1 Longitudinal $\Lambda$ and $\bar{\Lambda}$ polarization
   - Introduction
   - Extraction Method
   - Results

2 $\Lambda$ production from transversely polarized target
   - $\Lambda$ polarization and transversity
   - Extraction method
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3 Spontaneous transverse hyperon polarization
Why $\Lambda$ polarization?

Ideal probe to study spin effects in high energy reactions

Self-analyzing weak decay $\Lambda \rightarrow p \pi^-$, BR $\approx 64\%$

- Parity violation: polarization $P_S^\Lambda$ w.r.t. analyzer $\vec{S}$ reveals itself in angular distribution of decay daughters

\[
\frac{dN}{d\cos \theta} = \frac{N_0}{2} \left( 1 + \alpha_\Lambda P_S^\Lambda \cos \theta \right)
\]

with $\theta$ proton angle w.r.t. $\vec{S}$ in $\Lambda$ rest frame

$\alpha_\Lambda = 0.642 \pm 0.013$ decay asymmetry parameter

Extraction of angular distributions

- Suppression of background contaminations
- Correction of apparatus effects (acceptance)
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Fixed target experiment @ CERN SPS
- 2-stage spectrometer
- longitudinally polarized 160 GeV/c $\mu^+$-beam
- Longitudinally/transversely polarized $^6$LiD target

Setup 2003 (topview)

COMPASS is able to study all aspects of $\Lambda$ polarization.
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Boris Grube, TU München

$\Lambda$ Polarization Measurements at COMPASS
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1. **Longitudinal $\Lambda$ and $\bar{\Lambda}$ polarization**
   - Introduction
   - Extraction Method
   - Results

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3. **Spontaneous transverse hyperon polarization**
Longitudinal $\Lambda$ and $\Lambda$ polarization

$\Lambda$ production from transversely polarized target

Spontaneous transverse hyperon polarization

**Introduction**

**Extraction Method**

**Results**

Long. $\Lambda$ Polarization in Current Fragmentation Region

Accessible physics

- Study of spin transfer process $q^- \rightarrow \Lambda^+$
- $\Lambda$ spin structure
- Test of $q\bar{q}$ symmetry of strange sea in nucleon:
  - $s(x)$ vs. $\bar{s}(x)$
  - $\Delta s(x)$ vs. $\Delta \bar{s}(x)$

Boris Grube, TU München

$\Lambda$ Polarization Measurements at COMPASS
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Boris Grube, TU München
$\Lambda$ Polarization Measurements at COMPASS
Assuming $x_F > 0$ and quark fragmentation

$$P_L^\Lambda = \frac{\sum_q e_q^2 \left[ P_B \cdot D_L(y) \cdot q(x_{Bj}) + f \cdot P_N \cdot \Delta q(x_{Bj}) \right] \Delta D_{\Lambda/q}(z_h)}{\sum_q e_q^2 \left[ q(x_{Bj}) + f \cdot P_N \cdot P_B \cdot D_L(y) \cdot \Delta q(x_{Bj}) \right] \hat{D}_{\Lambda/q}(z_h)}$$

with $D_L(y) = \frac{1-(1-y)^2}{1+(1-y)^2}$ longitudinal depolarization factor

- $P_B$ beam polarization $\approx -76\%$
- $f$ target dilution factor $\approx 0.45$
- $P_N$ target polarization $\approx 50\%$

Measurement of polarized fragmentation function $\Delta D_{\Lambda/q}(z_h)$

averaging over target polarization $\implies P_N = 0$
Longitudinal Λ Polarization – Parton Model

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Model calculations

- Significant contribution from diquark fragmentation for $x_F > 0$
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- About 40% indirect $\Lambda$s from $\Sigma^0$, $\Sigma(1385)$, and $\Xi$
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Extraction Method for Angular Distributions

**Longitudinal polarization**
- **Analyzer** along virtual photon direction
- Angular distribution of proton w.r.t. $\gamma^*$ in $\Lambda$ rest frame

**Bin-by-bin Method**
- Event-by-event identification of hyperons not required
- Subdivision of sample into bins in $\cos \theta$
- For each bin invariant mass histogram
- Fit of histogram $\implies$ number of $\Lambda$s from fit parameter
  $\implies$ background corrected angular distribution

**Acceptance correction**
from MC simulations (LEPTO) of unpolarized $\Lambda(\bar{\Lambda})$ decays
Longitudinal polarization

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- **Analyzer** along virtual photon direction
- Angular distribution of proton *w.r.t. γ* in Λ rest frame

Bin-by-bin Method

- Event-by-event identification of hyperons **not required**
- Subdivision of sample into **bins in cos θ**
  - For each bin invariant mass histogram
  - Fit of histogram → number of Λs from fit parameter
  → background corrected angular distribution

Acceptance correction

from MC simulations (LEPTO) of unpolarized Λ(Λ) decays
Extraction Method for Angular Distributions

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from MC simulations (LEPTO) of unpolarized $\Lambda(\bar{\Lambda})$ decays
Background contributions

- No particle ID used in Λ selection
- Kinematically indistinguishable $K^0_S$
- Combinatorial background
- $e^+e^-$ pairs from $\gamma$ conversion

Kaon Background from MC

- Kaon distribution $K(m_{p\pi^-})$
- Data are fitted with $\text{Gauss}(x) + aK(x) + c_0 + c_1x$
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COMPASS 2003, Preliminary

Fit result
Total background
Kaons background

Boris Grube, TU München

Λ Polarization Measurements at COMPASS
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**MC improved Background Description**

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COMPASS 2003, Preliminary

Fit result
Total background
Kaons background
**Kinematics of $\Lambda$ Prod. (2003, $Q^2 > 1 \text{ GeV}^2$)**

**Total statistics 2003**

- $31,000 \Lambda$s
- $18,000 \bar{\Lambda}$s

**Mean values**

- $\langle x_{Bj} \rangle = 0.0283$
- $\langle x_F \rangle = 0.23$
- $\langle y \rangle = 0.48$
- $\langle z \rangle = 0.29$
- $\langle Q^2 \rangle = 3.55 \text{ GeV}^2$
- $\langle W \rangle = 11.7 \text{ GeV}$
Longitudinal $\Lambda$ and $\bar{\Lambda}$ polarization
$\Lambda$ production from transversely polarized target
Spontaneous transverse hyperon polarization

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Total statistics 2003
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$y$- and $x_{Bj}$-Dependence of long. Pol., $Q^2 > 1 \text{ GeV}^2$

Systematic errors $< 5\%$
**z- and $W^2$-Dependence of long. Pol., $Q^2 > 1 \text{ GeV}^2$**

**Systematic errors < 5 %**
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\( \Lambda \) production from transversely polarized target

Transversely polarized target

Measured process: \( \mu N^\uparrow \rightarrow \mu' \Lambda^\uparrow X \)

Underlying elementary QED process: \( \gamma^* q^\uparrow \) scattering

Transverse \( \Lambda \) polarization gives information about initial transverse quark polarization \( \Delta_T q(x_B) \) in nucleon

Boris Grube, TU München
Longitudinal $\Lambda$ and $\bar{\Lambda}$ polarization

$\Lambda$ production from transversely polarized target

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Quark scattering plane

Lepton scattering plane ($x,z$)

Transverse $\Lambda$ polarization gives information about initial transverse quark polarization $\Delta_T q(x_B)$ in nucleon
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Quark scattering plane

Lepton scattering plane $(x,z)$

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Λ polarization and Transversity

Assuming $x_F > 0$ and quark fragmentation

$$P_T^\Lambda = f \cdot P_N \cdot D_T(y) \frac{\sum q e_q^2 \Delta_T q(x_{Bj}) \Delta_T D_{\Lambda/q}(z_h)}{\sum q e_q^2 q(x_{Bj}) \hat{D}_{\Lambda/q}(z_h)}$$

with $D_T(y) = \frac{2(1-y)}{1+(1-y)^2}$ transverse depolarization factor

$f$ target dilution factor $\approx 0.45$

$P_N$ target polarization $\approx 50\%$

Chiral-odd partner of $\Delta_T q(x_{Bj})$: transversity fragmentation function

$$\Delta_T D_{\Lambda/q}(z_h) \equiv D_{\Lambda\uparrow/q\uparrow}(z_h) - D_{\Lambda\downarrow/q\uparrow}(z_h)$$

both $\Delta_T q(x_{Bj})$ and $\Delta_T D_{\Lambda/q}(z_h)$ unknown
Assuming $x_F > 0$ and quark fragmentation

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transverse depolarization factor

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2 target cells, each 60 cm long

0.5 T magnetic dipole field sustains transverse polarization
COMPASS Polarized Target

- 2 target cells, each 60 cm long
- 0.5 T magnetic dipole field sustains transverse polarization

COMPASS Acceptance (180 mrad)
Dilution refrigerator (T ~ 50 mK)
Superconducting solenoid (2.5 T)
SMC Acceptance (70 mrad)

3He-Precooler

6LiD target cells
Acceptance Correction – Bias Canceling

- Background subtraction using bin-by-bin method

Exploit symmetry

Assumptions
- Constant target polarization: \( P_N^{(1)} = P_N^{(2)} \)
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### Exploit symmetry
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Overall available Statistics (2002-03, $Q^2 > 1$ GeV$^2$)

All 2002+2003 transversity data

Number of $\Lambda$: ~20000

$Q^2 > 1$ (GeV/c)$^2$

$0.1 < y < 0.9$

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$x_{Bj}$-Dependence of Transv. $\Lambda$ Polarization, $Q^2 > 1 \text{ GeV}^2$

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Preliminary

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$\Lambda$ Polarization Measurements at COMPASS
Outline

1. Longitudinal \( \Lambda \) and \( \bar{\Lambda} \) polarization
   - Introduction
   - Extraction Method
   - Results

2. \( \Lambda \) production from transversely polarized target
   - \( \Lambda \) polarization and transversity
   - Extraction method
   - Results

3. Spontaneous transverse hyperon polarization
Spontaneous Transverse Hyperon Polarization

Production of polarized hyperons in **unpolarized** inclusive reactions

- Parity conservation
- Polarization **transverse to production plane**

**Naïve expectation**

- High energy $\implies$ large number of production channels: comparable magnitudes + various relative phases
- Random interference $\implies$ small polarization

**Big surprise 1976 at Fermilab**

- Discovery of sizeable transverse polarization $P_T^\Lambda = -28 \pm 8 \%$
  in $p$ Be $\implies$ $\Lambda \uparrow X @ p_{\text{Beam}} = 300$ GeV/c
- No model is able to explains all experimental data
- Only few data from photo-production
Longitudinal $\Lambda$ and $\bar{\Lambda}$ polarization
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- **Inclusive hyperon production** in reaction $\mu N \longrightarrow \mu' \Lambda \uparrow X$
- **Quasi-real** virtual photon $\gamma^*$ with $\langle Q^2 \rangle \approx 0.36 \text{ GeV}^2$
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![Diagram of hyperon production and decay](image-url)
Background Subtraction and Acceptance Correction

**Bin-by-bin method – separation of $K^0$ background**

- **Expansion** of $\Lambda$ invariant mass histogram with $K^0$ mass

- **Full two-dimensional fit** in $(m_{p\pi^-, m_{\pi^+\pi^-}})$ plane

- **Extraction of false $K^0$ background polarization** in same kinematical region as $\Lambda$

**Acceptance Correction – Bias cancelling**

- Exploits mid-plane symmetry of apparatus
- Cancels left-right asymmetry
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Results

First analysis on 2002 data, all $Q^2$

- 160,000 $\Lambda$s and 85,000 $\bar{\Lambda}$s
- Small positive $\Lambda$ polarization:
  \[ P^\Lambda_T = +2.7 \pm 0.9 \text{(stat.)} \pm 1.1 \text{(sys.)} \% \]
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Work in progress

- 2002 sample only 10 % of available statistics
- 2002-04, all $Q^2$: $1.6 \cdot 10^6$ $\Lambda$s and $0.9 \cdot 10^6$ $\bar{\Lambda}$s
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- 2003 data sample
- Similar longitudinal polarization of $\Lambda$ and $\bar{\Lambda}$
- Different production mechanism for $\Lambda$ and $\bar{\Lambda}$

Transverse polarization transfer

- 2002 + 2003 transversity data sample
- Slight tendency to negative polarizations
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- Systematic effects are smaller than statistical errors

Both analyses

Significant increase of statistics with 2004 data
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$\Lambda$ Polarization Measurements at COMPASS
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Kinematics of \( \bar{\Lambda} \) Prod. (2003, \( Q^2 > 1 \text{ GeV}^2 \))

Mean values

\[ \langle x_{Bj} \rangle = 0.0258 \]
\[ \langle x_F \rangle = 0.21 \]
\[ \langle y \rangle = 0.51 \]
\[ \langle z \rangle = 0.27 \]
\[ \langle Q^2 \rangle = 3.50 \text{ GeV}^2 \]
\[ \langle W \rangle = 12.1 \text{ GeV} \]
Angular Distributions (2002, $Q^2 > 1 \text{ GeV}^2$)

- $K^0$
- $\Lambda$
- $\bar{\Lambda}$

$\cos \Theta$

$w(\Theta)$

PRELIMINARY

Boris Grube, TU München

$\Lambda$ Polarization Measurements at COMPASS
Spin Transfer to $\Lambda$ and $\bar{\Lambda}$ (2002, $Q^2 > 1 \text{ GeV}^2$)

Spin transfer vs. $x_F$ for various experiments:
- $\Lambda$, COMPASS
- $\Lambda$, HERMES
- $\Lambda$, NOMAD
- $\Lambda$, E665

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$\Lambda$ Polarization Measurements at COMPASS
Selection cuts

- Primary vertex in target
- Secondary $V^0$ vertex outside of target
- Collinearity angle $\theta_{\text{col}} < 10 \text{ mrad}$
- $V^0$ decay daughters:
  - $p > 1 \text{ GeV}/c$ and
  - $p_T > 23 \text{ MeV}/c$
- $V^0$ momentum $p_{V^0} > 10 \text{ GeV}/c$
- DIS cut: $Q^2 > 1 \text{ GeV}^2$ and $0.2 < y < 0.9$
Kinematics of $\Lambda$ Production

- Mean virtual photon transverse depolarization factor
  $\langle D_T(y) \rangle \approx 0.8$

- Majority of $\Lambda$s produced in current fragmentation region $x_F > 0$

- Accessible $x_{Bj}$ ranges
  - All $Q^2$: $10^{-5} < x_{Bj} < 1$
  - $Q^2 > 1$ GeV$^2$: $3 \cdot 10^{-3} < x_{Bj} < 1$
$x_{Bj}$-Dependence of Transv. $\Lambda$ Polarization, All $Q^2$

All 2002+2003 transversity data

0.1 < $y$ < 0.9

Preliminary
Study of systematic Effects

- False $K^0$ polarization
- Subdivision of target cells into two halves
- Artificial change of orientation of target polarization: horizontal, random orientation

Systematic effects are smaller than statistical errors
Selection cuts

- Primary vertex in target
- Secondary $V^0$ vertex outside of target
- Collinearity angle $\theta_{\text{col}} < 10$ mrad
- $V^0$ decay daughters:
  - $p > 1$ GeV/$c$ and
  - $p_T > 23$ MeV/$c$
- $0.1 < y < 0.9$
Dependence of \( \Lambda \) Pol. on \( x_F \) and \( p_T \) (2002 Data, all \( Q^2 \))

- Preliminary for \( x_F \) and \( p_T \) distributions.

\( P_y [\%] \) vs \( x_F \) and \( p_T [\text{GeV}/c] \) scatter plots.
Dependence of $\bar{\Lambda}$ Pol. on $x_F$ and $p_T$ (2002 Data, all $Q^2$)

Preliminary results show a dependence of $\bar{\Lambda}$ polarization on $x_F$ and $p_T$. The plots illustrate the variation in polarization with changes in $x_F$ and $p_T$. The data includes events from 0 to 4000 and 0 to 1600, respectively, in the $x_F$ and $p_T$ histograms.
Overall available Statistics (2002-04, all $Q^2$)

1.6 $\cdot$ $10^6$ $\Lambda$s

0.9 $\cdot$ $10^6$ $\bar{\Lambda}$s