Measurement of $\Lambda$ polarisation observables
at the COSY-TOF spectrometer

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Abstract

In this work the $\bar{p}p \rightarrow pK^+\Lambda$ reaction is studied. Data were taken at the COSY-TOF experiment in 2002 with a polarised proton beam at the momenta of 2.75 GeV/c and 2.95 GeV/c. The calculated beam polarisation was 39.8% and 61.9% respectively. The experimental setup covers the whole phase space of the $\Lambda$ reaction. The exclusive measurement allows the extraction of polarisation observables not only in the beam fragmentation region ($x_F > 0$), but also in the target fragmentation region ($x_F < 0$).

Samples of 11991 $pK^+\Lambda$ events at 2.75 GeV/c and of 19243 events at 2.95 GeV/c beam momentum have been reconstructed. The $\Lambda$ polarisation, the $\Lambda$ analysing power and the spin transfer coefficient were extracted. The $\Lambda$ polarisation $P_\Lambda$ has a negative trend. The analysing power $A_\Lambda^y$ and the spin transfer coefficient $D_{NN}$ are found to be compatible with zero. The measured spin transfer coefficient is in contradiction with the only result published up to now at comparable beam momenta.

Kurzfassung

Im Rahmen dieser Arbeit wird die $\bar{p}p \rightarrow pK^+\Lambda$ Reaktion untersucht. Die Messung mit polarisiertem Strahl bei 2.75 GeV/c und 2.95 GeV/c Strahlimpuls fand 2002 an COSY-TOF statt. Die ermittelte Strahlpolarisation ist 39.8% bzw. 61.9% für die Strahlimpulse von 2.75 GeV/c und 2.95 GeV/c. Das Detektorsystem deckt den vollen Phasenraum der $\Lambda$-Reaktion ab. Die Exklusivität der Messung ermöglicht die Extraktion von Polarisationsobservablen sowohl im Strahlfragmentsbereich ($x_F > 0$) als auch im Targetfragmentsbereich ($x_F < 0$).

Bei 2.75 GeV/c Strahlimpuls wurden 11991 $pK^+\Lambda$ Ereignisse rekonstruiert, bei 2.95 GeV/c 19243 Ereignisse. Die $\Lambda$-Polarisation, die $\Lambda$-Analysierstärke und die Spindauermeinbarkeitswerte wurden extrahiert. Die $\Lambda$-Polarisation hat einen negativen Verlauf. Die $\Lambda$-Analysierstärke $A_\Lambda^y$ und der Spindauer $D_{NN}$ sind mit Null kompatibel. Das Ergebnis für den Spindauer steht in Widerspruch zu den einzigen bisher veröffentlichten Ergebnis bei vergleichbaren Strahlimpulsen.
Introduction

Hyperons and kaons were discovered in the 1940s in bubble chamber experiments and were classified as strange particles. The name “strange” comes from their unusual behaviour: these particles are produced via the strong interaction and are connected with a correspondingly short time scale. However, they decay with a rather long lifetime of about $10^{-10}$ s through a weak decay.

In strong interactions, strange particles are always produced as pairs of strange and antistrange particles. This phenomenon is also referred to as associated production, such as in the reaction:

\[ p + p \rightarrow K^+ \Lambda p \]

In the weak decay, the strangeness disappears: the $\Lambda$ decays into $p\pi^-$ 64% of the time and into $n\pi^0$ in the remaining 36%.

The study of associated strangeness production in $pp \rightarrow pKY$ processes ($Y$ for the hyperons $\Lambda$, $\Sigma$, etc.) aims to understand how the $s\bar{s}$ pair is produced.

The main intent of the COSY-TOF experiment is to study the associated strangeness production. The detector was especially built to study hyperon production near the reaction threshold. The good geometric reconstruction of the events over the whole phase space of the reaction, together with the high-quality beam of the COSY synchrotron, allow precise measurements of the cross section and of the differential observables in the hyperon channels. The use of a polarised beam, as in 2002, gives access to the $\Lambda$ analysing power and the spin transfer coefficient, important observables for a better understanding of the strangeness production mechanism. The $\Lambda$ polarisation itself, available also in unpolarised experiments via the weak self analysing decay, is of great value to study the internal structure of baryons and their interaction processes.

In the first chapter of this thesis, an overview on the existing data in $\Lambda$ production is given, focussing on the polarisation observables; then, some theoretical models are presented.

The COSY-TOF spectrometer is described in Chapter 2. The detector is modular and can be optimised for different reactions: the setup used to collect the data analysed in this work is presented here.

An overview of the analysis methods, paying particular attention to the reconstruction of the elastic reaction $pp \rightarrow pp$ and of the $pp \rightarrow K^+\Lambda p$ reaction, is given.
in Chapter 3.

Chapters 4 and 5 present the new results of this thesis. First, the methods for the extraction of the beam polarisation are described. The value of the beam polarisation is necessary for the determination of the \( \Lambda \) polarisation observables and is obtained from the elastic data sample. A background estimation for the reconstructed elastic events and a raw estimation of the systematic errors for the beam polarisation are given in Chapter 4. In the following chapter, the hyperon data are presented. Each of the polarisation observables (the \( \Lambda \) polarisation, the \( \Lambda \) analysing power and the spin transfer coefficient) is extracted with several methods. The results are compared.

Since for all three variables the methods proved to be equivalent and no reason was found to prefer one of them, the average was taken as the final result. In the last chapter, data from this work are presented together with theoretical models and previous measurements. Some conclusions on the \( \Lambda \) production mechanism are drawn.
Chapter 1

Λ production in proton-proton experiments and polarisation observables

1.1 Overview of the experimental situation

The strangeness production experiments in proton-proton reactions can be divided into two groups: inclusive and exclusive experiments. In exclusive measurements, all the end products are detected and reconstructed, e.g. $pp \rightarrow pK^+\Lambda$; inclusive experiments reconstruct only some of the outgoing produced particles, e.g. $pp \rightarrow \Lambda X$.

The first experiments were performed in the 1950s using bubble chambers. However, these exclusive measurements had a low statistical accuracy. On the other hand, inclusive kaon production measurements had a poor energy resolution and the disadvantage that it is not possible to distinguish directly produced Λ’s from the Λ’s coming from sigma decay.

1.1.1 Cross section measurements

Bubble chamber experiments

Exclusive measurements were performed in the 1960s at BNL in Brookhaven, at CERN in Geneva and at SLAC in Stanford. These experiments were made in bubble chambers filled with liquid hydrogen. Their data are summarized in a cross section compilation by [Fla85].

The complete reconstruction of the reaction made it possible to distinguish the produced hyperons and to obtain not only total cross sections, but also differential observables, like the invariant masses of the subsystems. A disadvantage of the bubble chamber experiments is the low statistical accuracy. Nevertheless, it was also possible to study the Dalitz plots. At all beam momenta, the distributions of the invariant masses of the $K\Lambda$ and $p\Lambda$ subsystems differ from the pure phase...
space, as shown in Figure 1.1. The increase in the \( K\Lambda \) subsystem at 1700 MeV is explained with the influence of \( N^* \) resonances that also causes the rise at large invariant masses in the \( p\Lambda \) subsystem. The opposite attempt, i.e. to describe the deviations of the \( K\Lambda \) subsystem as a reflection of a resonance in the \( p\Lambda \) system, fails as illustrated by the dashed lines.

![Data from a bubble chamber experiment: the solid lines are phase space distributions while the dashed lines show the effects of resonances (see text). From [Chi68]](image)

**COSY-11**

COSY-11 is an internal experiment at the COSY synchrotron [Bra96]. The proton beam hits a hydrogen cluster target. The magnet spectrometer detector has a limited angular acceptance, but a good momentum resolution; the particles can be identified through their time-of-flight. Measurements are performed close to threshold and they reach a very high luminosity.

The cross sections versus the excess energy\(^\dagger\) of the hyperon reactions measured by COSY-11 up to now are shown in Figure 1.2. The cross section follows roughly a three-body phase space behaviour (indicated in the figure with the dashed lines) but, especially for the \( \Lambda \) reaction, the \( p\Lambda \) final state interaction must be taken into account close to threshold.

An interesting result of COSY-11 is the ratio of the total cross sections for the \( pp \to pK^+\Lambda \) and \( pp \to pK^+\Sigma^0 \) reactions. At the same excess energy, an average value of about 28 was obtained for \( Q < 13 \) MeV, in contrast to the value of about 2.5 obtained at higher energies \( (Q > 300 \) MeV, [Bal88]). To explain this increase near threshold, strong \( p\Lambda \) final state interaction effects in the \( NY \) channel have to be taken into account. Figure 1.3 shows the ratio versus the excess energy together with model calculations. The predictions of the different models are of comparable quality, but none of them reproduces the data really well. For

\(^\dagger\)The excess energy \( Q \) is defined as \( Q = \sqrt{s} - (m_K + m_Y + M_p) \), with \( s \) being the invariant mass of the collision and \( m_K, m_Y, M_p \) the masses of kaon, hyperon and proton, respectively.
1. $\Lambda$ production in p-p experiments and polarisation observables

**Figure 1.2:** Total cross sections of hyperon production in dependence of the excess energy. Dashed line: phase space; solid line: phase space with final state interaction. From [Roz06].

**Figure 1.3:** Cross section ratio data from COSY-11 and from [Bal88] with theoretical curves versus the excess energy. The models are described in the text. From [Roz06].

Curve (1) the pion-kaon exchange model of Sibirtsev et al. [Sib98a, Sib00] was used. This overestimates the $\Sigma^0$ cross section near threshold, and so the predicted ratio is too low. The data are reproduced better by the resonance models of Tsushima [Tsu99, Sib00], and of Shyam [Shy99, Shy04], indicated with (2) and (3) respectively. The remaining curve (4) is a calculation by the Jülich theory group that is valid only for an excess energy smaller than 20 MeV [Gas01]. All these theory models are described in more detail at the end of the present chapter.

There are no $\Lambda$ polarisation data from COSY-11 due to the limited angular acceptance of the set up.

**COSY-TOF**

COSY-TOF has performed various measurements near threshold for both $pp \rightarrow pK^+ \Lambda$ and $pp \rightarrow pK^+ \Sigma^0$ reactions. Figure 1.4 shows the cross section results. The theoretical curves represent pion-kaon exchange models by Laget [Lag91] (a) and by Sibirtsev [Sib00] (b); and resonance models by Dillig et al. [Kle96] (c), Tsushima [Sib00] (d) and Shyam [Shy99] (e). None of the models reproduces the data well over the full energy range.
1.1.2 Hyperon polarisation

The $\Lambda$’s weak decay gives a direct access to its polarisation and was studied already in the 1970s especially in proton-beryllium scattering experiments. Most of the experiments have been performed on inclusively produced $\Lambda$’s ($pA \rightarrow \Lambda X$). It was observed that the $\Lambda$’s, inclusively produced in $pp$ scattering with high transverse momenta $p_T$, carry a large polarisation $P_\Lambda$ perpendicular to the $\Lambda$ production plane [Bun76]. This observation was surprising because the expectation was that the sum of the polarisations should average to zero in an inclusive reaction. In fact, in inclusive reactions the contributions of many different channels are added up, each with a polarisation of random sign.

The kinematic variables used to study the polarisation are normally the Feynman variable $x_F$, the $\Lambda$ transverse momentum $p_T$, and the polar angle in the centre of mass frame $\theta^\Lambda_{CM}$:

- **The Feynman variable**, $x_F$, is the $\Lambda$’s longitudinal momentum expressed as a fraction of its maximum kinematically allowed value: $x_F = p^*_z/\bar{p}_{max}^*$. For $x_F$ positive (beam fragmentation region), the produced hyperon is preferentially correlated with the proton from the beam.
For $x_F$ negative (target fragmentation region), the hyperon is mainly correlated with the target proton.

- **The transverse momentum**, $p_T$, is the component of the total $\Lambda$ momentum transverse to the beam direction.

- **The $\Lambda$ emission angle** is calculated in the centre of mass frame, $\theta^\Lambda_{CM}$.

  It is useful to resolve the contributions of the $\Lambda$’s produced forward ($\cos \theta^\Lambda_{CM} > 0$) from that of the $\Lambda$’s produced backward ($\cos \theta^\Lambda_{CM} < 0$) in the CM frame.

**Inclusive experiments**

Since the unexpected observation of $\Lambda$ polarisation in the experiment by Bounce et al. [Bun76], many experiments at BNL [Lom79, Ray80], at CERN [Erh79, Hel77, Smi87, Hen92, Fan99], at FERMILAB [Bun76, Sku78, Hel83, Lun89, Ram94] (most of them summarized in [Pon85, Lac96]) at KEK [Abe86] and in Argonne [Les75] with beam momentum between 6 GeV/$c$ to 2 TeV/$c$, and mainly with a beryllium target, report aspects of hyperon polarisation. Some of these use also hydrogen, deuterium, copper, lead, platinum, iridium or tungsten targets [Sku78, Lun89, Abe86, Hel77, Lom79].

Figure 1.5: $\Lambda$ polarisation versus the transverse momentum [Fan99, Ram94, Lun89, Hel78]. Plot from [Fan99].
1. $\Lambda$ production in p-p experiments and polarisation observables

All these inclusive experiments obtain data in the beam fragmentation region ($x_F > 0$), but not for negative $x_F$. Directly produced $\Lambda$’s cannot be separated from those originating from other decays (such as sigma decay); therefore to calculate the polarisation, it is necessary to make some hypothesis on the background contamination.

Generally, the results of all these experiments can be summarized as follow: the $\Lambda$ polarisation increases with $x_F$ up to $p_T < 1$ GeV/c and is independent of it above; it increases linearly with the transverse momentum $p_T$; it is almost independent of the beam energy; and its dependence on the target material is weak. Figure 1.5 shows some measurements versus the transverse momentum.

Exclusive experiments

The first exclusive measurements of the $\Lambda$ polarisation were made at BNL by Felix et al. [Fel96, Fel99] in $pp \rightarrow K^+\Lambda p(\pi^+\pi^-)^n$ with $n=1-4$ at 27.5 GeV/c. They obtained the first data in the target fragmentation region (Figure 1.6).

The $\Lambda$ polarisation in $pp$ collisions is antisymmetric in $x_F$ by virtue of its rotational invariance [Fel96]; since the detector used had uniform acceptance in $x_F$, the same polarisation magnitude was measured for positive and negative $x_F$. For this reason, the data for $x_F > 0$ and $x_F < 0$ can be combined multiplying $\cos\theta$ by the sign of $x_F$ with the advantage of improving the statistical accuracy.

This experiment concluded that the mechanism responsible for $\Lambda$ polarisation is independent of the $\Lambda$ production mechanism, since the behaviour of $\Lambda$ polarisation in $x_F$ and $p_T$ is the same for all the studied reactions $pp \rightarrow K^+\Lambda p(\pi^+\pi^-)^n$ ($n=1-4$).

Figure 1.6: $\Lambda$ polarisation versus the transverse momentum from [Fel96]. (a) The sample is splitted in $x_F > 0$ and $x_F < 0$. (b) The data (circles) for $x_F > 0$ and $x_F < 0$ are combined (see text) and compared with [Bun76] (squares).
The reaction $pp \to K^+\Lambda p$ has been measured exclusively with unpolarised beam also by COSY-TOF at the beam momenta of 2.75 GeV/c [Bil98, Met98], 2.85 GeV/c [Fri02], 2.95 GeV/c, and 3.20 GeV/c [Sch03]. The polarisation obtained for the 2.75 GeV/c sample is negative for $p_T \geq 0.3$ GeV/c. A similar trend is observed at 2.85 GeV/c beam momentum (Figure 1.7). At 2.95 GeV/c and 3.20 GeV/c it is compatible with zero. In all cases, the results are consistent within errors with other measurements at much higher energies.

![Figure 1.7: The $\Lambda$ polarisation versus the transverse momentum. Left: at 2.75 GeV/c from [Met98]. The unpolarised Monte Carlo sample, analysed under identical conditions, shows the expected value of zero. The data have a negative trend for growing momenta. Right plot: at 2.85 GeV/c from [Fri02].](image)

### 1.1.3 Experiments with polarised beam

The availability of a polarised proton beam allows the study of two additional parameters other than polarisation: the analysing power and the spin transfer coefficient.

The analysing power $A_\Lambda$ measures the left/right production asymmetry of the final state hyperon when the incident beam is transversely polarised.

The spin transfer coefficient $D_{NN}$ expresses the component of the beam polarisation along the normal to the production plane that is retained by the final state hyperon. A negative sign indicates that the $\Lambda$ polarisation is opposite to the beam spin direction.

#### Inclusive measurements

The $\Lambda$ polarisation in inclusive measurements at 13.3 and 18.5 GeV/c [Bon87, Bon88] and at 200 GeV/c [Bra95, Bra97] with proton-proton and proton-beryllium collisions show compatible results with the unpolarised measurements. The polarisation observables $A_\Lambda$ and $D_{NN}$ are both compatible with zero for values up to $x_F \simeq 0.5$ and $p_T \simeq 0.5$ (Figures 1.8-1.9). For larger $x_F$ and transverse momenta, the analysing power tends to be negative, while the spin transfer coefficient is positive (Figure 1.9). Inclusive experiments do not collect data in the target fragmentation region ($x_F < 0$).
1. \( \Lambda \) production in p-p experiments and polarisation observables

**Figure 1.8:** \( \Lambda \) analysing power (left) and spin transfer coefficient or depolarisation (right) versus \( x_F \) for different regions of transverse momentum measured by Bonner et al. From [Bon88].

**Figure 1.9:** \( \Lambda \) analysing power (left) and spin transfer coefficient (right) versus the transverse momentum measured by Bravar et al. From [Bra95, Bra97].

**DISTO experiment**

Until now, the only exclusive measurement with a polarised beam was performed by the DISTO collaboration in the 1990s [Mag95, Ber01].

DISTO was specifically designed to study the associated hyperon production in \( \bar{p}p \rightarrow pK^+ (\Lambda/\Sigma^0) \) near threshold. Data have been taken at three beam momenta: 2.94, 3.31 and 3.67 GeV/c.

A liquid hydrogen target is placed at the centre of a dipole magnet. All the detectors (scintillating fibres, multiwire proportional chambers and Cherenkov counters) are placed symmetrically on both sides of the beam. Angles and momenta of the primary proton, the kaon and of the hyperon decay products are fully reconstructed.

The results in Figure 1.10 show a large and negative spin transfer coefficient in the whole \( x_F \) range. For the sample that includes \( \Lambda \)'s coming from \( \Sigma^0 \) and \( Y^* \)
decays (indicated in the figure with semi-inklusiv) $D_{NN}$ also deviates clearly from the inclusive measurements at high energies described in the previous section.

At 3.67 GeV/c the analysing power reaches the largest negative values at the smallest and largest $x_F$ ($x_F \rightarrow \pm 1$). For positive $x_F$ its behaviour is almost linear, similar to the 200 GeV/c data [Bra95]. At 2.94 GeV/c the trend in the positive range of the Feynman variable is different.

1.1.4 Summary of the $\Lambda$ polarisation experimental results

From all the experiments, both inclusive and exclusive, carried out so far on the $\Lambda$ polarisation, some general behaviour can be described. It has been observed that:

- produced $\Lambda$'s are polarised along the direction normal to the $\Lambda$-proton production plane. This direction is defined by

\[
\hat{n}_\perp = \frac{\vec{p}_{beam} \times \vec{p}_\Lambda}{|\vec{p}_{beam} \times \vec{p}_\Lambda|}
\]

where $\vec{p}_{beam}$ and $\vec{p}_\Lambda$ are the momenta of the beam and of the produced $\Lambda$;

- $\Lambda$ particles are produced with negative polarisation;

- the polarisation increases linearly with the transverse momentum ($p_T$) of the $\Lambda$ up to about 1 GeV/c and remains constant beyond;

- the polarisation increases linearly with the Feynman variable $x_F$ for $p_T$ less than 1 GeV and is independent of $x_F$ above;

- for beam momenta from 12 up to 2000 GeV/c, the polarisation is almost energy independent [Abe86, Hel77];

- the polarisation is weakly dependent on the target type and decreases with increasing atomic weight $A$ [Hel78, Bun76, Pon85, Ray80].
The $\Lambda$ analysing power, $A_\Lambda^\Delta$, is compatible with zero for small values of the Feynman variable ($x_F < 0.5$) and transverse momenta ($p_T < 0.6$ GeV/c). It is negative at relatively large $x_F (>0.5)$ and moderate $p_T (>0.6$ GeV/c).

The situation on $D_{NN}$ is puzzling: close to the production threshold, the spin transfer coefficient is negative in $x_F$, while above incident energies of around 10 GeV/c, it is zero.

1.2 Theoretical models

Although the observations on $\Lambda$ polarisation have been known for more than twenty years, there is still no theoretical description which is able to explain properly all experimental observations. Theoretical models fall into two large groups that use the quark-exchange or the meson-exchange picture.

For energies close to threshold, it would be more natural to interpret the data using the meson-exchange picture. To give a more general overview, meson exchange models that do not make considerations on the hyperon polarisation are also presented here.

However, the first data on $\Lambda$ polarisation were obtained at significantly higher energies and were often interpreted in terms of quark based models. For this reason, some of these quark model predictions will also be briefly described at the end of this section.

1.2.1 Meson exchange models

There are meson exchange models that use simply a pion and/or kaon exchange to describe the nucleon-nucleon interactions and others that explicitly take into account the effects of resonances. Here a short description of the exchange model is given; some of them are presented with their predictions for the $pp \rightarrow pK^+\Lambda$ reaction.

![Feynman diagramm of pion and kaon exchange.](image)

The easiest case to describe the $pp \rightarrow pK^+\Lambda$ reaction in the meson exchange picture is a single pion exchange (Figure 1.11, left).
The total cross section can be calculated by integrating the differential cross section \( \frac{d\sigma}{dt ds_1} \) over the complete phase space:

\[
\sigma = \int dt ds_1 \frac{d\sigma}{dt ds_1} = \frac{1}{2^{9\pi^2} q^2 s} \int dt ds_1 \frac{q_K}{\sqrt{s_1}} |M(t, s_1)|^2
\]

where \( t \) stands for the four-momentum carried by the pion; \( s_1 \) the square of the centre of mass energy in the \( p \Lambda \) subsystem; \( q \) the momentum of the incident proton in the centre of mass (CM) system; \( s \) the square of the CM total energy; \( q_K \) the kaon momentum in the \( K\Lambda\)-CM-subsystem; and \( M(t, s_1) \) the amplitude of the reaction \( \pi p \to K Y \), as a function of \( t \) and \( s_1 \).

For a pion exchange, the matrix element is given by:

\[
|M(t, s_1)|^2 = g_{\pi\pi}^2 \frac{t}{(t - \mu^2)^2} \left[ \frac{\Lambda_\pi^2 - \mu^2}{\Lambda_\pi^2 - t} \right] |A_{\pi^0 p \to \Lambda K}(s_1)|^2
\]

with \( \mu \) the pion mass and \( g_{\pi\pi}^2 \) the \( \pi\pi \) coupling constant. The form factor \( \left[ \frac{\Lambda_\pi^2 - \mu^2}{\Lambda_\pi^2 - t} \right] \) at the \( \pi\pi \) vertex explicitly depends on the \( \Lambda_\pi \) cut-off mass.

The amplitude \( A(s_1) \) can be directly deduced from the total cross section of the reaction \( \pi^0 p \to \Lambda K^+ \). With \( q_\pi \) and \( q_K \) being the momentum of the pion and of the kaon, respectively, it follows:

\[
|A_{\pi^0 p \to \Lambda K}(s_1)|^2 = 16\pi s_1 \frac{q_\pi}{q_K} \sigma_{\pi^0 p \to \Lambda K}(s_1)
\]

The value of the total cross section \( \sigma_{\pi^0 p \to \Lambda K} \) is given by experimental data. In this way, the effects of resonances already in the cross section automatically enter the calculation. In the so-called resonance models, the effects of resonances are explicitly taken into account.

To describe the data in the region close to threshold, it is moreover necessary to take into account the final state interaction (FSI).

For the pion exchange models, the coupling constant and the \( \Lambda_\pi \) cut-off mass at the \( NN\pi \) vertex can be determined from the data of pion production in proton-proton interactions using the Bonn-\( NN \)-potential [Mac89].

In the pion-kaon exchange models, beside the pion exchange, kaon exchange is included (Figure 1.11, right). In these models, due to the poor existing data samples, the parameters at the \( KYN \) vertex are fitted separately.

The different and sometimes contradictory conclusions of the models presented below can be ascribed to the different values of coupling constants and cut-off parameters applied.

**Pion exchange model**

*Soffer* and *Tönnqvist* [Sof92] use the Reggeized one pion exchange model to describe the inclusive reaction \( pp \to X \Lambda \). They assume that the pion exchange diagram dominates (and reduce to the binary reaction \( p\pi \to K\Lambda \)); other exchange
diagrams, like kaon exchange, are neglected because they must be suppressed at high energy and do not contribute to the Λ polarisation. This approach predicts the absolute normalisation and the correct trend of the invariant inclusive cross section versus both $x_F$ and $p_T$. Since the cross section is best described for $x_F \approx 0.5$, Soffer and Törnqvist believe the polarisation is the most reliable at the same $x_F$. Figure 1.12 shows some data at two different energies for nearby $x_F$ values. The agreement of the model is good both in magnitude and sign. The differences observed are ascribed to an underestimation in the data by 10-20% of the Λ’s contamination from the sigma decay $\Sigma^0 \rightarrow \Lambda + \gamma$. The model reproduces both the energy independence of the polarisation and the flattening of the polarisation at large $p_T$.

Figure 1.12: Comparison of measured Λ polarisation with the theoretical predictions of the Soffer-Törnqvist model. Open circles: data from Fermilab [Pon85] at 400 GeV/c proton momentum with average $x_F=0.44$. Solid circles: from CERN ISR [Smi87] at $\sqrt{s}=62$ GeV/c and $x_F=0.58$. Plot from [Sof92].

Pion-kaon exchange models

In the pion and kaon exchange model by Laget [Lag91] and in the one by Sibirtsev et al. [Sib98a], the amplitudes of pion and kaon are summed up and the free parameters are fitted with the experimental data of the total cross sections. The basic difference of the calculations is that Laget takes both the $\pi N \rightarrow YK$ and $KN \rightarrow KN$ amplitudes off-shell, while Sibirtsev takes on-shell amplitudes. Both models can interpret the cross section data for different energies and different hyperon production reactions. In the $pp \rightarrow pK^+\Lambda$ reaction, both kaon and pion exchange are included in the model calculations, with a dominance of kaon exchange, to compare with the experimental data. On the contrary, in sigma production it is almost possible to reproduce the data using only pion exchange, while the kaon exchange amplitude is negligible.

The calculations describe the total cross section data well at high energies but substantially underestimate them in the threshold region because of the final state
interaction (FSI) between the proton and the hyperon. With the inclusion of the FSI, the calculation describes the Λ channel remarkably well, while it overestimates the sigma cross section very close to threshold (Figure 1.13).

The total cross section is not very sensitive to the details of the models, therefore a better test for a theory is the capability also to describe differential observables. For example in Figure 1.14 the invariant mass of the semi inclusive reaction $pp \rightarrow K^+ X$ is shown, plotted versus the invariant mass of the $YN$ subsystem. The model of Laget cannot describe the data with simple meson exchange, and a direct kaon emission must be added to describe the structure that appears at the $ΣN$ threshold, which is a direct reflection of the strong coupling between the $Δp$ and $ΣN$ channels. Considering the extra term gives a good agreement with the investigated differential observable, and at the same time does not change dramatically the calculation of the total cross section.

Another constraint on the theory can be obtained by polarisation measurements because spin observables tend to be very sensitive to the production mechanism. Among the pion-kaon exchange theories, only Laget makes a prediction for the Λ polarisation depending on the mechanism: it is expected to be positive for kaon exchange, and it shows more structure for combined pion and kaon exchange (Figure 1.15).

The *Jülich theory group* [Gas01] describes the hyperon production with pion
and kaon exchange and the final state interaction. In this model, the $\Lambda$ production is dominated by kaon exchange, whereas pion and kaon exchange have comparable magnitude for $\Sigma^0$ production. A destructive interference between pion and kaon exchange is suggested as an explanation for the observed suppression of the near-threshold $\Sigma^0$ production in comparison with the $\Lambda$ channel (Figure 1.3).

Resonance models

In resonance models, the strangeness is generated with meson exchange and the explicit inclusion of baryon resonance excitations. The resonances are responsible for the kaon and hyperon pair production and the mechanism goes as following: $pp \rightarrow N(R^* \rightarrow KY)$. In Figure 1.16, the Feynman diagrams of the resonance model by Tsushima et al. [Tsu99] are shown.

Included in the model are experimentally observed resonances such as $N^*(1650)$, $N^*(1710)$, and $N^*(1720)$ that are accessible with the energy of the $pp \rightarrow K^+\Lambda p$ process and can decay into $YK^+$. For the $\Sigma$ production, the resonance $N^*(1650)$ is ignored since its light mass is not enough to decay on-shell into $\Sigma^0K^+$. Only non-strange mesons can contribute to the $N^*$ excitations: $\pi$, $\eta$, and $\rho$ mesons are considered. Also in this case, the parameters are fitted to the total cross section. To obtain a satisfying description of the data at lower energies, it is necessary to introduce the final state interaction in the $YN$ subsystem.

Again, the differential observables are used to make predictions that might give a clue to the reaction mechanism. Tsushima studies the invariant mass spectrum of the $KY$ subsystem (Figure 1.17). At 100 MeV above threshold, one can clearly see
how the production mechanism influences the distribution of the invariant mass. Significant deviations from the phase space distribution are visible.

Another theoretical description is the effective Lagrangian model by Shyam [Shy99]. In this model, the interaction between the two nucleons is modelled by the exchange of $\pi$, $\rho$, $\omega$ and $\sigma$ mesons, and the $\Lambda K^+$ production proceeds via the excitation of the $N^*$ resonances. The $N^*(1650)$ resonance is included in both $\Lambda$ and $\Sigma$ production. The pion exchange amplitude dominates, while $\rho$, $\omega$ meson contributions are almost insignificant. Near threshold, the $\sigma$ exchange contributes to the total cross section and the $N^*(1650)$ resonance dominates. The importance of the $N^*(1710)$ resonance rises with increasing energies and above 3 GeV/c it dominates (Figure 1.18). For a consistent description of the data, it is necessary to consider the influence of the FSI in the $p\Lambda$ system. Moreover, the interference terms of the amplitudes corresponding to various resonances are found to be quite important, in contrast to the calculations of Tsushima, where these terms were ignored.

An investigation was made fitting a model by Sibirtsev to the COSY-TOF Dalitz plots at 2.85, 2.95, 3.20 and 3.30 GeV/c [Sch03, Sch03a, Abd06]. In the model, the meson contributions can be added in a coherent way, and the resonances $N^*(1650)$, $N^*(1710)$ and $N^*(1720)$ are taken into account. In good agreement with the predictions of Shyam, it is found that the resonance contribution is strongly dependent on the energy: at 2.85 GeV/c only the $N^*(1650)$ resonance is relevant; at 2.95 GeV/c a non negligible contribution of the $N^*(1710)$ also appears. At 3.20 GeV/c the amplitudes of both resonances are equal within the errors (Figure 1.19); at 3.30 GeV/c it is the $N^*(1710)$ that has a stronger weight.

Unfortunately, none of these resonance models make predictions on the polarisation observables.
1. \( \Lambda \) production in p-p experiments and polarisation observables

Figure 1.17: Invariant mass spectrum of the \( \Lambda K^+ \) subsystem for the resonance model of Tsushima at an excess energy of 100 MeV. From [Sib98].

Figure 1.18: Contributions of \( N^*(1650) \) (dotted line), \( N^*(1710) \) (dashed line) and \( N^*(1720) \) (dashed-dotted line) resonances to the total cross section of \( pp \to p K^+ \Lambda \) as calculated in Shyam’s model. From [Shy99].

Figure 1.19: Dalitz plot at 3.20 GeV/c beam momenta by COSY-TOF. Left: data; Right: result of the model calculations. From [Sch03].
1.2.2 Quark models

Since in the relatively low momentum region perturbative QCD is not expected to apply, QCD models are phenomenological models. The Lund semi-classical fragmentation model [And79] and the Thomas precession recombination model [DeG81] use semi-classical arguments for the Λ polarisation but offer different mechanisms by which the s quark is polarised. In both models the incident proton beam is treated as a ud diquark system plus a single u quark. The diquark singlet continues forward with its unchanged flavour and spin and picks up an s quark from the sea to form the final state Λ. The difference between the two models is the way in which the s quark is produced and how its polarisation is introduced.

The Lund model predicts equal polarisation for associate-y produced Λ and Λ̅ and a polarisation of Λ’s originating from Σ^0 decay of about 1/9 of the polarisation of directly produced Λ’s. The model does not include the Λ polarisation dependence on x_F, and probably also for this reason there is no quantitative agreement with the data (Figure 1.20).

In the model by De Grand et Miettinen [DeG81], the polarisation originates from the Thomas precession effect on the quark’s spin when it is affected by a confining force. Since the s quark will carry some transverse momentum, its velocity vector \( \vec{v} \) will not be parallel to the confining force \( \vec{F} \), and so it will experience a Thomas precession. In order to minimize the energy associated with this effect, the spin of the s quark should be opposite to \( \vec{F} \times \vec{v} \), which has a direction normal to the scattering plane \( \vec{p}_{\text{beam}} \times \vec{p}_{\Lambda} \). This model predicts \( p_T \) and \( x_F \) dependence which is in qualitative agreement with the data (Figure 1.21).

A more complete overview of the quark models applied to Λ polarisation studies is given by Felix [Fel99a].

Figure 1.20: Crude comparison of Λ polarisation data and the Lund model. From [Fel99a].
1.2.3 Spin transfer coefficient $D_{NN}$ to understand the production mechanism

Among the polarisation observables measured, $D_{NN}$ is especially sensitive to the production mechanism of the hyperons.

We limit our considerations to near-threshold energies, where it is more natural to use the meson exchange picture, and take the model of Laget. In the case of kaon or pion exchange, $D_{NN}$ is maximally different at large positive $x_F$ (Figure 1.22). If the reaction is dominated by kaon exchange, to conserve angular momentum and parity at the $\vec{p} \to K\Lambda$ vertex, one expects a spin flip leading to $D_{NN} \approx -1$ in the forward production ($x_F > 0$). On the contrary if pion exchange dominates, $D_{NN}$ is expected to be $\approx +1$. At the more negative $x_F$, since the hyperon is then connected preferentially to the unpolarised target proton, $D_{NN}$ tends toward zero for both mechanisms.

The large and negative $D_{NN}$ values obtained by DISTO (Figure 1.10) in the whole $x_F$ range are in contrast with this simple picture. Inclusive measurements obtain values around zero, with a positive trend for large $x_F > 0$ ([Bon87, Bon88, Bra97], also shown in Figure 1.10).

Quark based mechanism lead to different expectations [Vig93].
Figure 1.22: Calculations of $D_{NN}$ for various exclusive $\Lambda$ production mechanisms with different parametrisation using the model of Laget. Upper plot, from [Bal99]: kaon exchange (solid curve), pion exchange (dashed) or both combined (dot-dashed). Bottom, from [Bal01]: kaon exchange (solid curve), pion exchange (dotted) or both combined (dashed). The Feyman diagrams indicate the two contributions for positive vs. negative $x_F$. 
Chapter 2

The experiment

2.1 The COSY synchrotron

The experiments as detailed in this thesis were performed at the COoler SYnchrotron COSY in Jülich (Figure 2.1).

COSY is an oval synchrotron of about 180 m circumference where protons can be accelerated from 0.27 GeV/c to 3.7 GeV/c. The proton beam is characterised by a good momentum precision of $\Delta p/p < 10^{-3}$ and a small emittance.

$^-$ ions are accelerated up to 40 MeV in the cyclotron and then injected into the beamline. At the injection, the negative ions go through a stripfoil that separates the electrons from the protons. Protons are accelerated in the oval ring where bending and focussing magnets are continuously adapted to the beam energy (synchrotron method). A maximum of $2 \times 10^{11}$ protons are stored in the ring. In the case of a polarised beam, protons with a polarisation of up to 80%-85% can be stored in the synchrotron. For the external experiment COSY-TOF, protons are extracted with a stochastic method capable of extracting the beam slowly over a long period of time in spills of $10^7$ to $10^{11}$ particles/s. The spin is flipped at every spill to minimize any time-dependent asymmetries.

2.2 The COSY-TOF spectrometer

The Time-Of-Flight spectrometer COSY-TOF is a versatile detector with a modular construction (Figure 2.2). It consists of a start detector system, a tank of variable length and an endcap. This peculiar characteristic allows the adaptation of the detector geometry to obtain the best solution for each studied reaction.

The start detector system was expressly designed to have a good geometric track reconstruction; the Barrel and the Endcap detectors allow the time-of-flight measurements. The tank is evacuated in order to minimize secondary scattering reactions.

COSY-TOF is a “4π detector” for all the hyperon production reactions. Even at the maximum beam momentum reached by the COSY accelerator, the total
2. The experiment

Figure 2.1: COSY Accelerator Facility

energy is only few hundred MeV above the production threshold; therefore the particles have small transverse momenta and are scattered mainly in the forward direction.

2.2.1 The veto system

To exclude reactions that take place outside the target, three veto scintillators are placed upstream of it. A large scintillator surrounding the beam pipe is placed at two metre distance. A second veto is 300 mm upstream of the target and has a hole with a diameter of 8 mm. The last veto is at about 50 mm from the target and has a variable internal diameter (1.5-3.5 mm). This scintillator is used for beam focussing.

2.2.2 The target

The target cell is a copper cylinder of 4 mm length and 6 mm diameter. The two windows are closed by polyester foils of about 2 μm thickness. The target is filled with liquid H₂ that reaches a proton density of $1.8 \times 10^{22}$ protons/cm² at the working pressure of 200 mbar.

2.2.3 The ‘Erlangen’ start detector

The Erlangen Start Detector consists of four modular detectors with high granularity (Figure 2.3). Combining them in several ways or at several distances allows
the best configuration for different reactions to be reached.

Starttorte

The Starttorte is a scintillator detector with a diameter of 150 mm positioned at 22 mm downstream of the target. It consists of two layers with a thickness of 1 mm each, divided into 12 wedges. The layers are rotated by half a wedge in order to have 24 coincidences with an angular resolution of 15°. The internal radius of the wedges is 1 mm, to form the beam hole and allow the beam to pass through without interaction. The Starttorte covers a polar angular range from 3.4° to 74° and therefore the full angular range of hyperon reactions.

This detector provides the start signal in the time-of-flight measurement and the multiplicity of charged particles produced in the target.

Microstrip detector

The Microstrip detector is a 500 μm thick silicon detector of 62 mm diameter, with 100 concentric rings at the front side and 128 wedges at the rear side. It is positioned 30.6 mm downstream of the target and covers up to about 45°.

\footnote{with z position is always meant from the centre of the target to the centre of the detector. The z axis is along the beam direction.}
Figure 2.3: *Scheme of the start detector system with the track pattern of a $pp \rightarrow pK^+\Lambda$ decay.*

The hodoscopes

Two hodoscopes are also mounted in the start detector region, one at 104 mm and the second at 197 mm from the target. They are referred to Small and Large Hodoscope, respectively. Both of them consist of two layers of square scintillating fibres with a $2 \times 2$ mm$^2$ cross section. These layers are oriented perpendicular to each other. The Small Hodoscope has 96 fibres in each plane and has a size of about $20 \times 20$ mm$^2$. The Large Hodoscope measures $40 \times 40$ mm$^2$ and has 136 fibres in each plane. It is rotated by about 34° respect to the Small Hodoscope, in order to resolve ambiguities.
2. The experiment

2.2.4 The stop detector

The Stop Detector has also modular design and consists of Quirl, Ring and Barrel. Quirl and Ring together are also referred to as the Endcap. The Barrel length can be varied between about 3 m and 8 m.

Quirl and Ring

Quirl and Ring have a similar structure: they consist of three scintillator layers each 5 mm thick. The scintillators of the first layer are wedge-shaped; the other two layers are respectively left and right curved archimede spirals. Quirl has 48 straight wedges and 2×24 curved elements, while Ring has 96 wedges and 2×48 curved elements. Quirl and Ring together cover continuously the angular range from 0.7° to 24.8°.

Barrel

The Barrel detector covers the inside of the vacuum tank with 96 scintillating bars of 2.8 m length. The bars point in the direction of the beam axes. Pulse high and timing signals are read out by ADCs and TDCs at both ends of the bars. The polar angle information is obtained by the time difference of the signals at the opposite ends. The Barrel covers an angular range from 24.8° to 76.7°, but in the present configuration the angles larger than 70° are shielded by a steel flange that holds the start detector system.

2.3 Trigger

Only when the ADC and TDC signals satisfy certain trigger conditions are the data stored on tapes.

The characteristic increase of the number of charged particle tracks in the detector from 2 to 4, due to the delayed decay of the neutral Λ into \((p, \pi^-)\), is used to distinguish the reaction \(pp \rightarrow K^+\Lambda p\) from multi-pion reactions. The other hyperon production reactions \(pp \rightarrow K^+\Sigma^0 p\) and \(pp \rightarrow K^0\Sigma^+ p\) also satisfy the trigger condition \(2 \rightarrow 4\) and can be separated from the Λ sample only in the further analysis.

The \(pp \rightarrow pK^+\Lambda\) trigger is defined as: two Starttorte coincidences and at least three hits in the Stop detector (a hit is given by both ends in the Barrel or two out of three layers in the Endcap). The trigger is valid if the Veto detector has not fired.

In this trigger, the \(2 \rightarrow 4\) multiplicity is softened and \(2 \rightarrow 3\) events are also written on tape. This is done to take into account various factors that could reduce multiplicities in the Stop detector. Effects that reduce the multiplicity can be: inefficient detector zones, like aluminium cladding; inefficiencies of the detector itself; or particles absorbed in a detector layer. The fact that, near threshold, particles may fly at small angles through the beam hole of the detectors also reduces the multiplicity.
In addition to the main trigger, a second one is specifically built to record the elastic $pp \rightarrow pp$ reaction. Since the cross section of elastic scattering is at least two orders of magnitude larger in comparison to the lambda production, this trigger is scaled down by a factor of 200. In general, the elastic trigger requires only two Starttorte coincidences. Elastic events are used for calibrating the detector positions, to determine the luminosity and the beam polarisation (Chapter 4).
Chapter 3

Data Analysis

At the experiment, the data are stored on tape in a binary format and they must be converted to ASCII to be analysed by the software package \texttt{tdas2paw}. The ASCII files are written in a COSY-TOF specific format called TADE\textsuperscript{†}, containing for each event the ADC and TDC values of the hit detector elements.

The software package \texttt{tdas2paw} is used for calibrations and for the geometrical reconstruction of the events. First, the ADC thresholds are set and the energy loss is calibrated; TDCs are calibrated as well. This allows a prereduction of the data. Then, the detector geometry is determined. At this point, the events with the expected topology ($pp ightarrow pp$: two prompt tracks; $pp ightarrow pK^+\Lambda$: two prompt tracks and a delayed decay) are reconstructed.

For the elastic reaction $pp ightarrow pp$, the geometry reconstruction is performed by the software \texttt{tdas2paw}. The application of further cuts and the determination of the beam polarisation are done with C++ macros under ROOT [ROOT].

The $pp ightarrow pK^+\Lambda$ geometric reconstruction is also done by \texttt{tdas2paw}. The event selection is performed by a second software, \texttt{hypokrit}, that calculates the kinematics of the event, applies the appropriate cuts on mass and energy loss and if needed makes a kinematic fit.

The output of \texttt{hypokrit} is an Ntuple file that can be analysed with PAW [PAW]. The software to calculate the polarisation observables was written within this thesis under ROOT. Before this software can be applied on the data, the Ntuples must be converted into ROOT Tree structures.

The single analysis steps are described in the present chapter.

3.1 Calibrations

The TADE data format contains TDC and ADC values of each hit detector element (Appendix A). With the software \texttt{tdas2paw}, ADC and TDC spectra are plotted for

\textsuperscript{†}TADE stands for TDC, ADC, Detector, Element. See also Appendix A.
each channel (Figure 3.1).

![ADC and TDC spectra in the Large Hodoscope. The ADC cut is indicated by the dashed line (left spectrum).](image)

**3.1.1 ADC spectra and cuts**

The analysis of the ADC spectra allows pedestal cuts to be set and the energy gain to be determined. The cut on these spectra defines a hit in the detector: when the ADC input is higher than the cut value, the hit is stored as valid and used further in the analysis.

For Starttorte and Stop detector (Quirl, Ring, Barrel) a hit is valid if, in addition to the ADC value above threshold, the TDC has an entry.

In the Microstrip detector, ADC clusters are taken into account, due to the fine segmentation of the detector. Especially at large theta angles, a particle may hit two or three neighbouring rings; in this case the charge of neighbouring elements is summed up and the charge barycentre is taken as the valid hit position.

**3.1.2 TDC spectra and time calibration**

The detectors which carry TDC information are the Starttorte, Large Hodoscope, Quirl, Ring and Barrel. They are all used in common stop mode, except for the Starttorte that is used in common start. The fastest Starttorte signal is taken as reference.

The TDC signals are calibrated and corrected for:

- walk effect (for a given threshold, signals with different energies have different timing);
- offset due to electronics;
- light drift in scintillators.
The time-of-flight information can be used to extend the theta range in which elastic events are reconstructed (from $\theta_1$ and $\theta_2 \in [26^\circ, 45^\circ]$ to about $\in [12^\circ, 70^\circ]$, as explained in Appendix B). In the $pp \rightarrow pK^+\Lambda$ reaction it is not essential since this reconstruction is purely based on geometry.

### 3.1.3 Geometry calibration

The COSY-TOF coordinate system is left handed with the z axis pointing in the beam direction and the origin of the coordinates at the centre of the target. All detectors of the start detector system are positioned in $(x, y)$ with the help of an optical instrument at the beginning of each beamtime. To get more precise coordinates for the analysis, the position is determined with a geometrical calibration that uses the proton tracks of elastic events. The distance from the target to the Endcap is defined as a constant ($z_0$) and proton tracks of elastic events defined by the pixels in the Endcap are taken as a reference.

The calibration is carried out as follows. First, the $\phi$ rotation of each detector plane is calculated taking the difference of the reconstructed position in the detector to the projected reference track. Once the $\phi$ rotations have been adjusted, the positions in $z$ are examined. The $z$ positions are compared to those deduced from the reference track, whose polar angle $\theta$ and radius are known ($z = r/tan\theta$). A cross-check is made using the kinematics of elastic events. At this point, all detectors deliver the same $\theta$ angle. The optimal $x$ and $y$ positions are defined by minimising the width of the distribution of the $\theta$ difference calculated from all possible detector combinations (e.g. $\theta_{\text{Microstrip}} - \theta_{\text{Small Hodo}}$, $\theta_{\text{Small Hodo}} - \theta_{\text{Large Hodo}}$, etc.).

The geometrical calibration is explained in detail in [Wag00].

### 3.2 Geometric track reconstruction

Because of the high granularity of the start detector system, the $pp \rightarrow pK^+\Lambda$ events can be fully reconstructed with sufficient precision using only the geometrical information from the hit pattern in the various detector components. From the reconstructed directions together with the beam momentum, the four vectors of the reaction products can be calculated, as explained in Section 3.4.

Tracks are reconstructed using different methods for primary and secondary tracks [Fri02, Sch03].

The primary tracks, which come out of the target, must have constant $\phi$ and $\theta$ in the laboratory system for each detector plane. The reconstruction method is based on this fact, which is common to all reactions.

After the tracks originating in the target are reconstructed, secondary tracks are searched for using the remaining pixels. In the $pp \rightarrow pK^+\Lambda$ channel, the pattern of the $\Lambda$ decay is exploited in the secondary reconstruction, as explained in Section 3.2.2.
3.2.1 Primary track reconstruction

For the reconstruction of primary tracks, a matrix in $\phi$ and $\theta$ with 1° steps in both directions is defined. If a detector element is hit, the corresponding $\phi-\theta$ pair is filled into the matrix with a weight. Figure 3.2 shows the $\phi-\theta$ matrix for one event.

In this representation, the Starttorte coincidences are wide bands in phi, covering the whole theta range. Microstrip wedges and rings are sharp lines over theta or phi. Hodoscope fibres have a garland shape. In the Stop Detector (Barrel, Quirl and Ring) where only pixels are considered, hits are represented by small rectangles.

The weight is usually 1 for each layer. Therefore in the Starttorte and in the Endcap, where only the coincidence or the pixel are considered, the weight is respectively 2 and 3. Microstrip and Barrel are the only exceptions with a weight larger than 1 per layer. Due to their high precision, Microstrip elements are given a weight of 2. The Barrel is treated together with the Endcap and for practical reasons assigned the same weight (Table 3.1).

<table>
<thead>
<tr>
<th>Detector</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starttorte coincidence (2 layers)</td>
<td>2</td>
</tr>
<tr>
<td>Microstrip wedge (1 layer)</td>
<td>2</td>
</tr>
<tr>
<td>Microstrip ring (1 layer)</td>
<td>2</td>
</tr>
<tr>
<td>Hodoscope fibre (1 layer)</td>
<td>1</td>
</tr>
<tr>
<td>Quirl and Ring pixel (3 layers) or Barrel coincidence (2 layers)</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3.1: Detector weights in the $\phi-\theta$ matrix.

The enhancements in the $\phi-\theta$ matrix are candidates for primary tracks (Figure 3.2, right).
Each $\phi$-$\theta$ angle combination that satisfies the following conditions:

i) number of entries in the $\phi$-$\theta$ combination $\geq 8$;

ii) a Starttorte coincidence and at least $n$ pixel in $n$ other detectors (Microstrip, Small and Large Hodo, Stop Detector)

- $n=2$ for $\bar{p}p \rightarrow pK^+\Lambda$ reaction
- $n=1$ (or 2) for $\bar{p}p \rightarrow pp$ reaction

is labelled as ’good’.

All detector hits found in a corridor of 3$^\circ$ in $\phi$ and 2$^\circ$ in $\theta$ around a good $\phi$-$\theta$ combination are used in a line fit. Among all the possible element permutations, the one with the best chi-squared in the fit is chosen.

In the $pp \rightarrow pK^+\Lambda$ reconstruction at least two primary tracks are required, but there is no upper limit to the number of tracks that can be fitted.

Then, for all possible pairs of non-parallel tracks the distance of closest approach (DCA) is calculated. The pair with the best chi-squared and a DCA smaller than 2.0 mm is chosen to build the vertex.

The distribution of the primary vertices in $z$ is plotted in Figure 3.3. In the elastic analysis, when a vertex is found, the event is stored. In the case of $pp \rightarrow pK^+\Lambda$ reconstruction, the program continues with a search for secondary vertices.

![Figure 3.3: $z$ position of the primary vertex for $pp \rightarrow pK^+\Lambda$ reaction. The target width is $\pm 2$ mm. 93% of the events lie in the target region.](image)

### 3.2.2 Secondary track and vertex reconstruction

For reactions such as $pp \rightarrow pK^+\Lambda$, a secondary vertex also has to be reconstructed.

Pixels in the Hodoscopes and in the Stop Detector that do not belong to primary tracks are projected onto a $x$-$y$ plane at the $z$ position of the Large Hodoscope
3. Data Analysis

Figure 3.4: Representation of the search for secondary vertices. Hits in Small Hodoscope and in Stop detector (Barrel+Endcap) are projected on the Large Hodoscope plane. The projected pixel must be in sequence Stop-LargeHodo-SmallHodo-SmallHodo-SmallHodo-LargeHodo-Stop as shown in the sketch.

(Figure 3.4). In this projection, the tracks of charged particles produced by a primary particle in a delayed decay appear as one straight line. If the tracks have origin from a delayed decay, the sequence of the pixel in the line must be: Stop Detector, Large Hodoscope, Small Hodoscope, Small Hodoscope, Large Hodoscope, Stop Detector.

All the possible combinations of hit pixels in the Hodoscopes and in the Stop detector are fitted with a line. On the fitted line, at least 5 out of 6 pixels and the correct detector sequence are required. If this is the case, the two tracks are individually fitted and the distance of closest approach is calculated. This defines the secondary vertex.

Several decay vertices are allowed for one event, since it is possible to find more than two tracks. The best solution is chosen in the following analysis steps.

3.3 Selection of elastic events

For the precise determination of the beam polarisation a sample of elastic events $\bar{p}p \rightarrow pp$ was extracted.

In previous beamtimes, elastic events were used for calibration purposes but not further analysed and, although a reconstruction method was already present in the existing software tdas2paw, the reconstruction was restricted to those events with both protons hitting the hodoscope region ($\theta_1$ and $\theta_2 \in [26,45]$ degrees, indicated with “A” in Figure 3.5). Since it is easier to determine the polarisation when the analysing power is the largest, it is important to cover a theta range up to small (or large) angles. As shown in Figure 3.6, the analysing power is maximal at about 11 and 67° for both energies (2.75 and 2.95 GeV/c). For this reason, the analysis was extended to the full polar angular range covered by the COSY-TOF detector.
To get a nearly background-free sample, both tracks have to be reconstructed, and this is only possible in the angular range between about 11 and 70° ( "B" in Figure 3.5).

For convenience, protons are ordered according to the scattering angle; from now on, the proton with the smallest scattering angle is defined as “first” (θ₁ ≤ θ₂).

### 3.3.1 Elastic track reconstruction

Events with exactly two Starttorte coincidences are selected and the proton tracks are reconstructed using the φ-θ matrix method described in Section 3.2.1. For all possible pairs of track combinations, the distance of closest approach is calculated. The solution with the smallest chi square and a DCA smaller than 2.0 mm is taken to define the vertex. With this procedure, events where both protons fly through the Start Detector region are reconstructed (This class of event is called “type A” and illustrated in Figure 3.7, left).

In the case that fewer than two tracks are found in the matrix or when it is not possible to reconstruct a vertex, the event is not yet rejected: a different geometrical configuration is looked for. Events of this second class (“type B”) have a proton going through all Start Detectors and the second one scattering at a larger angle and hitting only Starttorte and Barrel. The first proton is reconstructed with the
Data Analysis

\(\phi-\theta\) matrix method additionally requiring a hit in Ring \((\theta_1 < 25^\circ)\) and choosing the solution with the smallest distance of closest approach from the \(z\)-axis. At the opposite \(\phi\) angle a Starttorte coincidence aligned with a Barrel hit is required. These two detector hits and the target’s centre define the second track (Figure 3.7, right).

\[\tan \theta_1 \cdot \tan \theta_2 = \frac{2 m_p}{2 m_p + T}\] (3.1)

must be satisfied. \(m_p\) stands for the proton mass and \(T\) is the kinetic energy of the beam proton. In practice a cut on \(\Delta \theta = \theta_{2,\text{expected}} - \theta_2\) is applied, with \(\theta_{2,\text{expected}}\) being the expected angle derived from Equation 3.1 (see also Appendix B).

For events of type B, where a proton track is reconstructed only with a hit in Starttorte and Barrel and therefore the \(\theta\) resolution is worse, the cut on the scattering angle is softened.

A more detailed description of the elastic event selection is given in the Appendix B.

3.4 Selection of \(pp \rightarrow pK^+\Lambda\) events

The geometry of the \(pp \rightarrow pK^+\Lambda\) events is reconstructed with the primary and secondary track search methods described in Section 3.2. Starting from the particle directions, the complete event kinematics is reconstructed with the software hypokrit.

\[^1\]As shown in Figure 3.5, when \(\theta_1 < 25^\circ\), the second proton scatters at too large an angle to be detected by the hodoscopes, and it is seen only in Starttorte and Barrel.
3.4.1 Missing mass and invariant mass

From the momentum conservation one gets:

\[
p_{\text{beam}} \cdot \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = p_1 \cdot \begin{pmatrix} \hat{x}_1 \\ \hat{y}_1 \\ \hat{z}_1 \end{pmatrix} + p_2 \cdot \begin{pmatrix} \hat{x}_2 \\ \hat{y}_2 \\ \hat{z}_2 \end{pmatrix} + p_\Lambda \cdot \begin{pmatrix} \hat{x}_\Lambda \\ \hat{y}_\Lambda \\ \hat{z}_\Lambda \end{pmatrix}
\]  

(3.2)

where \( p_i \) are the 3-momenta of beam, charged particles (1,2) and \( \Lambda \); \((\hat{x}_i, \hat{y}_i, \hat{z}_i)\) are the unit vectors in the particle directions. The beam momentum and its direction is known \emph{a priori}, and the unit vectors of the reaction products are obtained from the geometrical reconstruction: charged particles are directly measured, while the \( \Lambda \) direction is extracted from the positions of the primary and of the secondary vertex. Therefore, Equation 3.2 is a three-equation system, whose solution gives the momenta \( p_i \) (\( i=1, 2 \)) and \( p_\Lambda \).

The charged tracks must be assigned to the kaon and to the proton. The two possible combinations are tested with a mass hypothesis and the configuration with the smallest energy difference \( \Delta E \) in the total energy balance is taken:

\[
\Delta E = \frac{E_{\text{in}} - E_{\text{out}}}{E_{\text{in}}}
\]

\( E_{\text{in}} \) is the total energy of beam and target, \( E_{\text{out}} \) the sum of the energies of the produced particles, which are calculated using the extracted momenta \( p_i \). Events with a difference \( \Delta E \) larger than 13% are rejected.

Having determined the four-momenta of the charged particles, the missing mass of the neutral \( \Lambda \) can be computed as follows:

\[
m_\Lambda(\text{missing mass}) = \sqrt{(E_{\text{beam}} + m_p - E_p - E_K)^2 - (\vec{p}_{\text{beam}} - \vec{p}_p - \vec{p}_K)^2}
\]

The mass can also be reconstructed from the kinematics at the secondary vertex, using a mass assumption for the decay particles \((p, \pi)\). This is usually referred to as invariant mass:

\[
m_\Lambda(\text{invariant mass}) = \sqrt{(E_p + E_{\pi^-})^2 - (\vec{p}_p + \vec{p}_{\pi^-})^2}
\]

The mass assignment at the secondary vertex is unambiguous: the proton corresponds to the track with the smallest difference from the \( \Lambda \) direction (that is given by the trajectory primary vertex - secondary vertex).

3.4.2 Suppression of background reaction

In Figure 3.8 the missing mass peak at \( p_{\text{beam}}=2.75 \text{ GeV/c} \), obtained with the method explained in the previous sections, is shown. Now it is important to separate the \( pp \to pK^+\Lambda \) from the background reactions.
Figure 3.8: A missing mass peak of the 2.75 GeV/c sample before applying the cuts.

Figure 3.9: A missing mass peak of the 2.75 GeV/c sample after having applied the phase space and topology cuts.
The background is reduced with cuts on the phase space and on the reaction topology [Sch03]. Cuts on phase space reject particles whose momenta are not allowed by the kinematics of this reaction at the given energy. With the topology cuts, events are selected where the three particles produced at the target lie in a plane in the centre of mass system. Similarly, the coplanarity of the Λ and its decay products is required. Figure 3.9 illustrates the same sample of Figure 3.8 after applying the cuts.

### 3.5 Monte Carlo simulation

Simulations are necessary to gain information on the particle momenta and angle distributions, to test the reconstruction programs, to get the reconstruction efficiency and to optimise the cuts for background reduction.

The Monte Carlo simulation program KaYN (KAon, hYperon, Nucleon) is based on the GEANT 3.21 software package [GEA]. GEANT provides tools for detector definition, for the transportation of particles through the experimental setup, for the simulation of the detector response and for a graphical representation of the setup and of the particles’ trajectories.

The software KaYN was originally developed in Erlangen for the optimization of the start detector system design and of the trigger for the hyperon reactions [Par92, Met94, Kir94]. During a recent project of the COSY-TOF collaboration to compare all the presently available software at the different sites and in the context of this work, KaYN has been extensively tested together with the Las Vegas code written by a group from Dresden and a Geant based program from Jülich.

---

![Diagram](image.png)

**Figure 3.10:** *Scheme of the Monte Carlo (MC) output files and of the subsequent analysis steps.*

An important development has been the update of the output format (a scheme is in Figure 3.10). Besides an Hbook file\(^5\) with histograms of the relevant parameter,

---

\(^5\)Hbook is a file format used by PAW [PAW].
the information of the tracked particles per event and of the detector response are required as output of the Monte Carlo. Previously this information was packed together in an ASCII file; this ASCII file could be read by the analysis program \texttt{tdas2paw}. In the analysis, it was necessary to distinguish between Monte Carlo simulated input and experimental data files, due to their different formats. To solve this problem and to allow users of other analysis groups to exchange simulated data, a new output format was defined. This is common to all groups. Detector response data are written into a file whose format is analogue to the experimental TADE file; this makes it possible to analyse the simulated data in the same way as the experimental data. The kinematic information of the tracked particles are stored in a separate ASCII file. These data can be used to compare the analysed Monte Carlo data to test the reconstruction precision of the analysis software. A short description of the file formats is given in Appendix A.

In order to obtain a MC-TADE file looking exactly like an experimental TADE file, some updates of \texttt{KaYN} have been necessary. For example, the geometry of the hodoscopes had to be completely redefined to reproduce the fibre numbering scheme exactly as in the experiment (see Appendix C).

The extensive comparison of the Monte Carlo software with the Las Vegas code in Dresden and the Geant based program from Jülich was a good test for the stability of the programs and helped to find occasional bugs. For example, an error that occurred sometimes assigning wrong hits to Ring or Quirl could be corrected\footnote{During the tracking of a particle, GEANT stores automatically the hit volume number. The Archimedes’ spirals of Ring and Quirl are not predefined as GEANT volumes, therefore the assignment of the hit volume number must be calculated by the user [Par92].}. In addition the energy deposit mechanism and the clusters’ assignment in the Microstrip detector were extensively examined.

A further update of \texttt{KaYN} was made to take into account the new detector geometry. In October 2004, the Small Hodoscope was substituted with a similar one with three layers. A third detector plane was defined in the Monte Carlo. This layer can be independently switched on and off to reproduce the geometry of the 2002 (and previous) beam times or that of the 2004 beam time.
Chapter 4

Elastic events and beam polarisation

4.1 The elastic sample

As discussed, the elastic scattering was used to extract the beam polarisation with high precision. Elastic events were recorded over the whole beam time. The data at 2.75 GeV/c and 2.95 GeV/c beam momentum have been analysed as described in Chapter 3.

![Theta-CM distribution of the first proton (proton with the smallest scattering angle) of the reconstructed elastic events at 2.95 GeV/c beam momentum.](image)

Figure 4.1: Theta-CM distribution of the first proton (proton with the smallest scattering angle) of the reconstructed elastic events at 2.95 GeV/c beam momentum.

The theta distribution of the proton with the smallest scattering angle (first proton) in the CM-frame is shown in Figure 4.1 for the 2.95 GeV/c elastic data sample. The cuts on $\Delta\phi$ and $\Delta\theta$ (which are indicated as an example for events
of type A in Figure 4.2) have already been applied. More details about the cuts are found in Appendix B. The $\theta_1$ distribution covers the CM angles from about 42° to 90° in which the analysing power is fitted to extract the beam polarisation. This range corresponds to about 15° to 35° in the laboratory frame, covered by the proton with the smallest scattering angle $\theta_1$.

An estimation of the remaining background is made by comparison with Monte Carlo simulations.

![Graphs showing distributions](image)

Figure 4.2: Cuts on $\Delta \phi = (|\phi_1 - \phi_2| - 180^\circ)$ and $\Delta \theta = (\theta_{2,\text{expected}} - \theta_2)$ distributions for the reconstructed events of type A.

### 4.1.1 Estimation of the background

To estimate the background contamination in the elastic data sample, reactions with at least two charged particles in the final state have been simulated with the Monte Carlo program. The following reactions have been considered: $pp \rightarrow pn\pi^+$, $pp \rightarrow p\pi^0$ and $pp \rightarrow d\pi^+$. The last one is expected to give a larger contribution since there are only two particles in the final state and the coplanarity condition is fulfilled. The four particle reaction $pp\pi^+\pi^-$ has been studied as well.

The generated Monte Carlo files (see Section 3.5) are analysed with the same software as the experimental data. In Table 4.1, the reconstruction efficiencies $\eta$ and the cross sections $\sigma$ extrapolated to 2.95 GeV/c are listed.

Although the $pp \rightarrow d\pi^+$ events survive the coplanarity cut, they do not satisfy the cut on $\Delta \theta$. Since in addition the cross section for this reaction is small, the contribution to the background is minor. The other reactions have an even lower reconstruction efficiency because they do not fulfill the constraints given by the elastic cuts.
4. Elastic events and beam polarisation

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Rec. Efficiency</th>
<th>Cross Section</th>
<th>$\eta \cdot \sigma$</th>
<th>$\eta \cdot \sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow pp$</td>
<td>26.50</td>
<td>17.0</td>
<td>4.50</td>
<td>99.1</td>
</tr>
<tr>
<td>$pp \rightarrow d\pi^+$</td>
<td>0.93</td>
<td>0.4</td>
<td>0.004</td>
<td>0.1</td>
</tr>
<tr>
<td>$pp \rightarrow pp\pi^0$</td>
<td>0.63</td>
<td>3.8</td>
<td>0.024</td>
<td>0.5</td>
</tr>
<tr>
<td>$pp \rightarrow np\pi^+$</td>
<td>0.08</td>
<td>15.5</td>
<td>0.012</td>
<td>0.3</td>
</tr>
<tr>
<td>$pp \rightarrow pp\pi^+\pi^-$</td>
<td>0.009</td>
<td>2.6</td>
<td>0.0002</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 4.1: Elastic and its concurrent reactions: $\eta$ is the reconstruction efficiency once the elastic cut been applied; $\sigma$ is the cross section at 2.95 GeV/c [Fla85]. The cross section has been extrapolated for the reactions where no data were available at this energy. The product $\eta \cdot \sigma$ is expressed also as a percentage of the sum of the considered reactions.

The total background is estimated to be about 1%. In the data, some extra experimental background is observed, probably due to accidental coincidences and event mixing.

4.2 Beam polarisation

The elastic events are used to extract the beam polarisation. The polarised cross section is given by the relation:

$$\sigma_{\text{pol}}(\theta) = \sigma_{\text{unpol}}(\theta) \left[ 1 + P_B(\theta) A_y(\theta) \cos \phi \right] \quad (4.1)$$

with $P_B$ the beam polarisation and $A_y$ the analysing power. Assuming the same detection efficiency $\eta$ for up and down beam polarisation, the beam polarisation is given by the ratio of the measured asymmetry in the $\bar{p}p \rightarrow pp$ scattering process and the analysing power:

$$P_B(\theta) = \frac{N_1(\theta) - N_{\bar{1}}(\theta)}{N_1(\theta) + N_{\bar{1}}(\theta)} \cdot \frac{1}{A_y(\theta)} \quad (4.2)$$

$N_1$ and $N_{\bar{1}}$ are the measured number of protons which are produced with beam spin up and down. These depend on the scattering angle $\theta$ (usually expressed in the centre of mass system). The analysing power $A_y$ is known from EDDA [ED] or from the SAID database [SA].

In this work, the polarisation is determined with two different ways as explained in the following paragraph: a fit of the asymmetry data to the analysing power in slices of $\theta_{CM}$ and a single fit on a two dimensional histogram in the $\phi$-$\theta_{CM}$ plane. Results from the two methods are presented in the next section (Section 4.3).

Slice fit

Once the $\bar{p}p \rightarrow pp$ sample is extracted, the asymmetry is determined for different theta bins in a range from 42 to 90$^\circ$ in the centre of mass frame (Figure 4.3).
Figure 4.3: Asymmetry for some bins of theta fitted with $f = c_0 \cos \phi$.

Assuming that the absolute polarisation in the up direction is equal to the down polarisation, the asymmetry can be fitted with a cosine distribution in $\phi$:

$$\frac{N_1 - N_{\bar{1}}}{N_1 + N_{\bar{1}}} = c_0 \cos \phi$$  \hspace{1cm} (4.3)

From the comparison of the fit coefficients $c_0$ with the EDDA or SAID data for the analysing power (Figure 4.4), the polarisation is deduced. When fitting to EDDA points, EDDA errors are quadratically summed with the statistical errors of our measurement. SAID data that are extrapolated from several measurements are given without errors, since these should be negligible. In the general case of different beam polarisations in the up and down direction, the fit to the asymmetry depends on two parameters $c_1$ and $c_2$:

$$\frac{N_1 - N_{\bar{1}}}{N_1 + N_{\bar{1}}} = \frac{(c_1 - c_2) \cos \phi}{2 + (c_1 + c_2) \cdot \cos \phi}$$  \hspace{1cm} (4.4)

In this case too, the two polarisations are obtained by fitting the $c_i$ parameters to the analysing power.

The data have been fitted assuming equal and different up-down beam polarisation. Results are shown in Section 4.3.
4. Elastic events and beam polarisation

Figure 4.4: $c_\alpha$ values at 2.75 GeV/c compared to the asymmetry data from SAID (top) and from EDDA (bottom) plotted versus $\theta_{CM}$.

Two dimensional fit

The asymmetry is plotted in a two dimensional histogram of $\phi$ versus the scattering angle $\theta_{CM}$. This histogram is fitted to a $\phi$-$\theta_{CM}$ grid of the SAID data with $A_y$ multiplied by $\cos \phi$ (Figure 4.5).

This method has been applied only assuming equal polarisation in the up and down directions.
4. Elastic events and beam polarisation

Figure 4.5: Left: asymmetry of the pp elastic sample at 2.75 GeV/c plotted in $\phi$ and $\theta_{CM}$. Right: SAID analysing power multiplied by $\cos \phi$.

Figure 4.6: Polarisation as a function of the run numbers (≈ time) at 2.75 GeV/c (left) and at 2.95 GeV/c (right) obtained with the slice fit method. The solid line indicates the weighted mean.
4.3 Beam polarisation results

Data from each single run have been fitted assuming equal beam polarisation in the up and down directions. The *slice fit* method and the *two dimensional* fit to SAID delivers exactly the same polarisation values, with the exception of a few runs with very low statistics (less than 100 elastic events) where anyhow the difference lies within the (very large) statistical errors. Both methods are equivalent also in the size of the errors.

In Figure 4.6 the polarisation obtained with the *slice fit* method to SAID data is plotted for the single runs at 2.75 GeV/c and 2.95 GeV/c. For both energies the polarisation remains constant in time and therefore the fits have been repeated using the complete statistics.

4.3.1 Beam polarisation at 2.75 GeV/c

The results obtained with the complete elastic sample at this energy are the following:

\[
P_B = 0.58 \pm 0.05 \quad (\text{slice fit to EDDA}) \\
P_B = 0.619 \pm 0.005 \quad (\text{slice fit to SAID})
\]

The errors are statistical only; an estimation of systematic error is discussed in Section 4.4. From the *two dimensional fit* to SAID exactly the same polarisation as from the *slice fit* is obtained, proving again the equivalence of the methods.

The values fitting to EDDA or SAID are compatible within the error bars. The large difference in the errors is due to the fact that the EDDA uncertainties have also been considered, while SAID data are taken without errors. The SAID partial wave analysis is expected to be more accurate, since it averages over the total elastic data.

With the *slice* method it was also possible to test independently the polarisation in both directions, fitting the asymmetry with Equation 4.4. Within the precision of the data, difference in the up-down polarisation cannot be excluded, but the mean polarisation remains in agreement with the one obtained above. Moreover the fits of the asymmetry with one parameter (Equation 4.3) give already satisfactory $\chi^2$ values ($0.4 < \chi^2 < 2.$), and the introduction of a second parameter (Equation 4.4) does not improve the $\chi^2$ considerably. It was also tested that a possible difference in the up-down beam polarisation has no influence on the polarisation observables of the reaction $\bar{p}p \rightarrow pK^+\Lambda$ (Section 5.4).

The final value for the beam polarisation at 2.75 GeV/c is $P_B = 0.619 \pm 0.005$ stat. $\pm 0.03$ sys.\(^\dagger\).

\(^\dagger\)Systematic errors are discussed in Section 4.4
4.3.2 Beam polarisation at 2.95 GeV/c

Also at 2.95 GeV/c, the beam polarisation remains constant during time and the average polarisation has been obtained from a fit on the whole statistics:

\[
P_B = 0.33 \pm 0.04 \quad (\text{slice fit to EDDA})
\]
\[
P_B = 0.398 \pm 0.007 \quad (\text{slice fit to SAID})
\]

The errors are statistical only. The two dimensional fit to SAID delivers the same values as the slice fit.

The lower polarisation values, in comparison to those at 2.75 GeV/c beam momentum, are explained by the difficulties in maintaining the beam polarisation at this energy where more depolarising resonances must be crossed.

Also at this energy a difference in the up-down polarisation cannot be excluded, however the average polarisation remains constant. This is what influences the $\Lambda$ polarisation observables.

The beam polarisation at 2.95 GeV/c is $P_B = 0.398 \pm 0.007$ stat. $\pm 0.03$ sys.

4.4 Estimation of systematic errors

Tests on systematic errors were carried out varying the cuts for the elastic sample and the analysing power fit range. Some of the tests are presented in Figure 4.7 for the sample at 2.75 GeV/c. The $x$ axis indicates the test number. They have the following characteristics:

1. test no. 1. large elastic cuts; analysing power fitted in $\theta_{CM} \in [38,90]$
2. large elastic cuts; analysing power fitted in $\theta_{CM} \in [42,90]$
3. large elastic cuts; analysing power fitted in $\theta_{CM} \in [46,90]$
4. sharp elastic cuts; analysing power fitted in $\theta_{CM} \in [38,90]$
5. sharp elastic cuts; analysing power fitted in $\theta_{CM} \in [42,90]$
6. sharp elastic cuts; analysing power fitted in $\theta_{CM} \in [46,90]$

Sharp cuts are the typical cuts on $\Delta \theta$ and $\Delta \phi$ used for the selection of the elastic scattering. With large elastic cuts are indicated softer cuts on the same variables. These cuts are listed in Appendix B.

As expected, the polarisation value increases with sharper elastic cuts, since the unpolarised background is reduced (compare test 1 to test 4 or 2-5 or 3-6).

Within the same sample, a better agreement between the fits to EDDA or SAID is reached by limiting the fit in a range with higher statistics (cf. 1-2 or 4-5). Note from Figure 4.1 that the range of $\theta_{CM}$ between 38 and 42$^\circ$ contains very few events and so the error of the fitted asymmetry $c_0$ in the slice $[38,42]$ is very large. When fitting the $c_0$ coefficients to the the analysing power of SAID, this first $c_0$ point has only a small influence due to its large statistical error bars. This is not true when fitting to EDDA, since the dominating errors are those from EDDA. In this case, all the $c_0$ coefficients have comparable weights when fitting to $A_y$. 
4. Elastic events and beam polarisation

Figure 4.7: Beam polarisation values obtained with different cuts and fitting range. Explanations in text.

On the other hand, reducing too much the fitting range magnifies unnecessarily the errors without affecting the results (cf. 2-3 or 5-6). For this reason, the elastic routine had to be extended to the region outside the hodoscopes, i.e. for the events classified as type B in $\theta_{CM} \in [42,68]$ (Section 3.3).

The maximal difference of the polarisation for the SAID fits at 2.75 GeV/c is about 0.03. This is taken as systematic error. The values of test #5 have been given as the final polarisation result in Section 4.3. Analogue tests have been carried out for the data sample at 2.95 GeV/c beam momentum and the estimated systematic uncertainty is slightly less than 0.03.

4.4.1 Beam polarisation at 3.30 GeV/c as crosscheck

During the same beam time in 2002, unpolarised data at 3.30 GeV/c beam momentum were also acquired. Three runs of this period are used here as a test for the beam polarisation calculation (runs 1997-99). Unfortunately, it was not possible to retrieve the spill information.

To be able to calculate the polarisation, the data are assigned an artificial beam spin. This is done in two ways:

- The artificial beam spin is switched every $\sim$10000 events, simulating the spill length. There is no correlation between these spills and the real spills.

- The data are divided in four periods and the ‘artificial’ spin is switched only four times
In this way the polarisation routines as well as the stability of the measurement can be checked. In the first case, where the spills are simulated, the beam polarisation is compatible with zero as expected: $P_B = -0.022\pm0.019$ (Figure 4.8).

In the second case, using long periods, instrumental asymmetries play a role and therefore the beam polarisation may deviate from zero: $P_B = 0.066\pm0.019$. These instrumental asymmetries cancel in the data at 2.75 GeV/c and at 2.95 GeV/c since the spin is flipped at every spill.

Figure 4.8: Measured asymmetry ($c_0$ coefficients) in the case of beam spin flipped at every spill or flipped only four times (see text) compared with the analysing power from the SAID database at 3.30 GeV/c.
Chapter 5

Hyperon data and polarisation observables

5.1 The Λ sample

The data of the reaction $pp \rightarrow K^+\Lambda p$ at 2.75 GeV/c and at 2.95 GeV/c beam momentum have been analysed as explained in Chapter 3.

Figure 5.1: Reconstructed missing mass at 2.75 GeV/c (left) and at 2.95 GeV/c (right). The final cuts between 1.10 and 1.13 GeV/c$^2$ are also shown.

Figure 5.1 shows the Λ missing mass plots reconstructed from the two energies, after the cuts were applied. In the samples 21091 Λ’s at 2.75 GeV/c and 33551 Λ’s
at 2.95 GeV/c are found. Before computing the polarisation observables, a further cut is applied on the missing mass spectrum between 1.10 and 1.13 GeV/c². This reduces the yields to 11991 and 19243 Λ’s, respectively, but produces a sample with a very small background (less than 10%).

Polarisation observables are a suitable tool to study the hyperon production mechanism, as already discussed in Chapter 1. In the following, the methods to obtain the Λ polarisation $P_\Lambda$, the Λ analysing power $A_y^\Lambda$, and the spin transfer coefficient $D_{NN}$ are presented and compared. Each of the three observables is deduced from the experimental data applying different methods in order to investigate the systematic uncertainties of the result, possibly caused by inefficiencies in the COSY-TOF detector system. These observables are plotted versus the Feynman variable $x_F$, the Λ transverse momentum $p_T$ and the cosine of the Λ emission angle in the centre of mass frame $\cos \theta^\Lambda_{CM}$ (Section 1.1.2).

### 5.2 Λ polarisation

The Λ polarisation is measured from the asymmetry of its parity violating decay and can be extracted from the angular distribution of the decay proton, since the proton is preferentially emitted in the direction of the Λ spin.

With an unpolarised beam, parity conservation in the hadronic process $pp \rightarrow pK^+\Lambda$ restricts the Λ polarisation to be non-zero only transverse to the production plane (i.e. in the direction of $\vec{p}_{beam} \times \vec{p}_\Lambda$, indicated with $\hat{n}_\perp$). A sketch of the system is illustrated in Figure 5.2.

In the following sections the methods used to derive the Λ polarisation are described.

---

![Figure 5.2: Schematic depiction of the system.](image-url)
5. Hyperon data and polarisation observables

Weighted sum estimators

The angular distribution of the decay proton in the $\Lambda$ rest frame is:

$$\frac{dN(\theta^{**})}{d(\cos\theta^{**})} = N_0 \left(1 + \alpha P_\Lambda \cos\theta^{**}\right) \eta(\theta^{**}) \tag{5.1}$$

$N_0$ is the total number of events; $\alpha$ the decay asymmetry parameter $\alpha = 0.642 \pm 0.013$ [PDG06]; $\theta^{**}$ the angle between $\hat{n}_\perp$ and the decay proton direction in the $\Lambda$ rest frame; $P_\Lambda$ the $\Lambda$ polarisation; and $\eta(\theta^{**})$ the detection efficiency.

Assuming a symmetric detection efficiency $\eta(\theta^{**}) = \eta(\theta^{**} + \pi)$, which is the case for the TOF detector, but not requiring its isotropy and adapting the method of the \textit{weighted sums} [Bes79, Fri02], the $\Lambda$ polarisation can be expressed simply as a function of the $\theta^{**}$ angle:

$$P_\Lambda = \frac{1}{\alpha} \frac{\sum_i n_i \cos(\theta^{**}_i)}{\sum_i n_i \cos^2(\theta^{**}_i)} \tag{5.2}$$

$$\sigma_{P_\Lambda} = \frac{1}{\alpha} \frac{1}{\sum_i n_i \cos^2(\theta^{**}_i)} \tag{5.3}$$

$n_i$ is the number of events in the $i$-th bin of $\cos(\theta^{**}_i)$ or of $\cos^2(\theta^{**}_i)$. The sum is made over 40 bins in both estimators. $\sigma_{P_\Lambda}$ is the error.

Symmetric bins integration

A second way to extract the $\Lambda$ polarisation is taken from [Cho98] and is here referred to as the \textit{symmetric bins integration} method, since the $\Lambda$ polarisation is calculated by comparing the event yields in $\theta^{**}$ to those in $\pi - \theta^{**}$. Forming this asymmetry, the $\Lambda$ polarisation is calculated independently of the variation of the acceptance with the angle $\theta^{**}$.

The data are sorted in $2M=40$ bins of $\cos\theta^{**}$, then $M$ values of $P_\Lambda(\theta^{**}_i)$ are calculated:

$$P_\Lambda(\theta^{**}_i) = \frac{1}{\alpha \cos\theta^{**}_i} \left( \frac{\int_{\theta^{**}_i+\Delta\theta}^{\theta^{**}_i+\Delta\theta} dN - \int_{\pi-(\theta^{**}_i+\Delta\theta)}^{\pi-(\theta^{**}_i+\Delta\theta)} dN}{\int_{\theta^{**}_i+\Delta\theta}^{\theta^{**}_i+\Delta\theta} dN + \int_{\pi-(\theta^{**}_i+\Delta\theta)}^{\pi-(\theta^{**}_i+\Delta\theta)} dN} \right) \quad \text{for } 1 \leq i \leq M. \tag{5.4}$$

To get $P_\Lambda$, the weighted sum of the $P_\Lambda(\theta^{**}_i)$ over the various bins is evaluated, with the weights $w_i$ corresponding to the inverse squares of the statistical errors in each bin:

$$P_\Lambda = \frac{\sum_i w_i P_\Lambda(\theta^{**}_i)}{\sum_i w_i} \tag{5.5}$$

The statistical error of $P_\Lambda$ is obtained with the standard error propagation method.
5. Hyperon data and polarisation observables

Up-down integral

Another way to determine the $\Lambda$ polarisation is derived from the up-down integral method described in [Bon88]. With the hypothesis of a constant acceptance $\eta(\theta^{**})$, the expected event distribution is:

$$f(\cos \theta^{**}) = \frac{(N_1 + N_2)}{2} (1 + \alpha P_\Lambda \cos \theta^{**})$$  \hspace{1cm} (5.6)

and the $\Lambda$ polarisation can be expressed as:

$$P_\Lambda = \frac{2}{\alpha} \left( \frac{N_2 - N_1}{N_2 + N_1} \right)$$  \hspace{1cm} (5.7)

where $N_1$ and $N_2$ are the number of events with the decay proton produced under $(\cos \theta^{**}$ negative) or above $(\cos \theta^{**}$ positive) the production plane:

$$N_1 = \int_{-1}^{0} f(\cos \theta^{**}) \, d(\cos \theta^{**}) \hspace{1cm} (5.8)$$

$$N_2 = \int_{0}^{1} f(\cos \theta^{**}) \, d(\cos \theta^{**}) \hspace{1cm} (5.9)$$

The assumption of a constant acceptance looks reasonable since COSY-TOF is a symmetric detector covering at this beam energy the whole phase space of the $\bar{p}p \rightarrow pK^+\Lambda$ reaction.

5.2.1 Comparison of the three methods used

The $\Lambda$ polarisation is evaluated with the presented methods for each bin of $p_T$, $x_F$, and $\cos \theta_\text{CM}^\Lambda$.

Figures 5.3 and 5.4 show the $\Lambda$ polarisation for the 2.75 GeV/c and the 2.95 GeV/c beam momentum measurement, respectively. In both cases, the three methods used give very similar results, proving the stability of the procedures. The symmetric bins integration method has in absolute terms the smallest uncertainties, although the error differences from the weighted sum estimators are often only in the fourth place after the decimal point. From the small variation of the data points obtained with the three different methods, one may conclude that the systematic uncertainties, arising e.g. from detector efficiencies, are smaller than the statistical ones.

Since the methods proved to be compatible, the final result presented in Chapter 6 is obtained averaging the three values. The largest statistical uncertainties of each point are chosen as errors.
Figure 5.3: $\Lambda$ polarization at 2.75 GeV/c, different methods compared. All points in the same bin refer to the bin’s centre; points belonging to the same bins have been shifted on the $x$ axis for clarity.
Figure 5.4: A polarization at 2.95 GeV/c, different methods compared. All points in the same bin refer to the bin’s centre; points belonging to the same bins have been shifted on the x axis for clarity.
5.3 Λ analysing power

The analysing power reflects how the Λ production cross section depends on the spin direction of the beam. The analysing power has been calculated with two different methods.

**Left-right integral**

The analysing power $A_\Lambda^y$ is the ratio of the left-right asymmetry and the beam polarisation given by:

$$A_\Lambda^y = \frac{1}{P_B \cos \psi} \left( \frac{N_L(\psi) - N_R(\psi)}{N_L(\psi) + N_R(\psi)} \right)$$  \hfill (5.10)

where $\psi$ is the angle between the beam spin axis (corresponding to the $y$-axis of the lab-system) and the normal to the $p\Lambda$ production plane $\mathbf{n}_\perp$ (Figure 5.5); $P_B \cdot \cos \psi$ is the projection of the beam polarisation along $\mathbf{n}_\perp$; $N_L$ and $N_R$ are the number of Λ particles going left or right respect to the beam [Bon88].

![Figure 5.5: Definition of the $\psi$ angle](image)

The Λ particles are sorted according to the beam spin direction and their direction on the production plane: $N_{L1}$ are Λ’s going left with beam spin up, $N_{L1}$ are Λ’s going left with beam spin down; $N_{R1}$ and $N_{R1}$ are the analogue with Λ’s going right. Since the left-scattered particles with beam spin up are equivalent to the right-scattered particles with beam spin down, we can separate left from right and write:

$$A_{\Lambda,Left}^y(\cos \psi_i) = \frac{1}{P_B \cos \psi_i} \left[ \frac{N_{L1}(\cos \psi_i) - N_{L1}(\cos \psi_i)}{N_{L1}(\cos \psi_i) + N_{L1}(\cos \psi_i)} \right].$$  \hfill (5.11)

A corresponding expression can be written for $A_{\Lambda,Right}^y(\cos \psi_i)$. Both left and right expressions are calculated for 30 bins of $\cos \psi_i$.

The final value of $A_\Lambda^y$ is computed by taking the mean value of $A_{\Lambda,Left}^y$ and $A_{\Lambda,Right}^y$, each averaged over the bins of $\cos \psi$ with the weights $w_i$:

$$A_\Lambda^y = \frac{1}{2} \left[ \frac{\sum_i w_i^L A_{\Lambda,Left}^y(\cos \psi_i)}{\sum_i w_i^L} + \frac{\sum_i w_i^R A_{\Lambda,Right}^y(\cos \psi_i)}{\sum_i w_i^R} \right].$$  \hfill (5.12)

$w_i^L$ and $w_i^R$ are again the inverse squares of the statistical errors in each bin.
Cross Ratio

\( A_y^\Lambda \) has been also deduced using the cross ratio method described in [Cho98]

\[
A_y^\Lambda = \frac{1}{P_B \langle \cos \psi \rangle} \frac{r - 1}{r + 1},
\]

(5.13)

where

\[
r = \sqrt{\frac{(N_{L1})(N_{R1})}{(N_{L1})(N_{R1})}}.
\]

(5.14)

\( N_{L1} \) is the total number of \( \Lambda \)'s, integrated over \( \psi \), scattered left with beam spin up (and analogue meanings for \( N_{R1}, N_{L1}, N_{R1} \)). Hence \( r \) is determined from the ratio of the total \( \Lambda \)-yields integrated over \( \psi \). With \( \langle \cos \psi \rangle \) is indicated the mean value of the \( \cos \psi \) distribution averaged for the positive and the negative range.

The statistical error of \( A_y^\Lambda \) is obtained with the standard error propagation method.

5.3.1 Comparison of the methods used

In Figures 5.6 and 5.7 the \( \Lambda \) analysing power for the 2.75 GeV/c and the 2.95 GeV/c data samples is shown. At both energies the results obtained from the different methods are compatible within the statistical uncertainties.

The left-right integral procedure delivers the smallest uncertainties, for this reason these values are chosen to compute \( D_{NN} \) (Section 5.4). Anyway, \( A_y^\Lambda \) values from other methods do not vary the result of \( D_{NN} \), since the analysing power is small, typically \( |A_y^\Lambda| < 0.1 \). In Appendix D.1, it is demonstrated that the value of \( A_y^\Lambda \) has a negligible influence on the spin transfer coefficient.

The average of the two methods is taken as final result, with the errors corresponding to the the largest statistical uncertainties of the two. Results are presented with data from other experiments in Chapter 6.
Figure 5.6: Analysing power at 2.75 GeV/c, comparison of different methods. All points in the same bin refer to the bin's centre; points belonging to the same bins have been shifted on the x axis for clarity.
Figure 5.7: Analysing power at 2.95 GeV/c, comparison of different methods. All points in the same bin refer to the bin’s centre; points belonging to the same bins have been shifted on the x axis for clarity.
5.4 Spin transfer coefficient $D_{NN}$

The depolarisation or spin transfer coefficient $D_{NN}$ measures the transfer of polarisation from the beam to the produced $\Lambda$. $D_{NN} = 0$ indicates that the spin of the $\Lambda$ is independent of the initial proton polarisation, while $D_{NN} = +1$ or $-1$ means maximum polarisation transfer. Negative values indicate a spin flip.

The definition of the angles and of the weights $w_i$ is the same as in the previous sections (see also Figures 5.2 and 5.5). The errors are computed with the standard propagation method on the statistical errors.

Up-down difference

The spin transfer coefficient can be expressed as a difference of the measured $\Lambda$ polarisation with beam spin up $P_{\Lambda^1}$ and down $P_{\Lambda^1}$ [Bon87].

$$D_{NN} = \frac{1}{2 P_B \cos \psi} \left[ P_{\Lambda^1} (1 + P_B A_{\theta}^\Lambda < \cos \psi >) - P_{\Lambda^1} (1 - P_B A_{\theta}^\Lambda < \cos \psi >) \right]$$

The values of $P_{\Lambda^1}$ ($P_{\Lambda^1}$) are obtained from Equation 5.4 in the case of events with beam spin up (down). $A_{\theta}^\Lambda$ is taken from the left-right integral method, which is the one with smallest error bars.

Since we measured a relatively small $A_{\theta}^\Lambda$ (usually $|A_{\theta}^\Lambda| < 0.1$) and since $P_B < 0.6$, $D_{NN}$ can be approximated to:

$$D_{NN} \simeq \frac{1}{2 P_B \cos \psi} \left[ P_{\Lambda^1} - P_{\Lambda^1} \right].$$

In Appendix D.1 is shown that the difference of the results with this approximation or from Equation 5.15 is minimal and also the error bars remain practically unchanged.

Efficiency independent

From Equation 5.1 one can derive, as described in [Bon88], an expression for the spin transfer coefficient that gives a result independent of the detector efficiency, since the efficiency does not change between spin up and spin down:

$$D_{NN} = \frac{1}{\alpha P_B \cos \psi} \left[ B \left( 1 + \frac{\cos \theta^*}{\cos \theta^{**}} \right) \right] - \frac{A_{\theta}^\Lambda}{\alpha} \frac{1}{\cos \theta^{**}}.$$ (5.17)

Also $B$ depends on $\theta^{**}$ and is the asymmetry of the $\Lambda$’s produced by beam protons with spin up and down:

$$B(\theta^{**}) = \frac{N_1(\theta^{**}) - N_1(\theta^{**})}{N_1(\theta^{**}) + N_1(\theta^{**})}.$$ (5.18)
To apply the Formula 5.17, the data are sorted in 20 bins of $\cos \theta^{**}$ and a weighted sum over the bins is taken

$$D_{NN} = \frac{1}{\alpha P_B < \cos \psi>} \left[ \sum_i \left( \frac{B_i (1 + \alpha P_B \cos \theta_i^{**})}{\cos \theta_i^{**}} - \frac{A_y \cos \theta_i^{**}}{\cos \theta_i^{**}} \right) w_i \right] \frac{1}{\sum w_i}.$$  

(5.19)

The values of $P_\Lambda$ from the symmetric bin integration method and the ones of $A_y^\Lambda$ from the left-right integral are used.

In Chapter 4, it was shown that it is in principle possible to calculate independently up and down beam polarisation. Since at both energies the data cannot exclude a difference in the up-down beam polarisation, it was investigated if this could in some way affect the spin transfer coefficient. In the general case that the up beam polarisation is different from the down beam polarisation $P_B^\up = -P_B^\down$, Equation 5.17 assumes the form:

$$D_{NN} = -\frac{2}{\alpha < \cos \psi >} \left[ \frac{B(1 + \alpha P_\Lambda \cos \theta^{**})}{[B(P_B^\up + P_B^\down) - (P_B^\up - P_B^\down)] \cos \theta^{**}} \right] - \frac{A_y^\Lambda}{\alpha \cos \theta^{**}}.$$  

(5.20)

In this case, too, a weighted sum over the bins in $\cos \theta^{**}$ was made. As expected, it was found that the spin transfer coefficient is practically independent of a difference in the beam polarisation and only the mean polarisation has an influence.

**DISTO method**

In order to have a better comparison of the $D_{NN}$ values obtained from our data with the data from literature, it was decided to apply the same method used by the DISTO experiment, which was up to now the only experiment that measured the $\bar{p}p \rightarrow pK^+\Lambda$ reaction exclusively. The evaluation of $D_{NN}$ is made with the procedure described in detail in [Mag99] at pages 324-325.

### 5.4.1 Comparison of the methods used

Figures 5.8 and 5.9 show a comparison of the $D_{NN}$ values obtained at 2.75 GeV/c and at 2.95 GeV/c with the three methods presented here. All methods are stable and deliver similar values, compatible within errors. The DISTO method has always in absolute the smallest error bars.

Also in this case, the variation of the results obtained with the different methods is small compared to the statistical accuracy of the data points; for this reason the systematic uncertainties are expected to be smaller than the statistical ones.

For the final result in Chapter 6, the average is taken. The errors of the average correspond to the largest statistical uncertainties obtained by one method for each point.
Figure 5.8: Spin transfer coefficient at 2.75 GeV/c, comparison of different methods. All points in the same bin refer to the bin’s centre; points belonging to the same bins have been shifted on the x axis for clarity.
Figure 5.9: Spin transfer coefficient at 2.95 GeV/c, comparison of different methods. All points in the same bin refer to the bin’s centre; points belonging to the same bins have been shifted on the x axis for clarity.
Chapter 6
Discussion and conclusions

The data of the polarisation observables obtained with the methods described in Chapter 5 are presented and discussed here. Note that for each variable, the average obtained from the different methods (with unaltered statistical uncertainties) is shown. The results obtained within this work are compared with previous measurements and theoretical models.

6.1 Λ polarisation

In Figures 6.1 and 6.2, the Λ polarisation data of this work are compared with a measurement at 2.75 GeV/c [Met98], one at 2.85 GeV/c [Fri02] and one at 2.95 GeV/c [Sch03] all obtained by COSY-TOF with an unpolarised beam. Data are plotted versus the transverse momentum, the Feynman variable and versus the cosine of the Λ emission angle $\cos \theta_{CM}$. There is a good agreement of the data at 2.85 GeV/c (Figure 6.1). Data at 2.75 GeV/c by [Met98] show some deviations, that are however comparable with the large statistical fluctuations. A very good agreement is obtained at 2.95 GeV/c for all three distributions (Figure 6.2).

These results are in fair agreement also with data from other experiments. The polarisation observed so far has been presented in Chapter 1: the polarisation is negative and increases linearly with the transverse momentum. Considering the statistical uncertainties, the results of this work are at both energies in agreement with the previous measurements that found the polarisation to be $P_\Lambda \approx -0.1$ at $p_T = 0.5$ GeV/c (e.g. [Fel96], here in Figure 1.6).

A comparison of the data with the theory model of Laget [Lag91] does not bring clear statements on the Λ production mechanism. Laget’s predictions depending on $p_T$ are shown in Figure 6.3: in the case of kaon exchange, slightly positive polarisation values are expected; in the case of combined pion and kaon exchange, a positive peak around $p_T=0.07$ GeV/c and then a negative trend. The predictions are limited to $p_T < 0.2$ GeV/c. Our data are small in the whole range ($0 < p_T < 0.45$ GeV/c) and the positive enhancement at $p_T \approx 0.07$ GeV/c is not observed. In this respect, these data cannot confirm this pion and kaon exchange calculation of
The prediction for kaon exchange is positive and looks closer to the data. However, within the accuracy of this measurement and the freedom of the model and its parameters, a significant pion exchange contribution in the Λ production mechanism cannot be excluded.

Figure 6.1: Λ polarisation at 2.75 GeV/c compared with previous unpolarised measurements at COSY-TOF [Met98, Fri02].
This work, 2.95 GeV/c

W. Schroeder, 2.95 GeV/c

Figure 6.2: A polarisation at 2.95 GeV/c compared with a previous unpolarised measurement at COSY-TOF at the same energy [Sch03]. Data by Schroeder were extracted from the plots in [Sch03].
6. Discussion and conclusions

Figure 6.3: A polarisation versus the transverse momentum at 2.75 and 2.95 GeV/c and theoretical model by Laget [Lag91]: the dashed line represents kaon exchange, the solid line pion and kaon exchange. Points at 2.95 GeV/c belong as well to the bins’ centre but are shifted for clarity.
6.2 \( \Lambda \) analysing power

Figure 6.4 shows the \( \Lambda \) analysing power \( A_\Lambda^y \) obtained in this work compared with the data from literature. Within the large error bars, the data of this work show a good agreement with the trend of the previous measurements: in the negative range of the Feynman variable, our results reproduce good the points of DISTO [Bal01]; at positive \( x_F \), the results compare well even with the data at high energy from the inclusive measurements [Bon87, Bon88, Bra95].

![Figure 6.4: \( \Lambda \) analysing power \( A_\Lambda^y \) versus \( x_F \) at 2.75 and 2.95 GeV/c. Data at 2.95 GeV/c are shifted on the horizontal axis for clarity. Data at 13 GeV/c and 18 GeV/c are from [Bon88], at 200 GeV/c from [Bra95]. Data at 2.94 GeV/C and at 3.67 GeV/c from DISTO were extracted from a plot in [Bal01].](image)

6.3 Spin transfer coefficient

An observable which should provide more information on the \( \Lambda \) production mechanism is the spin transfer coefficient, \( D_{NN} \). The predictions for \( D_{NN} \) in the meson exchange picture of Laget should distinguish clearly between pion and kaon exchange, as already discussed in Section 1.2.3.

In Figure 6.5, the spin transfer coefficient versus the transverse momentum at 2.75 GeV/c and at 2.95 GeV/c is shown in comparison with the measurement of
[Bra95] at very high momentum. In the common range, the points are consistent within the errors. Up to \( p_T < 0.45 \text{ GeV/c} \), the measured spin transfer coefficient is compatible with zero.

![Graph showing \( D_{NN} \) vs. \( p_T \) in comparison with literature data from [Bra95] at 200 GeV/c. Data at 2.95 GeV/c are shifted on the horizontal axis for clarity.]

Figure 6.5: \( D_{NN} \) vs \( p_T \) in comparison with literature data from [Bra95] at 200 GeV/c. Data at 2.95 GeV/c are shifted on the horizontal axis for clarity.

The data at 2.75 GeV/c and at 2.95 GeV/c are plotted versus the Feynman variable together with the results from other experiments in Figure 6.6. The results of this work are compatible with zero in the whole range. Fair agreement with the inclusive data at high energies (13 GeV/c, 18 GeV/c and 200 GeV/C) is obtained, while there is a noticeable contradiction with the DISTO points at 2.94 GeV/c and at 3.67 GeV/c, which are large and negative.

The DISTO results were interpreted as indicating kaon exchange dominance, although a significant deviation is seen for negative \( x_F \) where the points remain negative (especially at 3.67 GeV/c) and the model suggests \( D_{NN} \approx 0 \). The results of this work are consistent with zero, exclude a pure or dominant kaon exchange and suggest a dominant pion component in the production mechanism (Figure 6.7). The exclusion of a kaon exchange dominance in \( \Lambda \) production is also consistent with previous results of unpolarised \( \Lambda \) production by COSY-TOF. In [Sch03, Sch03a, Abd06] the Dalitz plots are fitted with a model by Sibirtsev (discussed in Section 1.2.1): the results show that, at least near threshold, the contribution of the \( N^* \) resonances and the exchange of non-strange mesons are dominant (since only these mesons lead to excitations of the \( N^* \) resonances).

In summary, the polarisation results obtained in this work are in nice agreement with previous data, apart from DISTO. The conclusion drawn from the polarisation observables and the previous Dalitz plot analysis suggest a preference of the pion exchange in the \( \Lambda \) production process. This picture is valid down to the production threshold.
6. Discussion and conclusions

Figure 6.6: $D_{NN}$ versus $x_F$ in comparison with literature data. The DISTO values are extracted from the plot in [Bal01]. The inclusive measurements at 13 GeV/c and 18 GeV/c are from [Bon88] and at 200 GeV/c from [Bra97]. Data at 2.95 GeV/c are shifted on the horizontal axis for clarity.

Figure 6.7: $D_{NN}$ versus $x_F$ at 2.75 GeV/c (triangles) and at 2.95 GeV/c (squares) with the model calculation by Laget extracted from [Bal01]: pion exchange (dotted curve), combined pion and kaon exchange (dashed), kaon exchange (solid). Data at 2.95 GeV/c are shifted on the horizontal axis for clarity. Blue diamonds: DISTO data at 2.94 GeV/c from [Bal01].
Summary

In this thesis the Λ polarisation observables, obtained from the study of the $pp \rightarrow pK^{+}\Lambda$ reaction in a polarised measurement in 2002 at COSY-TOF at 2.75 GeV/c and at 2.95 GeV/c beam momentum, are presented. Together with DISTO, COSY-TOF is the only experiment close to threshold with a polarised proton beam where the Λ reaction is fully reconstructed. In this way, not only can the polarisation observables be extracted in the whole $x_F$ range, but also the background originating from Λ’s of the sigma decay ($\Sigma^0 \rightarrow \Lambda\gamma$) can be suppressed. In contrast, inclusive experiments cannot distinguish these Λ’s from those directly produced in the target, and must consequently estimate the contamination. This is one source of uncertainties for inclusive experiments.

An accurate knowledge of the beam polarisation is necessary for the extraction of the polarisation observables. In this thesis, the beam polarisation is determined from the simultaneously measured elastic sample $\vec{p}\vec{p} \rightarrow pp$ by comparing the asymmetry in the proton distribution to the EDDA or to the SAID analysing power. The fits deliver compatible values, and the fit to SAID is taken as the result, because the SAID partial wave analysis averages over the total $\vec{p}\vec{p} \rightarrow pp$ data set and therefore should be more accurate. Systematic errors were investigated and estimated to be in the order of a few percent ($\pm 3\%$). The beam polarisation is stable in time at both beam energies. It is 40% and 62% for the 2.75 GeV/c and the 2.95 GeV/c beam momenta, respectively. As a cross-check, the polarisation was deduced for an unpolarised measurement: some runs at 3.30 GeV/c beam momentum were analysed and as expected the extracted polarisation is compatible with zero.

Each of the Λ polarisation observables was determined with different calculation methods. Their results proved to be all compatible and stable with respect to possible detector asymmetries or inefficiencies. The final results were obtained by averaging the results of the different methods and taking the largest statistical errors. These final data were compared to previous experiments and theoretical models. The polarisation observables are, within the statistical errors, generally in good agreement with the other measurements. This is also valid in comparison to the inclusive experiments which were carried out at much higher incident energies (13 GeV/c - 200 GeV/c).

A significant disagreement is found in the spin transfer coefficient. DISTO
measured large and negative $D_{NN}$. The present data, however, are compatible with zero in the whole $x_F$ range. The DISTO data were often interpreted as indicating a kaon exchange dominance. In fact, the model calculation of Laget predicts large and negative $D_{NN}$ for $x_F > 0$ in the case of kaon exchange; in the case of pion exchange, large and positive $D_{NN}$ are expected (for $x_F > 0$). The data obtained for this thesis exclude a pure kaon exchange mechanism in the $\Lambda$ production. A past analysis by COSY-TOF fitted a resonance model to the Dalitz plot and concluded that at these energies the exchange of non-strange mesons is dominant. This is in agreement with the current result.

The polarisation data presented in this work, in particular the results concerning the spin transfer coefficient $D_{NN}$, provide a basis for more refined model calculations. Such new computations would certainly help to deepen our understanding of the $\Lambda$ production mechanism.

On the basis of these results, more measurements are planned by the COSY-TOF collaboration in order to obtain a much larger sample to extract the spin transfer coefficient $D_{NN}$ with significantly improved statistical accuracy.
Appendix A

File format

A.1 TADE file

The experimental data are written in an ASCII format used by COSY-TOF called TADE. TADE stands for ‘TDC ADC Detector Element’. The file looks as follow:

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</tr>
</tbody>
</table>

Each event contains a header with the event number, the number of lines to the next event, the run number, the trigger number of the current event and a string of text. Then follows a list with TDC and ADC values, the corresponding hit detector number and element (channel). Detectors without TDC information have a −1 in the first column.

Also the Monte Carlo simulation output that reproduces the data files is written in this TADE format. There is no substantial difference between a data TADE file and a Monte Carlo TADE file.

A.2 Monte Carlo track file

In a simulation it is essential to know the original direction of the particles tracked through the detectors. Beside the TADE file, the Monte Carlo simulation stores
also all the generated particles, their type, their directions and momenta in the
track file.

Every event in the track file begins with a header where the event number, the
total number of generated tracks and a comment are written. Then every track is
listed with:

- a consecutive number (beginning from 0);
- the track identity (following GEANT’s particle ID convention);
- the \((x, y, z)\) coordinates of the start point in cm;
- the \((p_x, p_y, p_z)\) coordinates of the start momentum in GeV/c;
- the \((x, y, z)\) coordinates of the end point (last point simulated);
- the \((p_x, p_y, p_z)\) coordinates of the end momentum;
- the ‘mother’ particle (the consecutive number corresponding to the track that
decayed into the current track; primary tracks originating in the target have
-1).

Here an example of the track file for one \(\Lambda\) event is shown:

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<tr>
<td>4</td>
<td>14</td>
<td>0.577006</td>
<td>-0.876579</td>
<td>3.456665</td>
<td>0.232852</td>
<td>-0.309964</td>
<td>1.003772</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>99.950620</td>
<td>-133.101532</td>
<td>430.300903</td>
<td>0.232295</td>
<td>-0.310382</td>
<td>0.992606</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

↑ GEANT-ID number (11 = \(K^+\), 18 = \(\Lambda\), etc.)
↑ consecutive number
↑ mother particle
here: particle #3 and #4
are decay products of #1
Appendix B

Selection of the elastic sample

Elastic events $pp \rightarrow pp$ are reconstructed with the primary track routine described in Chapter 3. Protons are ordered according to the scattering angle, so that the first proton or 1 is always the proton scattering at the smallest angle ($\theta_1 \leq \theta_2$).

Elastic events must fulfill certain geometric conditions: the two protons have to be coplanar:

$$\Delta \phi = |\phi_1 - \phi_2| - 180^\circ = 0.$$  \hspace{1cm} (B.1)

The scattering angles are related to the energy by the kinematic Equation 3.1, therefore also the difference

$$\Delta \theta = \arctan \left[ \frac{2 m_p}{(2 m_p + T) \tan \theta_1} \right] - \theta_2$$  \hspace{1cm} (B.2)

must go to zero. Cuts on the differences $\Delta \phi$ and $\Delta \theta$ are used to separate the elastic events from the background.

Events where both tracks are reconstructed with the $\phi$-$\theta$ matrix are called type A. The angular range of these events is between 68 and 90° in the centre of mass angle of the first proton (it corresponds to about 26 to 35° in the laboratory system).

The angular range of the reconstructed sample is extended by taking also events where only one proton is reconstructed in the $\phi$-$\theta$ matrix (type B). For this proton a hit in the Ring detector is required, in order to have the TOF information. The second proton scatters at a large angle and hits only the Starttorten and the Barrel detector.

The angular distributions of the first proton for the two classes of events are shown in Figure B.1. At 2.75 GeV/c, a discontinuity at around 68° is observed. It is due to the restriction applied to events of class B, where the first proton must hit the Ring. This detector covers scattering angles up to 25°, which corresponds to 68° in the CM frame.

An attempt was made including in the sample also a third class of events: the first proton is reconstructed with the $\phi$-$\theta$ method and the second hits only the Starttorten. In this case, the scattering angle $\theta_2$ remains unknown and it is not
possible to apply a $\Delta \theta$ cut. To distinguish elastic events from the background, a
cut on the velocity $\beta$ of the first proton was introduced. However, the $\beta$ resolution is
not good enough to suppress the background in a satisfactory way. For this reason,
these events without the complete geometrical information have been rejected from
the sample.

Events of classes A and B have been reconstructed both from Monte Carlo files
and data. The $\Delta$ differences defined above (Equations B.1 and B.2) are plotted in
Figure B.2. The $\Delta \phi$ plots are centred at zero, as expected. The enhancements every
$3.75^\circ$ are due to the structure of the Barrel detector (96 elements in $360^\circ$). The
Monte Carlo distributions of $\Delta \theta$ are centred at zero too, while the data distributions
are centred at about $0.5^\circ$. This small deviation may be caused by a non-perfect
geometric calibration or by a difference in the beam energy from the nominal value.
The cuts in $\Delta \theta$ take into account this deviation from zero.

In Table B.1 the cuts applied to select the elastic events from the data are listed.
The $\Delta \phi$ cuts for Monte Carlo data are the same as for the real data. In $\Delta \theta$ they
have the same width but are centred at zero (e.g. Monte Carlo sharp cut for Class
A: $-2. < \Delta \theta < 2.$).

The two sets of cuts (large and sharp) were defined to perform the investigations
on systematic errors for the beam polarisation (in Section 4.4). The so-called sharp
cuts are chosen for the final elastic event selection.

<table>
<thead>
<tr>
<th></th>
<th>Large cuts</th>
<th>Sharp cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class A</td>
<td>$-2.86 &lt; \Delta \phi &lt; 2.86$</td>
<td>$2. &lt; \Delta \phi &lt; 2.$</td>
</tr>
<tr>
<td></td>
<td>$-2.5 &lt; \Delta \theta &lt; 3.5$</td>
<td>$-1.5 &lt; \Delta \theta &lt; 2.5$</td>
</tr>
<tr>
<td>Class B</td>
<td>$-5. &lt; \Delta \phi &lt; 5.$</td>
<td>$-3. &lt; \Delta \phi &lt; 3.$</td>
</tr>
<tr>
<td></td>
<td>$-2.5 &lt; \Delta \theta &lt; 3.5$</td>
<td>$-2.5 &lt; \Delta \theta &lt; 3.5$</td>
</tr>
</tbody>
</table>

Table B.1: Definition of the elastic cuts for the data.
Figure B.2: $\Delta \phi$ and $\Delta \theta$ plots at 2.95 GeV/c for real data (black solid line) and Monte Carlo data (red filled, scaled to real data). The dashed lines indicate the range of the sharp cuts on the data.
Appendix C

Monte Carlo updates

C.1 Modification of the hodoscopes’ geometry in the simulation program

In order to obtain a MC-TADE file looking exactly like an experimental TADE file, the geometry of both hodoscopes had to be completely redefined to reproduce the fibre numbering scheme exactly as in the experiment. The update is illustrated in Figure C.1 for the case of the Small Hodoscope. It must be pointed out that the previous numbering was not ‘wrong’ since the Monte Carlo files were treated differently from the data during the analysis.

Figure C.1: Modification of the Small Hodoscope fibre numbering scheme. Left: all fibres have the same length; the central fibre is a single volume (#48) and the beam hole is made in GEANT with a volume subtraction. Right: the experimental fibre numbering scheme is reproduced defining two independent volumes in the middle of the detector (fibres #48 and #49).
Appendix D

Polarisation observables

D.1 Comparison of $D_{NN}$ calculated with the measured $A_y$ values or with the approximation $A_y^\Lambda = 0$

Figures D.1 and D.2 show the spin transfer coefficient calculated with the formula of Equation 5.15 and with the approximation of Equation 5.16, where it is assumed that $A_y^\Lambda \cdot P_B$ is small. Since typically $A_y^\Lambda < 0.1$, its influence on the spin transfer coefficient is negligible.
Figure D.1: Spin transfer coefficient at 2.75 GeV/c, calculated with the up-down difference method: comparison taking $A_y^K = 0$ or $A_y^K$ from the measurement (compare Equations 5.15 and 5.16).
Figure D.2: Spin transfer coefficient at 2.95 GeV/c, calculated with the up-down difference method: comparison taking $A_y^\Lambda = 0$ or $A_y^\Lambda$ from the measurement (compare Equations 5.15 and 5.16).
D.2 Dependence on the binning

Tests have been made on the dependence of the polarisation observables on the binning in $\cos \psi$ and $\cos \theta^{**}$. In general all methods are stable and the variation of the results is very small in comparison to the error bars. Also the magnitude of the error bars remains almost unchanged.

As an example, Figure D.3 shows the calculation for the spin transfer coefficient in some different binning of $\cos \psi$ and $\cos \theta^{**}$:

\[
\begin{align*}
\text{(bins cos } \psi) \times \text{(bins cos } \theta^{**}) & = 2 \times 20 \\
& = 4 \times 12 \\
& = 6 \times 6.
\end{align*}
\]

The efficiency independence is influenced by the binning in $\cos \psi$ indirectly, since the used $A_y^\Lambda$ depends on it.

It was observed that, among all the variables and the methods, the most sensitive to the binning is the DISTO method. Anyhow the variation of the values is still consistent with the statistical error, as shown in Figure D.3, bottom. For this reason the systematical error caused by different binning is estimated to be significantly smaller than the statistical uncertainties.
Figure D.3: Spin transfer coefficient at 2.95 GeV/c, calculated with different binning in cos $\psi$ and cos $\theta^{\ast\ast}$. Top: $D_{NN}$ calculated with the efficiency independent method; bottom: $D_{NN}$ with the DISTO method.
D.3 Final results: $P_\Lambda$

Values are obtained averaging the polarisation results obtained with the methods illustrated in Chapter 5. The statistical errors of the method with the largest uncertainties are taken as uncertainties of the average.

Figure D.4: Mean values for the $\Lambda$ polarisation at 2.75 (top) and 2.95 GeV/c (bottom) versus the $\Lambda$ transverse momentum.
Figure D.5: Mean values for the Λ polarisation at 2.75 (top) and 2.95 GeV/c (bottom) versus the Feynman variable.

Figure D.6: Mean values for the Λ polarisation at 2.75 (top) and 2.95 GeV/c (bottom) versus the cosine of the Λ emission angle.
### Table D.1: Λ polarisation (mean values) versus the transverse momentum.

<table>
<thead>
<tr>
<th>$p_T$</th>
<th>at 2.75 GeV/c $P_\Lambda$</th>
<th>at 2.95 GeV/c $P_\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.045</td>
<td>$-0.028 \pm 0.101$</td>
<td>$0.028 \pm 0.093$</td>
</tr>
<tr>
<td>0.135</td>
<td>$0.025 \pm 0.053$</td>
<td>$-0.037 \pm 0.048$</td>
</tr>
<tr>
<td>0.225</td>
<td>$-0.023 \pm 0.046$</td>
<td>$-0.067 \pm 0.039$</td>
</tr>
<tr>
<td>0.315</td>
<td>$-0.045 \pm 0.061$</td>
<td>$-0.023 \pm 0.043$</td>
</tr>
<tr>
<td>0.405</td>
<td>$0.233 \pm 0.166$</td>
<td>$-0.097 \pm 0.069$</td>
</tr>
</tbody>
</table>

### Table D.2: Λ polarisation (mean values) versus the Feynman variable.

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>at 2.75 GeV/c $P_\Lambda$</th>
<th>at 2.95 GeV/c $P_\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>−0.8</td>
<td>$0.068 \pm 0.136$</td>
<td>$0.043 \pm 0.101$</td>
</tr>
<tr>
<td>−0.4</td>
<td>$-0.100 \pm 0.058$</td>
<td>$0.150 \pm 0.045$</td>
</tr>
<tr>
<td>0.</td>
<td>$0.040 \pm 0.050$</td>
<td>$-0.091 \pm 0.040$</td>
</tr>
<tr>
<td>0.4</td>
<td>$-0.028 \pm 0.051$</td>
<td>$-0.173 \pm 0.041$</td>
</tr>
<tr>
<td>0.8</td>
<td>$0.106 \pm 0.095$</td>
<td>$-0.062 \pm 0.073$</td>
</tr>
</tbody>
</table>

### Table D.3: Λ polarisation (mean values) versus the cosine of the Λ emission angle.

<table>
<thead>
<tr>
<th>$\cos \theta_{CM}^\Lambda$</th>
<th>at 2.75 GeV/c $P_\Lambda$</th>
<th>at 2.95 GeV/c $P_\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>−0.8</td>
<td>$-0.004 \pm 0.069$</td>
<td>$0.064 \pm 0.051$</td>
</tr>
<tr>
<td>−0.4</td>
<td>$-0.101 \pm 0.068$</td>
<td>$0.106 \pm 0.054$</td>
</tr>
<tr>
<td>0.</td>
<td>$-0.007 \pm 0.066$</td>
<td>$-0.095 \pm 0.055$</td>
</tr>
<tr>
<td>0.4</td>
<td>$0.074 \pm 0.062$</td>
<td>$-0.167 \pm 0.051$</td>
</tr>
<tr>
<td>0.8</td>
<td>$-0.010 \pm 0.056$</td>
<td>$-0.106 \pm 0.043$</td>
</tr>
</tbody>
</table>

### D.4 Final results: $A^\Lambda_y$

Values are obtained averaging the polarisation results obtained with the methods illustrated in Chapter 5. The statistical errors of the method with the largest uncertainties are taken as uncertainties of the average.
Figure D.7: Mean values for the $\Lambda$ analysing power at 2.75 (top) and 2.95 GeV/c (bottom) versus the $\Lambda$ transverse momentum.

Figure D.8: Mean values for the $\Lambda$ analysing power at 2.75 (top) and 2.95 GeV/c (bottom) versus the Feynman variable.
Figure D.9: Mean values for the $\Lambda$ analysing power at 2.75 (top) and 2.95 GeV/c (bottom) versus the cosine of the $\Lambda$ emission angle.

Table D.4: $\Lambda$ analysing power (mean values) versus the transverse momentum.
### D.5 Final results: $D_{NN}$

Values are obtained averaging the polarisation results obtained with the methods illustrated in Chapter 5. The statistical errors of the method with the largest uncertainties are taken as uncertainties of the average.

#### Table D.5: $\Lambda$ analysing power (mean values) versus the Feynman variable.

<table>
<thead>
<tr>
<th>$x_F$</th>
<th>at 2.75 GeV/c</th>
<th>at 2.95 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.8</td>
<td>$-0.155 \pm 0.112$</td>
<td>$-0.0008 \pm 0.128$</td>
</tr>
<tr>
<td>-0.4</td>
<td>$-0.024 \pm 0.048$</td>
<td>$-0.102 \pm 0.057$</td>
</tr>
<tr>
<td>0.0</td>
<td>$0.019 \pm 0.041$</td>
<td>$-0.085 \pm 0.051$</td>
</tr>
<tr>
<td>0.4</td>
<td>$-0.016 \pm 0.042$</td>
<td>0.071 $\pm$ 0.053</td>
</tr>
<tr>
<td>0.8</td>
<td>$-0.019 \pm 0.079$</td>
<td>$-0.039 \pm 0.093$</td>
</tr>
</tbody>
</table>

#### Table D.6: $\Lambda$ analysing power (mean values) versus the cosine of the $\Lambda$ emission angle.

<table>
<thead>
<tr>
<th>$\cos \theta_{CM}^\Lambda$</th>
<th>at 2.75 GeV/c</th>
<th>at 2.95 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.8</td>
<td>$-0.075 \pm 0.057$</td>
<td>$-0.023 \pm 0.065$</td>
</tr>
<tr>
<td>-0.4</td>
<td>$-0.003 \pm 0.056$</td>
<td>$-0.126 \pm 0.068$</td>
</tr>
<tr>
<td>0.0</td>
<td>$-0.005 \pm 0.054$</td>
<td>$-0.082 \pm 0.070$</td>
</tr>
<tr>
<td>0.4</td>
<td>$-0.010 \pm 0.051$</td>
<td>0.026 $\pm$ 0.065</td>
</tr>
<tr>
<td>0.8</td>
<td>0.011 $\pm$ 0.046</td>
<td>0.002 $\pm$ 0.055</td>
</tr>
</tbody>
</table>
Figure D.10: Mean values for the spin transfer coefficient at 2.75 (top) and 2.95 GeV/c (bottom) versus the $\Lambda$ transverse momentum.

Figure D.11: Mean values for the spin transfer coefficient at 2.75 (top) and 2.95 GeV/c (bottom) versus the Feynman variable.
D. Polarisation observables

Figure D.12: Mean values for the spin transfer coefficient at 2.75 (top) and 2.95 GeV/c (bottom) versus the cosine of the $\Lambda$ emission angle.

<table>
<thead>
<tr>
<th>$p_T$</th>
<th>at 2.75 GeV/c $D_{NN}$</th>
<th>at 2.95 GeV/c $D_{NN}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.045</td>
<td>$-0.10 \pm 0.23$</td>
<td>$-0.50 \pm 0.33$</td>
</tr>
<tr>
<td>0.135</td>
<td>$-0.12 \pm 0.12$</td>
<td>$0.13 \pm 0.17$</td>
</tr>
<tr>
<td>0.225</td>
<td>$-0.11 \pm 0.10$</td>
<td>$0.08 \pm 0.13$</td>
</tr>
<tr>
<td>0.315</td>
<td>$-0.03 \pm 0.14$</td>
<td>$0.11 \pm 0.15$</td>
</tr>
<tr>
<td>0.405</td>
<td>$0.58 \pm 0.40$</td>
<td>$0.002 \pm 0.244$</td>
</tr>
</tbody>
</table>

Table D.7: $\Lambda$ spin transfer coefficient (mean values) versus the transverse momentum.
Table D.8: \( \Lambda \) spin transfer coefficient (mean values) versus the Feynman variable.

<table>
<thead>
<tr>
<th>( x_F )</th>
<th>( D_{NN} ) at 2.75 GeV/c</th>
<th>( D_{NN} ) at 2.95 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>−0.8</td>
<td>−0.50 ± 0.33</td>
<td>−0.14 ± 0.37</td>
</tr>
<tr>
<td>−0.4</td>
<td>−0.16 ± 0.14</td>
<td>0.003 ± 0.158</td>
</tr>
<tr>
<td>0.0</td>
<td>−0.04 ± 0.11</td>
<td>0.13 ± 0.14</td>
</tr>
<tr>
<td>0.4</td>
<td>0.02 ± 0.11</td>
<td>0.04 ± 0.14</td>
</tr>
<tr>
<td>0.8</td>
<td>−0.11 ± 0.21</td>
<td>0.21 ± 0.24</td>
</tr>
</tbody>
</table>

Table D.9: \( \Lambda \) spin transfer coefficient (mean values) versus the cosine of the \( \Lambda \) emission angle.

<table>
<thead>
<tr>
<th>( \cos \theta_{CM} )</th>
<th>( D_{NN} ) at 2.75 GeV/c</th>
<th>( D_{NN} ) at 2.95 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>−0.8</td>
<td>−0.10 ± 0.16</td>
<td>−0.03 ± 0.18</td>
</tr>
<tr>
<td>−0.4</td>
<td>−0.34 ± 0.16</td>
<td>−0.10 ± 0.19</td>
</tr>
<tr>
<td>0.0</td>
<td>0.13 ± 0.15</td>
<td>0.21 ± 0.19</td>
</tr>
<tr>
<td>0.4</td>
<td>−0.11 ± 0.14</td>
<td>0.06 ± 0.18</td>
</tr>
<tr>
<td>0.8</td>
<td>−0.002 ± 0.124</td>
<td>0.16 ± 0.14</td>
</tr>
</tbody>
</table>
Acknowledgements

I would like to thank prof. Wolfgang Eyrich for giving me the opportunity to work on this project and for his support during these years.

My gratitude to all my colleagues for their help and encouragements. In particular, I would like to thank Albert Lehmann, Andreas Teufel, and my former colleague Richard Webb for reading my thesis and for many useful discussions.

An acknowledgment to prof. Franco Bradamante for suggesting the undertaking of this experience in Germany.

Finally a big ‘thank you’ to my family and to all my friends, in particular to the cavoli.
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[GEA] GEANT detector description and simulation tool, CERN Program library long writeup W5013.


[Hel78] K. Heller, P. T. Cox, J. Dworkin et al., Polarization of $\Lambda$’s and $\bar{\Lambda}$’s produced by 400 GeV protons, Phys. Rev. Lett 41, no. 9 (1978) 607-611.


[PAW] PAW Physics Analysis Workstation, CERN Program library long writeup Q121.


