Measurement of the $\boldsymbol{\Lambda}$ Hyperon Polarization in $\boldsymbol{\nu_\mu}$ Charged Current Interactions in the NOMAD Experiment

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The Λ hyperon polarization in ν_μ charged current interactions has been measured in the NOMAD experiment. The event sample (8087 reconstructed Λ's) is more than an order of magnitude larger than that of previous bubble chamber experiments, while the quality of the event reconstruction is comparable. We observe a negative polarization along the W-boson direction which is enhanced in the target fragmentation region: $P_x(x_F < 0) = -0.21 \pm 0.04(\text{stat}) \pm 0.02(\text{sys})$. In the current fragmentation region we find $P_x(x_F > 0) = -0.09 \pm 0.06(\text{stat}) \pm 0.03(\text{sys})$. These results provide a test of different models describing the nucleon spin composition and the spin transfer mechanisms. We also observe a significant transverse polarization (in the direction orthogonal to the Λ production plane) for the first time in a neutrino experiment: $P_y = -0.22 \pm 0.03(\text{stat}) \pm 0.01(\text{sys})$. The dependence of the absolute value of P_y on the Λ transverse momentum with respect to the hadronic jet direction is in qualitative agreement with the results from unpolarized hadron-hadron experiments. The dependence of the Λ polarization on the type of target nucleon in ν_μ scattering has been also studied.

1. Introduction

1.1. The NOMAD experiment

The main goal of the NOMAD experiment [1] is the search for $\nu_\mu \to \nu_\tau$ oscillations in the wide-band neutrino beam from the CERN SPS (the relative beam composition is predicted to be $\nu_\mu : \bar{\nu}_\mu : \nu_e : \bar{\nu}_e = 1.00 : 0.0612 : 0.0094 : 0.0024$ with average energies of 23.5, 19.2, 37.1 and 31.3 GeV, respectively). This search [2] uses kinematic criteria to identify ν_τ charged current (CC) interactions and requires a very good quality of event reconstruction similar to that of bubble chamber experiments. This has indeed been achieved by the NOMAD detector, and, moreover, the large data sample collected during four years of data taking (1995-1998) allows a detailed study of neutrino interactions. Real data are compared to the results of a Monte Carlo (MC) simulation based on LEPTO 6.1 and JETSET 7.4 generators for neutrino interactions and on a GEANT based program for the detector response.

An analysis of the full NOMAD data sample (corresponding to 1.3×10^6 ν_μ CC events) devoted to the study of the Λ hyperon polarization in neutrino deep inelastic scattering (DIS) is presented in this article. The large statistics of the data combined with the good

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quality of event reconstruction in the NOMAD detector allows a detailed study of the Λ polarization as a function of different kinematic variables to be performed.

1.2. Theoretical considerations

Some important questions which arose in connection to the proton spin puzzle are still challenging theoretical and experimental investigations, namely: are strange quarks polarized inside the nucleon? what is the spin content of other baryons?

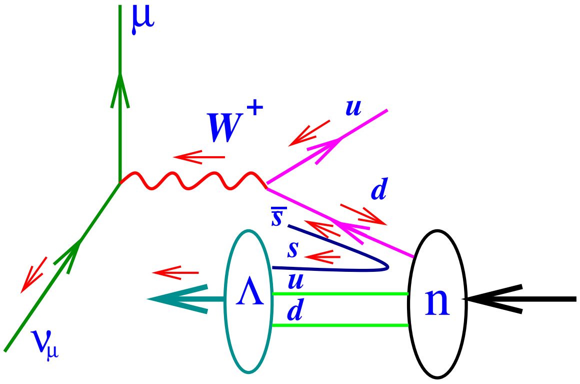

Figure 1. Dominant diagram for Λ production in the target fragmentation region due to scattering on a valence d quark in a neutron.

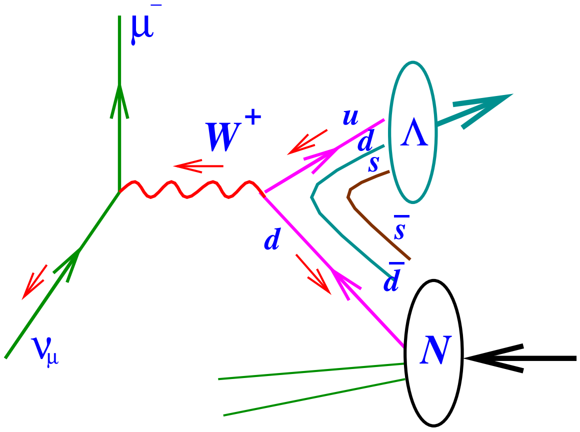

Figure 2. Dominant diagram for Λ production in the current fragmentation region due to scattering on a valence d quark.

A study of polarized lepton-nucleon DIS with a Λ hyperon in the final state can help answering those questions. Λ hyperons are unique among other baryons due to their relatively large production rate and because of their parity violating weak decay $\Lambda \to p\pi^-$. Different physical mechanisms are responsible for the Λ polarization in different $x_F = 2p_L^*/W$ regions.

In the target fragmentation region ($x_F < 0$) the origin of the Λ polarization could be either polarized strange quarks from the target nucleon [3] (see Fig. 1), or the polarization transfer from the polarized di-quark which is left behind after the lepton nucleon DIS [4,5], or both.

Among sources of polarized beams, neutrinos and antineutrinos can play an exceptional role. The (anti)neutrino in deep inelastic scattering from a nucleon interacts with a *polarized quark of specific flavour* in the nucleon (see Fig. 2), and this particular property makes (anti)neutrino DIS processes an ideal experimental tool to study flavour dependent quark fragmentation functions, testing different spin transfer mechanisms.

In the current fragmentation region ($x_F > 0$) the polarized struck quark transfers its polarization to the Λ hyperon, giving access to the spin transfer coefficient C_u^Λ [6–8].

2. Identification of neutral strange particles

Having made a selection of ν_μ CC interactions, the first step of the Λ polarization analysis consists in building a robust and efficient neutral strange particle identification procedure.

Λ hyperons are identified via their decays $\Lambda \to p\pi^-$ which appear in the NOMAD detector (see Fig. 3) as two charged tracks of opposite charge emerging from a common vertex separated from the primary neutrino interaction vertex (V^0-like signature, see Fig. 4).

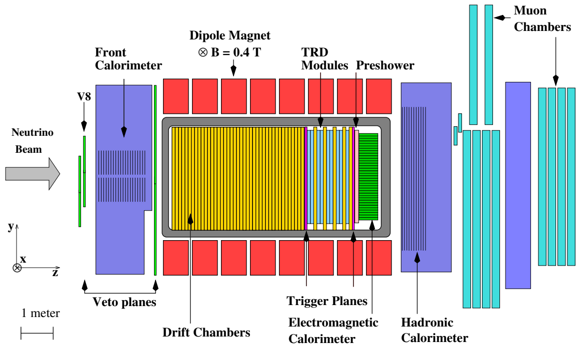

Figure 3. A side view of the NOMAD detector.

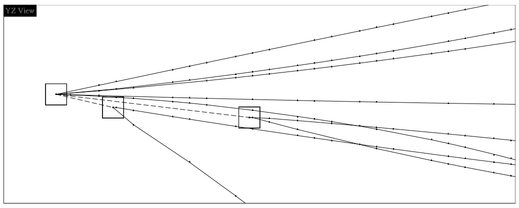

Figure 4. A reconstructed data event containing 2 V^0 vertices identified as Λ and $\bar{\Lambda}$ decays by the identification procedure. To define the scale on this plot: the size of the vertex boxes is 3×3 cm^2.

To minimize the statistical errors and to get rid of any background-related systematic bias, our identification procedure should optimize both the selection efficiency and the purity of the final Λ sample. Special efforts are needed to suppress as much as possible γ-related background (photon conversions) and contamination from other neutral strange particle decays. This is achieved by a selection based on a constrained kinematic fit. Results of the selection are summarized in Table 1.

Table 1
Purity and efficiency of the identification procedure for each selected V^0 sample. Numbers of identified neutral strange particles in the real data are also shown.

V^0	P (%)	ε (%)	Data
K^0_s	97.2 ± 0.1	22.1 ± 0.1	15 074
Λ	95.9 ± 0.1	16.4 ± 0.1	8 087
$\bar{\Lambda}$	89.7 ± 0.7	18.6 ± 0.5	649

3. Polarization analysis

The Λ polarization is measured using the asymmetry in the angular distribution of the protons in the parity violating decay process $\Lambda \to p\pi^-$. In the Λ rest frame the decay protons are distributed as:

$$\frac{1}{N}\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha\,\mathbf{P}\cdot\mathbf{k}), \qquad (1)$$

where $\mathbf{P}$ is the Λ polarization vector, $\alpha = 0.642 \pm 0.013$ is the decay asymmetry parameter [9] and $\mathbf{k}$ is the unit vector along the decay proton direction.

In our MC simulation Λ hyperons are not polarized.

3.1. Reference system

To measure the Λ polarization one has to choose a reference system which is correlated with the expected polarization. For the polarization analysis described below we use the "J" reference system, where axes are defined as follows (in the Λ rest frame):

- the $\mathbf{n}_x$ axis is chosen along the reconstructed W-boson direction ($\vec{e}_W$);
- the $\mathbf{n}_y$ axis is orthogonal to the Λ production plane (defined as the plane containing both the target nucleon and the W-boson vectors):
  $\mathbf{n}_y = \vec{e}_W \times \vec{e}_T / |\vec{e}_W \times \vec{e}_T|$.
- the $\mathbf{n}_z$ axis is chosen to form a right-handed coordinate system: $\mathbf{n}_z = \mathbf{n}_x \times \mathbf{n}_y$.

It is important to demonstrate the ability of our detector to reconstruct correctly the direction of the outgoing decay proton in the "J" reference system defined above. Fig. 5 shows obvious correlations between the reconstructed and simulated angular variables $\cos\theta_i = \mathbf{n}_i \cdot \mathbf{k}$.

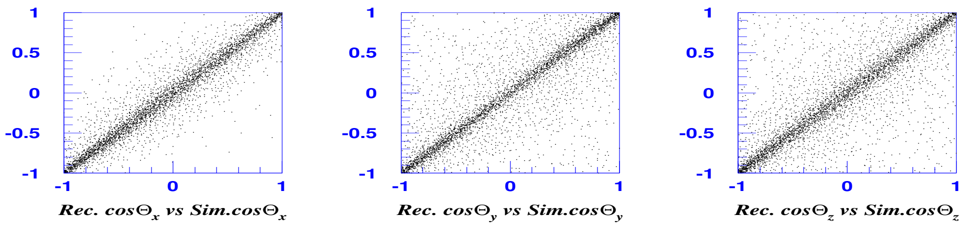

Figure 5. Correlations between the simulated and reconstructed $\cos\theta_i$ for identified Λ's in ν_μ CC MC events.

3.2. Polarization measurement

The method most frequently used to extract the Λ polarization (taking into account the detector acceptance) consists of histogramming the one-dimensional *reconstructed* $\cos\theta_i$ distributions both for simulated events and for data and by doing a least squares fit to their bin-by-bin ratio using a linear function (as illustrated in Fig. 6). Smearing effects in the angular distributions due to reconstruction errors have to be taken into account, though the corresponding corrections are expected to be rather small.

Another method which takes into account differences between simulated and reconstructed angular variables has been developed. The essence of this method is the following: we introduce a "polarization" as a free parameter for *simulated* events, i.e. we associate an appropriate polarization weight to each Λ hyperon. Then we try to fit the "polarized" MC angular distribution distorted by the detector acceptance to the angular distribution observed in the data. In what follows we will present the results obtained using this method.

3.3. Control sample

A useful control sample is provided by K^0_s mesons which, being spinless, should not exhibit "polarization" along any direction. We have analyzed the K^0_s sample by fitting

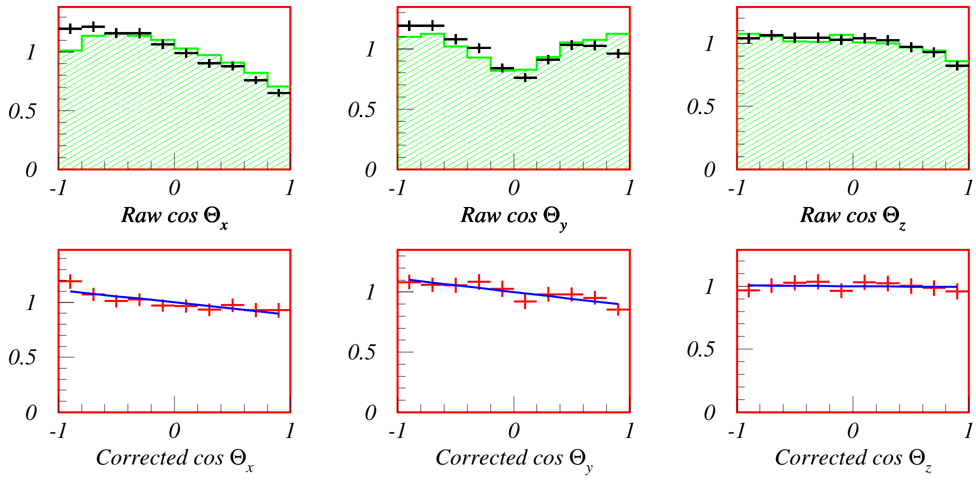

Figure 6. Top: normalized raw distributions of $\cos\theta_i$ for Λ's in reconstructed Monte Carlo events (histogram) and in the data (points with error bars). Bottom: angular distributions in the data after correction for detector acceptance; the polarization is given by the slope of the corresponding linear fit.

the angular distributions of the decay π^+ in exactly the same manner as for the Λ's (while setting the decay asymmetry parameter to $\alpha = 1$).

At each step of our analysis we have checked that the "polarization" of the K^0_s sample is consistent with zero.

4. Systematic errors

In the analysis of the Λ hyperon polarization particular attention should be paid to a correct determination of the systematic errors.

Several potential sources of systematic uncertainties have been studied in the current analysis and the summary is given in Table 2 for the full data sample. The estimate of the total systematic error is obtained by adding all the contributions in quadrature.

The systematic errors have been calculated in the same way for all the kinematic selections used in this study. The value of the systematic error can reach 0.05 in some kinematic regions.

Table 2
Summary of systematic errors on the three components of the Λ polarization vector.

P_i	ν energy reconstruction	V^0 induced background	variation of cuts	spin precession	total
P_x	$3.4 \cdot 10^{-3}$	$3.5 \cdot 10^{-3}$	$1.7 \cdot 10^{-2}$	$1.4 \cdot 10^{-3}$	$1.8 \cdot 10^{-2}$
P_y	$8.5 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$	$7.2 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
P_z	$1.2 \cdot 10^{-2}$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	$8.6 \cdot 10^{-4}$	$1.9 \cdot 10^{-2}$

5. Results

The Λ polarization measurement for the full NOMAD data set is given in Table 3. We observe a *negative* polarization along the W-boson direction (P_x) and in the direction orthogonal to the Λ production plane (P_y). This is the first time that a neutrino experiment observes a non-zero transverse polarization P_y.

The large statistics of our experimental data set allows the dependence of the polarization on several kinematic variables to be studied.

Table 3
The Λ polarization measurement for the full NOMAD data set. Dependence of the Λ polarization on x_F in ν_μ CC events (statistical errors only).

			Λ Polarization		
Selection	Entries	$< x_F >$	P_x	P_y	P_z
full sample	8087	-0.18	-0.15 ± 0.03	-0.22 ± 0.03	-0.04 ± 0.03
$x_F < 0$	5608	-0.36	-0.21 ± 0.04	-0.26 ± 0.04	-0.08 ± 0.04
$x_F > 0$	2479	0.21	-0.09 ± 0.06	-0.10 ± 0.06	0.02 ± 0.06

5.1. Dependence of the polarization on x_F

As discussed in Section 1.2 different physical mechanisms are responsible for the Λ polarization in the target and in the current fragmentation regions. Imposing cuts on x_F, we obtain the results presented in Table 3. The absolute value of the longitudinal polarization P_x is larger in the target fragmentation region ($x_F < 0$) than in the current fragmentation region ($x_F > 0$).

The result obtained for the longitudinal polarization in the current fragmentation region provides a measurement of the spin transfer coefficient $C_u^\Lambda = -P_x(x_F > 0) = 0.09 \pm 0.06(\text{stat}) \pm 0.03(\text{sys})$ at $< z >= 0.44$.

5.2. Dependence of the polarization on p_T

We wish to emphasize another important feature of the results presented here: the presence of the negative transverse Λ polarization.

A strong dependence of the transverse polarization on the transverse momentum of Λ with respect to the incoming beam direction has been firmly established in hadron-hadron experiments [10].

We have performed a similar study of the transverse polarization, obtaining the results presented in Table 4. The absolute value of the measured transverse polarization increases with increasing p_T of the Λ with respect to the hadronic jet axis. This is the first observation of such an effect with small statistical errors in neutrino experiments and it is in qualitative agreement with hadron-hadron measurements.

The transverse polarization observed in ν DIS formally has an opposite direction compared to hadron-hadron experiments. However, the results obtained in hadron-hadron experiments correspond to the region of $x_F > 0$, while the NOMAD data correspond mainly to the region $x_F < 0$. Thus taking into account the opposite directions of motion

Table 4
Dependence of the Λ polarization on p_T in ν_μ CC events (statistical errors only).

Selection (p_T^2 in (GeV/c)^2)	Entries	$< p_T >$ GeV/c	Λ Polarization P_x	P_y	P_z
$p_T^2 < 0.06$	1629	0.16	-0.25 ± 0.08	-0.02 ± 0.08	-0.06 ± 0.08
$0.06 < p_T^2 < 0.15$	1712	0.32	-0.35 ± 0.07	-0.19 ± 0.07	-0.02 ± 0.07
$0.15 < p_T^2 < 0.28$	1669	0.46	0.01 ± 0.07	-0.30 ± 0.07	-0.00 ± 0.07
$0.28 < p_T^2 < 0.55$	1746	0.62	-0.01 ± 0.07	-0.31 ± 0.06	-0.06 ± 0.07
$0.55 < p_T^2$	1332	0.95	-0.25 ± 0.08	-0.25 ± 0.08	-0.11 ± 0.08

of Λ's in the W boson-nucleon and in the hadron-hadron centre-of-mass systems, the *physical* vectors of the transverse polarization point in the same direction for both the NOMAD and hadron-hadron experiments.

5.3. Dependence of the polarization on the type of target nucleon

A possible way to investigate the origin of the Λ polarization is to study its dependence on the type of target nucleon. In NOMAD it is possible to separate neutrino interactions on neutrons and protons by using the sum of charges (Q_{tot}) of all the outgoing tracks at the primary neutrino interaction vertex.

We select νp events by requiring $Q_{tot} \geq 1$. The corresponding sample of proton-like events contains about 76% of true νp interactions. The νn events are selected by the requirement $Q_{tot} \leq 0$. The purity of the corresponding neutron-like sample is about 85%.

Table 5
The dependence of the Λ polarization on the type of target nucleon.

Target	Entries	Λ Polarization P_x	P_y	P_z
"proton"	3472	-0.26 ± 0.05	-0.09 ± 0.05	-0.07 ± 0.05
$x_F < 0$	2407	-0.29 ± 0.06	-0.10 ± 0.06	-0.09 ± 0.06
$x_F > 0$	1065	-0.23 ± 0.09	-0.06 ± 0.09	-0.02 ± 0.10
"neutron"	4615	-0.09 ± 0.04	-0.30 ± 0.04	-0.03 ± 0.05
$x_F < 0$	3201	-0.16 ± 0.05	-0.37 ± 0.05	-0.07 ± 0.05
$x_F > 0$	1414	0.01 ± 0.08	-0.11 ± 0.08	0.04 ± 0.09

The results of the Λ polarization measurements in the proton-like and neutron-like samples are summarized in Table 5. One can conclude that there is a strong dependence of the Λ polarization on the type of target nucleon: while negative longitudinal polarization is observed in both cases, the absolute value of the longitudinal polarization is smaller for neutron-like than for proton-like events. Such a dependence could be attributed to the difference between the Λ production mechanisms in νp and νn DIS.

Indeed, according to the LUND model predictions[2] for the conditions of the NOMAD experiment, the fraction of prompt Λ's produced in νn DIS is about 55%, while the fraction of prompt Λ's produced in νp DIS is about 29% with major additional contributions coming from $\Sigma^{\star +}$ resonance (about 36%) and Σ^0 decay (about 16%).

6. Conclusion

The full sample of ν_μ CC data of the NOMAD experiment has been analyzed. A kinematic fit has been used for the identification of neutral strange particles. The method used to extract the three components of the Λ polarization vector accounts for the smearing of the angular variables.

Results of the analysis are given in the "J" reference system, which is found to be the only system in which the P_z component of the polarization is always consistent with zero suggesting that the choice of the reference system has been properly made. We observe *negative* polarization along the W-boson direction (P_x) and in the direction orthogonal to the production plane (P_y). It is the *first* time that a neutrino experiment observes a significant non-zero transverse polarization P_y. The dependence of the polarization on x_F and p_T as well as on the type of the target nucleon has been studied in detail.

The theoretical interpretation of the results reported in this article should take into account the effects due to secondary Λ's originating from the decays $\Sigma^\star \to \Lambda\pi$, $\Sigma^0 \to \Lambda\gamma$ and $\Xi \to \Lambda\pi$ where the polarization of the secondary Λ's is inherited from the polarization of the parent particles and is different from the polarization of the directly produced Λ's.

A detailed paper on the Λ polarization measurement in ν_μ charged current interactions in the NOMAD experiment has been recently published [11].

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[2]with default JETSET parameters used in our MC simulation.