Polarization of $\Lambda^0$ and $\bar{\Lambda}^0$ inclusively produced by 610 GeV/c $\Sigma^-$ and 525 GeV/c proton beams

(The SELEX Collaboration)

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We have measured the polarization of $\Lambda^0$ and $\bar{\Lambda}^0$ inclusively produced by 610 GeV/c $\Sigma^-$ and 525 GeV/c proton beams in the experiment SELEX during the 1996/7 fixed target run at Fermilab. The polarization was measured as a function of the longitudinal momentum fraction $x_F$ and transverse momentum $p_t$. For the $\Lambda^0$ produced by $\Sigma^-$ the polarization is increasing with $x_F$, from slightly negative at $x_F \sim 0$ to about 15% at large $x_F$; it shows a non-monotonic behavior as a function of $p_t$. For the proton beam, the $\Lambda^0$ polarization is negative and decreasing as a function of $x_F$ and $p_t$. The $\bar{\Lambda}^0$ polarization is compatible with 0 for both beam particles over the full kinematic range. The target dependence was examined but no statistically significant difference was found.

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A large number of theoretical models have been constructed over the years since it was first observed that inclusively produced hyperons are polarized. These models have met with varying degrees of success, but it is clear that more data and theoretical work are needed to clarify the picture. A review of the current status is found in [1–4]. A polarization is well studied with a proton beam, both in inclusive [5] and exclusive [6–8] reactions. For Σ− beam, only the WA89 experiment at CERN reports polarization measurements for Λ0 and Λ̄0 as function of \( p_t \) for one average value of \( x_F \) [9], and for Λ0 as function of both \( p_t \) and \( x_F \) [10]. In the latter case the polarization is negative for small \( x_F \), incrementing to positive values with \( x_F \), but with a non-monotonic behavior as a function of \( p_t \) for different values of \( x_F \).

In this study we exploit the capabilities of the SELEX apparatus to measure the polarization of Λ0 and Λ̄0 inclusively produced by Σ− and proton beams. The goal is to measure the polarizations as functions of \( x_F \) and \( p_t \) with higher beam momenta as the earlier WA89 measurement, using a different analysis method presenting different systematics, and extending the Λ̄0 polarization measurements to several values in \( x_F \); in addition, we add as a cross check the measurements with proton beam within the same experiment.

The SELEX (E781) experiment at Fermilab is a fixed target experiment designed primarily for high statistics studies of charmed baryons produced by a charged hyperon beam incident on a segmented copper/carbon target. However, the versatility of the apparatus allowed for the study of other reactions [11] in the same target. In this work we study the polarization of inclusively produced Λ0 and Λ̄0. More specifically we determine the polarization and its \( x_F \) and \( p_t \) dependence. We follow the Basel Convention [12] for the sign of the polarization.

The charged hyperon beam, which we use as a primary beam for Λ production, was obtained in the Fermilab proton center beamline by steering 500 GeV/c protons from the Tevatron onto a 1 mm×2 mm×40 cm beryllium target located at the entrance of a 7.3 m, 3.5 T hyperon magnet [13]. A curved channel in this magnet selected a beam of negative (positive) particles with a mean momentum of 610 GeV/c (520 GeV/c) and a spread of \( \Delta p/p \approx 8 \% \) HWHM. The negative beam consisted of approximately equal parts Σ− and \( \pi^- \) with a small admixture of \( \Xi^- \) and \( K^- \), while the positive beam contained about 92 % protons, in a total of \( 6 \times 10^8 \) beam particles per second. The targeting angle was set to zero degrees, thereby insuring an unpolarized incident beam.

The portion of the experimental setup relevant to this analysis, which is shown in Fig. 1, consisted of a beam spectrometer, a vertexing region and two downstream spectrometers (M1 and M2). The beam spectrometer included the hyperon magnet, beam transition radiation detectors (BTRD) and beam silicon strip detectors (VSSD), which resolved the interaction vertex and secondary vertices. For VSSD tracks, the transverse position resolution was 4 \( \mu \)m at 600 GeV/c. The M1 spectrometer was a wide angle spectrometer, designed to analyze particles with momenta between \( \sim 2.5 \) and \( \sim 15 \) GeV/c. This spectrometer contained the M1 magnet (\( \Delta p_t = 0.74 \) GeV/c), large angle silicon strip detectors (LASD), and proportional multi-wire chambers (PWC). The second spectrometer (M2), downstream of M1, analyzed particles with momenta \( \gtrsim 15 \) GeV/c. Its components were the M2 magnet (\( \Delta p_t = 0.845 \) GeV/c), LASD, PWC, and a ring-imaging Cherenkov (RICH) detector [14] used for particle identification, which provided \( \pi/p \) separation up to 330 GeV/c. A hardware trigger and software filter were used in SELEX to select the secondary interactions. The hardware trigger consisted of the beam, veto and hodoscope scintillation counters. The first level synchronized the trigger to beam parti-
FIG. 2: Invariant mass distributions for $p\pi^-$ (left) and $p\pi^+$ (right) for $\Sigma^-$ (top) and proton (bottom) beams. The signal and sideband regions are indicated.

III. DATA ANALYSIS

The $\Lambda^0 \rightarrow p\pi^-$ ($\bar{\Lambda}^0 \rightarrow \bar{p}\pi^+$) candidates were selected by requiring oppositely charge track pairs to form a vertex at least 5 $\sigma$ downstream of the primary vertex, where $\sigma$ is the combined error of the $z$-coordinates of the primary and secondary vertex, and upstream of the first VSSD plane. The positive (negative) track was required to be identified by the RICH as a proton candidate. In Fig. 2 we show the invariant mass distributions of these $p\pi^-$ and $\bar{p}\pi^+$ candidates, and in Table I we summarize the available statistics. The $K_S^0 \rightarrow \pi^+\pi^-$ decays are also included to be able to cross check the analysis procedure.

The polarization analysis consisted of extracting the polarization $\mathbf{P}$ from a fit to the proton decay distribution

TABLE I: Number of $\Lambda^0$, $\bar{\Lambda}^0$ and $K_S^0$ for the different beams.

<table>
<thead>
<tr>
<th>Beam Particle</th>
<th>$&lt;p&gt;$</th>
<th>$# \Lambda^0$</th>
<th>$# \bar{\Lambda}^0$</th>
<th>$# K_S^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma$</td>
<td>611 GeV/$c$</td>
<td>1,360,000</td>
<td>112,000</td>
<td>4,698,000</td>
</tr>
<tr>
<td>$p$</td>
<td>525 GeV/$c$</td>
<td>162,000</td>
<td>35,700</td>
<td>752,000</td>
</tr>
</tbody>
</table>

in the $\Lambda$ rest frame:

$$\frac{dN_{\text{meas}}}{d \cos \theta} \propto A(\cos \theta, x_F, p_t)[1 + \alpha \mathbf{P} \cdot \mathbf{P}]$$  (1)

where the $y$-axis is normal to the production plane (defined by the vector of the incoming beam particle and the outgoing $\Lambda$), the $z$-axis is the direction of the $\Lambda$ line-of-flight, and the $x$-axis completes the orthogonal triad. $N_{\text{meas}}$ is the number of events, $\theta$ is the angle between the proton line of flight and the coordinate axes, $\alpha = 0.642 \pm 0.013$ is the asymmetry parameter [15], and $A$ is the acceptance function. By parity conservation in the production process, the only polarization allowed is along the $y$-axis. Clearly, no polarization should be measured along the $x$ or $z$ direction.

Apparatus (or false) asymmetries are present along all axes. The false asymmetries can be removed by using a bias canceling technique, or by modeling the acceptance function $A$ with Monte Carlo simulations. Bias canceling requires a subdivision of the available statistics, while the Monte Carlo simulation requires a good understanding of the apparatus and extensive computing time. Due to the overall low statistics compared to other measurements we present here results obtained [16] with the latter; however, with the bias canceling technique we obtained compatible results [17]. The analysis methods were validated by a non-observation of polarization in the forbidden projections, by analyzing the $K_S^0$ with the same programs, and by Monte Carlo simulation via re-obtaining a known polarization.

To obtain the polarization of $\Lambda^0$ produced by a $\Sigma^-$ beam, we divided the data into 100 bins, 10 each in $0.0 \leq x_F \leq 1.0$, and in $0.0 \text{GeV}/c \leq p_t \leq 2.0 \text{GeV}/c$. The dependence of the acceptance function $A$ on $x_F$ and $p_t$ can be neglected within one bin, and only the dependence on $\cos \theta$ has to be taken into account. For each $[x_F, p_t]$ bin a two-dimensional histogram of the cosine of the angle versus the invariant mass of the $p\pi^-$ is filled and the $dN_{\text{meas}}/d \cos \theta$ distribution is obtained via sideband subtraction (see also Fig. 2). To correct for the acceptance, we obtain the same distribution from Monte Carlo simulation (we verified that the acceptance is independent of an initial polarization of the Monte Carlo sample), and correct for the acceptance in each $[x_F, p_t]$ bin separately. A straight line fit is performed to the final distribution, and the polarization is extracted according to equation 1.

For the lower statistics sample of $\bar{\Lambda}^0$ and the proton beam data, it was not possible to subdivide the available data as before. Only measurements as a function of $x_F$ and $p_t$, averaging over the other variable, could
be performed. As described above, a two-dimensional histogram was filled, but this time with a weight factor obtained from an acceptance model which takes into account the \( x_F \), \( p_t \) as well as the primary interaction target dependence of the acceptance [18].

### IV. SYSTEMATIC CHECKS

We performed several systematic checks to verify our analysis method, including the algorithm as well as the acceptance model. We simulated samples of known polarization, and always re-obtained the expected results. We observed asymmetries in forbidden projections compatible with 0. We also measured the asymmetry of \( K^0_S \rightarrow \pi^+\pi^- \) decays which again is compatible with 0 over the full kinematic range as shown in the last columns of tables III and IV.

Other systematics checks included harder cuts on the separation between primary vertex and \( \Lambda \) decay vertex, requiring that also the pion track reaches the M2 spectrometer, and that the pion is identified with the RICH detector. We always obtained, within the statistical errors, the same results for all polarizations. For these reasons we only quote statistical errors on all our measurements.

### V. RESULTS

In Figs. 3 and 4, as well as in table II we present our results for the \( \Lambda^0 \) polarization with a \( \Sigma^- \) beam as function of \( x_F \) and \( p_t \).

Figure 5 shows the polarization of \( \Lambda^0 \) and \( \Lambda^0 \) produced by \( \Sigma^- \) and protons. Due to the lower statistics available, only the distributions for an average value of \( x_F \) and \( p_t \) are shown. The same information is presented in tables III and IV.

### VI. DISCUSSION AND CONCLUSIONS

For the inclusive production of \( \Lambda^0 \) by a \( \Sigma^- \) beam, our results confirm the WA89 [9, 10] measurements (obtained via the bias canceling method) of a generally positive polarization, increasing with \( x_F \), as shown in Fig. 3 and 4. At small \( p_t \) and \( x_f \) the polarization is almost 0, and in general the dependence on \( p_t \) is non-monotonic for different bins of \( x_F \), increasing and decreasing after reaching some maximum value. Comparing to the earlier, lower-
TABLE III: Polarization (in %) of $\Lambda^0$ and $\bar{\Lambda}^0$ produced by $\Sigma^-$ and protons, as function of $p_t$, averaged over $x_F$. The same information is presented graphically in Fig. 5 (left). Also shown are the asymmetry values measured for the $K_S^0$.

<table>
<thead>
<tr>
<th>$p_t$ (GeV/c)</th>
<th>$pN \rightarrow \Lambda^0 X$</th>
<th>$pN \rightarrow \bar{\Lambda}^0 X$</th>
<th>$\Sigma^- N \rightarrow \bar{\Lambda}^0 X$</th>
<th>$\Sigma^- N \rightarrow \Lambda^0 X$</th>
<th>$\Sigma^- N \rightarrow K_S^0 X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>$-2.9 \pm 1.9$</td>
<td>$-1.0 \pm 3.9$</td>
<td>$2.8 \pm 2.8$</td>
<td>$0.1 \pm 0.9$</td>
<td>$-0.1 \pm 0.4$</td>
</tr>
<tr>
<td>0.3</td>
<td>$-6.6 \pm 1.8$</td>
<td>$-7.3 \pm 3.6$</td>
<td>$2.5 \pm 2.4$</td>
<td>$2.7 \pm 0.6$</td>
<td>$0.6 \pm 0.3$</td>
</tr>
<tr>
<td>0.5</td>
<td>$-3.7 \pm 2.0$</td>
<td>$-6.0 \pm 3.9$</td>
<td>$-0.9 \pm 2.6$</td>
<td>$4.0 \pm 0.6$</td>
<td>$-0.1 \pm 0.3$</td>
</tr>
<tr>
<td>0.7</td>
<td>$-5.9 \pm 2.6$</td>
<td>$0.8 \pm 5.4$</td>
<td>$-1.5 \pm 3.3$</td>
<td>$5.7 \pm 0.7$</td>
<td>$0.3 \pm 0.4$</td>
</tr>
<tr>
<td>0.9</td>
<td>$-12.4 \pm 3.7$</td>
<td>$15.8 \pm 8.2$</td>
<td>$0.7 \pm 4.9$</td>
<td>$4.2 \pm 1.2$</td>
<td>$-1.0 \pm 0.7$</td>
</tr>
<tr>
<td>1.1</td>
<td>$-9.2 \pm 5.4$</td>
<td>$14.3 \pm 13.3$</td>
<td>$0.4 \pm 7.2$</td>
<td>$-0.3 \pm 1.7$</td>
<td>$0.3 \pm 1.0$</td>
</tr>
<tr>
<td>1.3</td>
<td>$-8.8 \pm 4.2$</td>
<td>$14.0 \pm 13.3$</td>
<td>$0.4 \pm 7.2$</td>
<td>$-0.3 \pm 1.7$</td>
<td>$0.3 \pm 1.0$</td>
</tr>
<tr>
<td>1.5</td>
<td>$-8.4 \pm 3.9$</td>
<td>$13.6 \pm 12.3$</td>
<td>$0.4 \pm 7.2$</td>
<td>$-0.3 \pm 1.7$</td>
<td>$0.3 \pm 1.0$</td>
</tr>
<tr>
<td>1.7</td>
<td>$-8.0 \pm 3.7$</td>
<td>$13.2 \pm 11.3$</td>
<td>$0.4 \pm 7.2$</td>
<td>$-0.3 \pm 1.7$</td>
<td>$0.3 \pm 1.0$</td>
</tr>
<tr>
<td>1.9</td>
<td>$-7.6 \pm 3.6$</td>
<td>$12.8 \pm 10.3$</td>
<td>$0.4 \pm 7.2$</td>
<td>$-0.3 \pm 1.7$</td>
<td>$0.3 \pm 1.0$</td>
</tr>
</tbody>
</table>

TABLE IV: Polarization (in %) of $\Lambda^0$ and $\bar{\Lambda}^0$ produced by $\Sigma^-$ and protons, as function of $x_F$, averaged over $p_t$. The same information is presented graphically in Fig. 5 (right). Also shown are the asymmetry values measured for the $K_S^0$.

<table>
<thead>
<tr>
<th>$&lt;p_t&gt;$</th>
<th>$pN \rightarrow \Lambda^0 X$</th>
<th>$pN \rightarrow \bar{\Lambda}^0 X$</th>
<th>$\Sigma^- N \rightarrow \bar{\Lambda}^0 X$</th>
<th>$\Sigma^- N \rightarrow \Lambda^0 X$</th>
<th>$\Sigma^- N \rightarrow K_S^0 X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.59$ GeV/c</td>
<td>$-3.8 \pm 1.5$</td>
<td>$-3.3 \pm 3.0$</td>
<td>$1.7 \pm 2.2$</td>
<td>$0.6 \pm 0.6$</td>
<td>$0.4 \pm 0.2$</td>
</tr>
<tr>
<td>$0.60$ GeV/c</td>
<td>$-6.4 \pm 2.1$</td>
<td>$-0.7 \pm 6.4$</td>
<td>$-5.4 \pm 4.3$</td>
<td>$-0.2 \pm 0.5$</td>
<td>$0.0 \pm 0.3$</td>
</tr>
<tr>
<td>$0.63$ GeV/c</td>
<td>$-7.2 \pm 3.1$</td>
<td>$42 \pm 15$</td>
<td>$0 \pm 14$</td>
<td>$-1.0 \pm 0.7$</td>
<td>$-0.3 \pm 0.5$</td>
</tr>
<tr>
<td>$0.57$ GeV/c</td>
<td>$-17.4 \pm 4.4$</td>
<td>$-23 \pm 36$</td>
<td>$-29 \pm 50$</td>
<td>$3.3 \pm 0.8$</td>
<td>$-0.4 \pm 1.0$</td>
</tr>
<tr>
<td>$0.55$ GeV/c</td>
<td>$-5.0 \pm 6.3$</td>
<td>$25 \pm 61$</td>
<td>$7.2 \pm 1.6$</td>
<td>$7.2 \pm 1.6$</td>
<td>$4.4 \pm 5.2$</td>
</tr>
<tr>
<td>$0.65$ GeV/c</td>
<td>$-7.3 \pm 9.2$</td>
<td>$14.2 \pm 2.4$</td>
<td>$7 \pm 14$</td>
<td>$10.1 \pm 3.9$</td>
<td>$48 \pm 46$</td>
</tr>
<tr>
<td>$0.75$ GeV/c</td>
<td>$-7.3 \pm 9.2$</td>
<td>$14.2 \pm 2.4$</td>
<td>$7 \pm 14$</td>
<td>$10.1 \pm 3.9$</td>
<td>$48 \pm 46$</td>
</tr>
<tr>
<td>$0.85$ GeV/c</td>
<td>$-7.3 \pm 9.2$</td>
<td>$14.2 \pm 2.4$</td>
<td>$7 \pm 14$</td>
<td>$10.1 \pm 3.9$</td>
<td>$48 \pm 46$</td>
</tr>
<tr>
<td>$0.95$ GeV/c</td>
<td>$-7.3 \pm 9.2$</td>
<td>$14.2 \pm 2.4$</td>
<td>$7 \pm 14$</td>
<td>$10.1 \pm 3.9$</td>
<td>$48 \pm 46$</td>
</tr>
</tbody>
</table>

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FIG. 4: Polarization of $\Lambda^0$ inclusively produced by $\Sigma^-$ as a function of $p_t$ for different $x_F$ values. Also shown are data from ref. [10]. The SELEX data points are also given in table II.


FIG. 5: Polarization of $\Lambda^0$ (top) and $\bar{\Lambda}^0$ (bottom) produced by $\Sigma^-$ and protons, as function of $p_t$ (left) and $x_F$ (right). Also shown are data from Refs. [5, 9]. The SELEX data points are also given in tables III and IV.