The $\Lambda^0$ polarization as a function of $p_t$ for the three $x_F$ data sets

| $\langle p_t\rangle$, GeV/$c$ | $\langle x_F\rangle$ $0.16^{+0.09}_{-0.12}$ | $\langle x_F\rangle$ $0.35^{+0.08}_{-0.13}$ | $\langle x_F\rangle$ $0.56^{+0.12}_{-0.17}$ |
|---|---|---|---|
| | $\mathcal{P}$, % | $\mathcal{P}$, % | $\mathcal{P}$, % |
| 0.20 | $-1.2 \pm 0.9$ | $-1.8 \pm 1.2$ | $+1.2 \pm 2.7$ |
| 0.32 | $-3.4 \pm 0.8$ | $-2.9 \pm 1.0$ | $-2.1 \pm 2.1$ |
| 0.48 | $-1.0 \pm 1.0$ | $-6.4 \pm 1.0$ | $-6.2 \pm 2.1$ |
| 0.61 | $-2.0 \pm 1.4$ | $-7.5 \pm 1.1$ | $-7.8 \pm 2.3$ |
| 0.77 | $-1.6 \pm 2.0$ | $-8.7 \pm 1.5$ | $-12.8 \pm 2.8$ |
| 0.91 | $-0.4 \pm 2.9$ | $-12.4 \pm 2.1$ | $-20.4 \pm 3.6$ |
| 1.17 | $-1.4 \pm 3.6$ | $-8.9 \pm 2.2$ | $-23.5 \pm 3.8$ |
| all $p_t$ | | | |
| 0.50 | $-1.9 \pm 0.5$ | $-5.7 \pm 0.5$ | $-7.9 \pm 1.0$ |

## 5 Systematic errors

The major contribution to the possible systematic error of the measured $\mathcal{P}$ is from the detector asymmetry and precision of neutron beam geometry definition.

In order to check the systematic error caused by the set-up asymmetry, the polarization has been measured for the two data sets recorded at reverse polarities of magnetic field. The observed difference in polarization of 0.008 av-

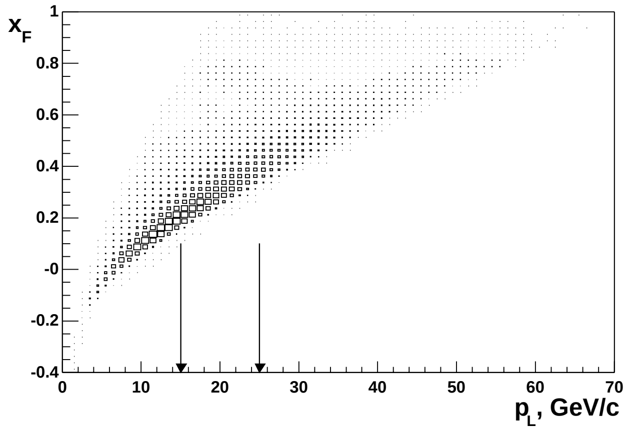


**Fig. 7.** Correlation between $x_{\mathrm{F}}$ and $p_{\mathrm{L}}$ of $\Lambda^0$. Arrows indicate the chosen $p_{\mathrm{L}}$ intervals which correspond to the selected $x_{\mathrm{F}}$ regions

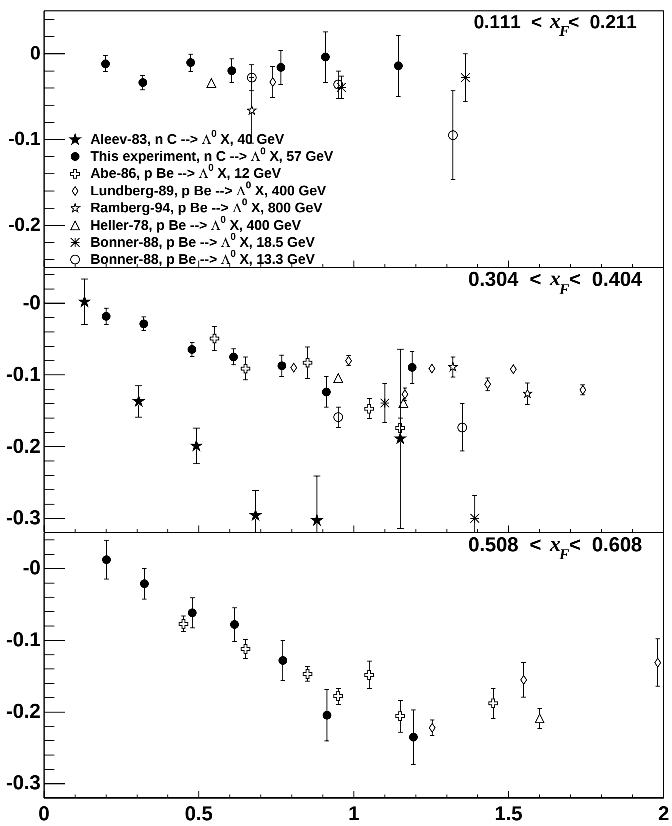


**Fig. 8.** The polarization of $\Lambda^0$ produced inclusively as a function of $p_{\mathrm{t}}$ in the $x_{\mathrm{F}}$ intervals indicated on the plot. The data of the present experiment are compared with the ones obtained in [1–5, 9]

eraged over all $p_{\mathrm{t}}$ intervals is considered as the relevant systematic error.

To estimate the systematic errors related with the uncertainty of the neutron beam direction the inner target position has been varied within the known precision. This yields a systematic error in $\mathcal{P}$ equal to 0.002.

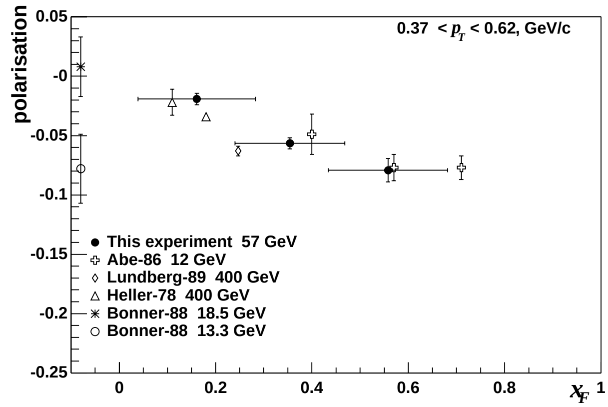


**Fig. 9.** The polarization of $\Lambda^0$ produced inclusively as a function of $x_{\mathrm{F}}$. The $p_{\mathrm{t}}$ values of other experiments are limited to be made similar to the ones indicated on the plot

An independent check of the systematic errors has been done by measuring the asymmetry in $K^0_S \to \pi^+\pi^-$ decay. The asymmetry measured for 700 000 such selected decays is equal to $+0.003 \pm 0.003$. The related average systematic error on the $\Lambda^0$ polarization is $+0.005 \pm 0.005$. The variation of the measured asymmetries with the variations of the applied cuts has been studied as well. No statistically significant changes in $\mathcal{P}$ have been found. Thus, the estimated systematic errors are essentially lower than the statistical ones and have not been indicated in the measured $\mathcal{P}$.

## 6 Conclusions

The $\Lambda^0$ polarization has been measured in the inclusive production in nC interactions with average beam energy $\approx$ 50 GeV. The kinematic range of the detected $\Lambda^0$s is $0.1 \lesssim x_{\mathrm{F}} \lesssim 0.6$ and $0.2 \le p_{\mathrm{t}} \le 1.2\,\mathrm{GeV}/c$, which extends the existing $\Lambda^0$ polarization data to low $p_{\mathrm{t}}$. Our measurement shows that the polarization has nearly a linear dependence within the whole range of $p_{\mathrm{t}}$: $0 \div \lesssim 1\,\mathrm{GeV}/c$ at fixed $x_{\mathrm{F}}$. The polarization increases roughly linearly with $x_{\mathrm{F}}$ at fixed $p_{\mathrm{t}}$. The ($x_{\mathrm{F}}$,$p_{\mathrm{t}}$) dependence of the polarization is consistent with the data [1–5] taken in the proton beam at different beam energies (see Fig. 8 and 9). There is a difference, however, with the results of the neutron beam experiment [9].

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