Feasibility studies of Λ transverse polarization in p+p interactions within NA61/SHINE at the CERN SPS

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Introduction

Motivation

None of the theoretical models\textsuperscript{[1–3]} describes well all experimental data on transverse $\Lambda$ polarization, its dependence on the transverse momentum of the hyperon and on the Feynman variable $x_F$.

Transverse polarization definition:
1. Rotate from Lab frame to production plane coordinate system:
   \[ \hat{n}_x = \frac{\vec{p}_{\text{beam}} \times \vec{p}_\Lambda}{|\vec{p}_{\text{beam}} \times \vec{p}_\Lambda|}, \quad \hat{n}_z = \frac{\vec{p}_\Lambda}{|\vec{p}_\Lambda|}, \quad \hat{n}_y = \hat{n}_z \times \hat{n}_x \]
2. Boost along $\hat{n}_z$ to $\Lambda$ rest frame.
3. Calculate cosine of angles between proton momentum $\vec{p}_p$ and axes: $\cos \theta_i = p_{p_i}/|\vec{p}_p|$, $i = x, y, z$
4. Fit distribution of the $\cos \theta_i$ to the theoretical prediction and extract $P_i$ – projection of polarization.
   \[ f(\cos \theta_i) = \frac{1 + \alpha P_i \cos \theta_i}{2}, \]
   where $\alpha = 0.732 \pm 0.014$.

According to parity conservation in the strong interaction, $P_y \equiv P_z \equiv 0$ if the incident proton beam is unpolarized. Thus the measurements of $P_y$ and $P_z$ are usually used for checking the systematic uncertainties.
Bias due to $\Lambda$ selection cuts and limited detector acceptance

- $10^8$ events of inelastic p+p simulated within EPOS\cite{4} & Geant3\cite{5} at 158 GeV/c beam momentum
- In EPOS, $P_x \equiv 0$: no $\Lambda$ polarization.
- $10^7$ $\Lambda$’s with $p\pi^-$ channel

Selection cuts\cite{6} were applied:
- $Z$ difference between $\Lambda$ vertex and primary vertex
  \[ \Delta z = z_\Lambda - z_{PV} \] based on rapidity $y$:
- Number of points in VTPC’s $>10$ for both $p$ and $\pi^-$ tracks

Distributions of $\cos \theta_i$:

\[ P_x = \left(-0.08 \pm 1.5\right) \cdot 10^{-3} \]
\[ P_y = \left(-7.1 \pm 0.2\right) \cdot 10^{-2} \]
\[ P_z = \left(-4.1 \pm 0.2\right) \cdot 10^{-2} \]
The equation of motion of the spin vector $\vec{S}$ in $\Lambda$ rest frame is

$$\frac{d\vec{S}}{d\tau} = \frac{\mu_{\Lambda}\mu_N}{\hbar} \left[ \vec{S} \times \vec{B} \right]$$

Considering $dz = \frac{p_z}{mc} cd\tau$, integrate eq. using NA61/SHINE magnetic field $\vec{B}$ [7]. Initial condition: generate random spin vectors $\vec{S}$ uniformly distributed on unit sphere. Among these vectors, choose one with maximum angle change, $\phi_{max} = \max(\angle(\vec{S}_{\text{init}}, \vec{S}_{\text{final}}))$.

To estimate magnetic field impact on $\Lambda$ polarization bias, for every $\Lambda$,

- Assign polarization vector $\vec{S}$ uniformly distributed value,
- Propagate it in magnetic field until decay,
- Project $\vec{S}$ on $\hat{n}_x$, $\hat{n}_y$, $\hat{n}_z$ and fit their distributions.
Bias due to magnetic field: Magnetic field impact on $\Lambda$ polarization estimation

Distribution of $\vec{S}_{\text{init}}$ (before precession):

Distribution of $\vec{S}_{\text{final}}$ (after precession):

Despite $\phi_{\text{max}}$ is significant, polarization bias is $\sim 10^{-4}$ due to averaging over all $\Lambda$s.
• NA61/SHINE has a large potential to study Λ transverse polarization in p–p and p–A collisions.

• Geometrical acceptance significantly biases the result and it should be taken into account via MC corrections.

• **Magnetic field impact** on Λ polarization due to precession is smaller than detector acceptance-based polarization bias.

• To limit possible precession-based bias, \( \Delta z < 1 \text{ m} \) (\( \phi_{\text{max}} < 0.05 \)) cut can be used.

**Bibliography**

(5) *CERN Program Library Long Writeup* W5013 (1993)
(7) *JINST* **9** P06005 (2014)
Backup Slides
The Λ transverse polarization measured by ATLAS compared to measurements from lower center-of-mass energy experiments. In NA61/SHINE experiment, $p_{\text{lab}} = 158 \text{ GeV}/c$ corresponds to $\sqrt{s} = 17 \text{ GeV}$ and Λ peaked at $x_F \approx 0.1$. [ATLAS Collaboration, *Phys. Rev. D* **91** 032004 (2015)].

Distribution of simulated Λ over $x_F$ defined as $x_F = (p_z)^{\text{CMS}}/(p_z)^{\text{CMS}}_{\text{max}}$. Left part - distribution of Λ with negative $x_F$, right part - with positive $x_F$.