Hyperon's Production and Polarization in Neutrino Nucleon Interactions

OUTLINE

1. Spin Problem of the Proton … for Pedestrians
   - How to attack the problem?
   - Why strange hyperons?
   - Strange Particles Production
2. Other Spin Phenomena

1. NOMAD: experimental Observations and Analysis Procedure
2. Theoretical Description and Open Questions
3. Conclusions

Alushta, Crimea, September 2003

Dmitry Naumov, LNP JINR
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Introduction

Data analysis

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Spin Problem of the Proton
... for Pedestrians

Spin being a relativistic object is qualitatively presented as a rotation of point-like particle...

Can we understand hadron’s magnetic moments which are bound states of u,d,s,... quarks?

Yes!
1. Let us build QM wave functions of hadrons in terms of quarks
2. Given magnetic moment of each quark provides us an estimation of magnetic moment of a hadron
3. Compare to the data

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Building $SU(6)=SU(3)_F \times SU(2)_S$ non relativistic wave functions of octet baryons:

\[ p, n, \Sigma^+, \Sigma^0, \Sigma^-, \Lambda^0, \Xi^0, \Xi^- \]

\[
\begin{align*}
p^+ & = \frac{1}{\sqrt{18}} \left( 2u^+d^+u^+d^+ - u^+u^+d^+d^+ - w^+w^+d^+ + \right. \\
n^+ & = \frac{1}{\sqrt{18}} \left( 2d^+d^+u^+ - d^+d^+u^+ - d^+d^+u^+ + \right. \\
\Sigma^{++} & = \frac{1}{\sqrt{18}} \left( 2u^+u^+s^+ - u^+u^+s^+ - u^+u^+s^+ + \right. \\
\Sigma^{++} & = \frac{6}{1} \left( 2(u^+d^+ + d^+u^+)s^+ - s^+(u^+d^+ + d^+u^+) - d^+s^+u^+ - u^+s^+d^+ + \right. \\
\Sigma^{-} & = \frac{1}{\sqrt{18}} \left( 2d^+d^+s^+ - d^+d^+s^+ - d^+d^+s^+ + \right. \\
\Sigma^{-} & = \frac{1}{\sqrt{12}} \left( u^+d^+s^+ - u^+d^+s^+ - d^+u^+s^+ + d^+u^+s^+ + \right. \\
\Lambda^{0} & = \frac{1}{\sqrt{18}} \left( 2s^+s^+u^+ - s^+s^+u^+ - s^+s^+u^+ + \right. \\
\Xi^{0} & = \frac{1}{\sqrt{18}} \left( 2s^+s^+d^+ - s^+s^+d^+ - s^+s^+d^+ + \right. \\
\Xi^{-} & = \frac{1}{\sqrt{18}} \left( 2s^+s^+s^+ - s^+s^+s^+ - s^+s^+s^+ + \right. \\
\end{align*}
\]
QM operator of the hadron's magnetic moment reads:

\[ \mu_B = \sum_q \mu_q \sigma_q, \]

Magnetic moment of a baryon (B) can be computed as:

\[ \mu(B) = \langle B | \mu_B | B \rangle \]

\[ \mu_q = \frac{e_q}{2m_q} \]

- \( e_q \) is quark charge
- \( m_q \) is quark mass
- \( \sigma_q \) is quark spin operator

Taking \( m_u = m_d = 336 \) MeV, \( m_s = 510 \) MeV we can reasonably well describe the data:

<table>
<thead>
<tr>
<th>Magnetic moment</th>
<th>formula</th>
<th>value</th>
<th>experiment</th>
<th>Exp/SU(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu(p) )</td>
<td>( \frac{1}{2} \mu_u - \frac{1}{2} \mu_d )</td>
<td>(input)</td>
<td>2.793</td>
<td>1</td>
</tr>
<tr>
<td>( \mu(n) )</td>
<td>( \frac{1}{2} \mu_d - \frac{1}{2} \mu_u )</td>
<td>-1.86</td>
<td>-1.913</td>
<td>1.028</td>
</tr>
<tr>
<td>( \mu(\Lambda^0) )</td>
<td>( \mu_s )</td>
<td>(input)</td>
<td>-0.613 ± 0.004</td>
<td>1</td>
</tr>
<tr>
<td>( \mu(\Sigma^+) )</td>
<td>( \frac{1}{3} \mu_u - \frac{1}{3} \mu_d - \frac{1}{3} \mu_s )</td>
<td>-1.04</td>
<td>-1.16 ± 0.025</td>
<td>0.91 ± 0.004</td>
</tr>
<tr>
<td>( \mu(\Sigma^-) )</td>
<td>( \frac{1}{3} \mu_d - \frac{1}{3} \mu_u - \frac{1}{3} \mu_s )</td>
<td>-1.44</td>
<td>-1.25 ± 0.014</td>
<td>1.12 ± 0.02</td>
</tr>
<tr>
<td>( \mu(\Xi^0) )</td>
<td>( \frac{1}{3} \mu_s - \frac{1}{3} \mu_u - \frac{1}{3} \mu_d )</td>
<td>-0.51</td>
<td>-0.679 ± 0.031</td>
<td>0.87 ± 0.01</td>
</tr>
<tr>
<td>( \mu(\Xi^-) )</td>
<td>( \frac{1}{3} \mu_s - \frac{1}{3} \mu_u - \frac{1}{3} \mu_d )</td>
<td>-1.84</td>
<td>-1.94 ± 0.22</td>
<td>1.33 ± 0.06</td>
</tr>
<tr>
<td>( \mu(\Omega^-) )</td>
<td>( \frac{1}{3} \mu_s )</td>
<td>(input)</td>
<td>-1.94 ± 0.22</td>
<td>1.05 ± 0.12</td>
</tr>
</tbody>
</table>
Thus we can conclude that a non relativistic SU(6) model is adequate to describe the baryons magnetic moments through magnetic moments (proportional to the spin) of constituents quarks.

It is natural to ask: “what is the quark’s contribution to the Proton Spin?”
1. Evidence for point-like partons in the proton came from late 60s from SLAC e-p scattering.

2. R. Feynman formulated quark-parton model (QPM) of proton.

3. Gell-Mann created Quantum Color Dynamics (QCD) theory describing interactions between partons.

How proton is made?

...quarks, kinematics and all that

Kinematic variables:

\[ \nu = \frac{P-q}{M} = E - E' \]

\[ Q^2 = -q^2 = 2(EE' - kk') - m_t^2 - m_q^2 \approx 4EE' \sin^2(\theta/2) \]

\[ x = \frac{Q^2}{2Mv} \]  
\[ y = \frac{\nu}{E} \]

\[ W^2 = (P+q)^2 = M^2 + 2M\nu - Q^2 = M^2 + Q^2 \left( \frac{1}{x} - 1 \right) \]

\[ s = (k+P)^2 = 2ME + M^2 = \frac{Q^2}{xy} + M^2 \]  

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Deep inelastic cross-section is expressed via:

**Proton structure function**
- \( F_1, F_2 \) unpolarized
- \( g_1, g_2 \) polarized

**Quark (gluon) distributions in QPM**
- \( q(x), G(x) \) unpolarized
- \( \Delta q(x), \Delta G(x) \), polarized

Longitudinally polarized leptons off longitudinally polarized nucleon are to probe spin structure of the nucleon:

\[
\frac{d^2\sigma^{\uparrow \downarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow \uparrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{Q^2 EM_\nu} \left[ (E + E'\cos\theta) g_1(x, Q^2) - 2xM g_2(x, Q^2) \right]
\]

Experimentally measured:

\[
\Gamma_{1e}^{ep} = \int_0^1 dx g_i^{ep} = \frac{1}{12} (\Delta u - \Delta d) + \frac{1}{36} (\Delta u + \Delta d - 2\Delta s) + \frac{1}{9} (\Delta u + \Delta d + \Delta s)
\]

... known from hyperon \( \beta \) decays

QCD corrections

...proton spin carried by quarks

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Model independent Bjorken Sum Rule reads

\[
\int_0^1 dx \ g_1^{ep}(x, Q^2) - g_1^{em}(x, Q^2) = \frac{1}{6} \frac{g_A}{g_V} \left\{ 1 - \frac{\alpha_s(Q^2)}{\pi} - \frac{43}{12} \frac{\alpha_s^2(Q^2)}{\pi^2} \right. \\
+ \left. \frac{M^2}{Q^2} \int_0^1 x^2 dx \left\{ \frac{2}{9} g_1^{ep-em}(x, Q^2) + \frac{1}{6} g_2^{ep-em}(x, Q^2) \right\} \right. \\
- \frac{1}{Q^2} \frac{4}{27} F^{u-d}(Q^2)
\]

Corrections:

- QCD
- Final target mass
- Higher twist effects

<table>
<thead>
<tr>
<th>Theory</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.181 ± 0.003</td>
<td>0.174 ± 0.005</td>
</tr>
</tbody>
</table>

4% difference and well agrees within errors

Bjorken Sum Rule is OK!

Ellis-Jaffe Sum Rule (assuming Δs=0 and exact SU(3)) is violated...

<table>
<thead>
<tr>
<th>Theory</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>\Gamma_p(\bar{Q}^2 = 5 \Gamma_3 B^2) = 0.163 ± 0.004</td>
<td>0.118 ± 0.004 ± 0.007</td>
</tr>
<tr>
<td>\Gamma_n(\bar{Q}^2 = 5 \Gamma_3 B^2) = -0.019 ± 0.004</td>
<td>-0.058 ± 0.005 ± 0.008</td>
</tr>
</tbody>
</table>

Naïve SU(6) gives:

\[ \Delta u^p = 4/3, \quad \Delta d^p = -1/3, \quad \Delta s^p = 0 \]

Ellis-Jaffe expected:

\[ \Delta u + \Delta d + \Delta s = 0.579 \]

...if \( \Delta G = 0 \)

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A. Efremov, O. Teryaev.  
G. Altarelli, G. Ross.  
R. Carlitz, J. Collins, A. Mueller

showed that a possible gluon polarization gives:

\[ \Delta q \rightarrow \Delta q - \frac{\alpha_s}{2\pi} \Delta G \]

Proton Spin Sum Rule:

\[ \frac{1}{2} = \frac{1}{2}(\Delta u + \Delta d + \Delta s) + \text{orbital momentum of partons} + \Delta G \]

\[ \Delta G = 2 \text{ is enough to explain the data with } \Delta s = 0 \text{ and } \Delta u + \Delta d + \Delta s = 0.27 \ldots \]

Important questions:

1. Are gluons polarized?
2. Are strange (and sea) quarks polarized?
3. Is there a spin problem for hyperons?

Today COMPASS and HERMES attack \( \Delta G \) problem

“Prompt” measurement in (anti) neutrino (quasi)elastic scattering, strange hyperons polarization

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$\Delta s$ can be measured directly in (anti)neutrino (quasi) elastic scattering...

(see talk by W. Alberico)

This is challenging experimentally!

$\Lambda$ Polarization in DIS is sensitive indirect tool to probe $\Delta s$

J. Ellis, et al. suggested a qualitative model for negative strangeness in the proton

Strong force in $0^-$ channel ($\pi, \eta$)

Expected spin anti-correlation

Negative proton strangeness should give a negative Lambda polarization in target fragmentation region

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Why $\Lambda$?
$\Lambda \rightarrow p\pi^-$ weak decay provides information on $\Lambda$ polarization vector

R.L. Jaffe suggested to measure $\Lambda$ polarization in the quark (current) fragmentation region.
...if spin problem for proton then on the same foot spin problem for $\Lambda$ and other hyperons.

Naïve SU(6) predicts:
$\Delta u = \Delta d = 0$
$\Delta s = 1$

Spin Problem for $\Lambda$ predicts:
$\Delta u = \Delta d \approx -0.2$

$\Lambda$ polarization is being measured in:

1. e$^+e^-$ at $Z^0$ pole (LEP)
2. Lepton nucleon DIS (E665, HERMES, COMPASS)
3. (anti) neutrino nucleon DIS (old bubble chambers, NOMAD)

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Parity conservation forbids to produce longitudinally polarized Lambda hyperons if beam or target are unpolarized. However Lambda hyperons can be transversally polarized (orthogonal to the production plane).

Transverse polarization in HERMES

- No transverse polarization found in old bubble chambers experiments
- No transverse polarization found in $e^+e^-$ at $Z^0$ pole

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Why Neutrinos?

Neutrinos

1. are naturally polarized particles
2. interact with left handed quarks and right handed anti-quarks
3. interact with quarks and anti-quarks of specific flavor

Thus...
Neutrino beams are clean and power tools for the Spin Physics
A (short) history of neutrino detectors

Reactor anti-Neutrino detection by Reines and Cowan (1953)
Neutrinos come to CERN

A (short) history of neutrino detectors

Le DéTECTEUR NOMAD

CDHS
CHARM
CHARMII
BEBC
CHORUS
NOMAD

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Drift chambers used as a target (2.7 tons) and for momentum measurement (3.5% resolution)

- Magnetic field: 0.4 T
- TRD and Preshower for electron identification
- ECAL and HCAL for energy measurement
- Muon chambers: detect and identify muon
NOMAD had wide neutrino beam mainly made of muon neutrinos

The CERN SPS neutrino beam composition (as predicted by the beam simulation program)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>23.5</td>
<td>1</td>
<td>43.8</td>
<td>1</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>19.2</td>
<td>0.0612</td>
<td>42.8</td>
<td>0.0255</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>37.1</td>
<td>0.0094</td>
<td>58.3</td>
<td>0.0148</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>31.3</td>
<td>0.0024</td>
<td>54.5</td>
<td>0.0016</td>
</tr>
</tbody>
</table>

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1. Reconstruction and selection of $\nu_\mu$ CC events
2. Preliminary selection of $V^0$
3. Kinematic fit with energy and momenta constraints

<table>
<thead>
<tr>
<th>$V^0$ type</th>
<th>$T_{DATA}^{V^0}$</th>
<th>$T_{MC}^{V^0}$</th>
<th>$T_{MC}^{V^0}/T_{DATA}^{V^0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_S^0$</td>
<td>$6.76 \pm 0.06$</td>
<td>$9.50 \pm 0.02$</td>
<td>$1.40 \pm 0.01$</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>$5.04 \pm 0.06$</td>
<td>$8.10 \pm 0.02$</td>
<td>$1.61 \pm 0.02$</td>
</tr>
<tr>
<td>$\bar{\Lambda}$</td>
<td>$0.37 \pm 0.02$</td>
<td>$0.60 \pm 0.01$</td>
<td>$1.62 \pm 0.03$</td>
</tr>
</tbody>
</table>

$V^0$ yields (in %)
Yields in data are 40-60% below than default JETSET

$M_{K_S^0}$: mean = 497.9, sigma = 9.7 (MeV)
$M_{\Lambda}$: mean = 1115.8, sigma = 3.8 (MeV)
$M_{\bar{\Lambda}}$: mean = 1116.0, sigma = 3.1 (MeV)
$V^0$ integral yields in NOMAD compared to previous measurements

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$&lt;E_\nu&gt;$ (GeV)</th>
<th>$N_{ko}$</th>
<th>$K^0$ rate (%)</th>
<th>$N_\Lambda$</th>
<th>$\Lambda$ rate (%)</th>
<th>$N_\bar{\Lambda}$</th>
<th>$\bar{\Lambda}$ rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>this analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu - Ne$</td>
<td>46</td>
<td>15075</td>
<td>13.52 ± 0.12</td>
<td>8087</td>
<td>5.04 ± 0.06</td>
<td>649</td>
<td>0.37 ± 0.02</td>
</tr>
<tr>
<td>$\nu - p$</td>
<td>51</td>
<td>2279</td>
<td>16.8 ± 1.2</td>
<td>1843</td>
<td>6.5 ± 0.5</td>
<td>93</td>
<td>0.46 ± 0.08</td>
</tr>
<tr>
<td>$\nu - Ne$</td>
<td>150</td>
<td>831</td>
<td>19.0 ± 0.9</td>
<td>491</td>
<td>5.2 ± 0.3</td>
<td>27</td>
<td>0.34 ± 0.07</td>
</tr>
<tr>
<td>$\nu - p$</td>
<td>43</td>
<td>502</td>
<td>19.0 ± 0.9</td>
<td>285</td>
<td>12.7 ± 1.4</td>
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<tr>
<td>$\nu - n$</td>
<td>103</td>
<td>203</td>
<td>40.6 ± 4.8</td>
<td>285</td>
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<td>27</td>
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<tr>
<td>$\nu - p$</td>
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<td>$\nu - p$</td>
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<td>23</td>
<td>17.5 ± 0.9</td>
<td>285</td>
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<td>27</td>
<td>1.5 ± 0.5</td>
</tr>
<tr>
<td>$\nu - p$</td>
<td>30</td>
<td>23</td>
<td>17.5 ± 0.9</td>
<td>285</td>
<td>12.7 ± 1.4</td>
<td>27</td>
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</tr>
</tbody>
</table>

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V⁰ differential yields in NOMAD

$\times_F = 2p_L^*/W$

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Strange resonances in NOMAD

Resonance/V° in data and default JETSET:
Factor 1.5–2 difference

<table>
<thead>
<tr>
<th></th>
<th>$K^{*+}$</th>
<th>$K^{*-}$</th>
<th>$\Sigma^{*+}$</th>
<th>$\Sigma^{*-}$</th>
<th>$\Sigma^0$</th>
<th>$\Xi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA</td>
<td>15.5 ± 0.9</td>
<td>8.7 ± 0.7</td>
<td>5.8 ± 1.1</td>
<td>2.6 ± 0.8</td>
<td>7.3 ± 2.4</td>
<td>1.9 ± 1.7</td>
</tr>
<tr>
<td>JETSET</td>
<td>31.4</td>
<td>13.1</td>
<td>16.6</td>
<td>3.9</td>
<td>12.7</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Resume:
Before doing a polarization Analysis → tune JETSET

... by Artyom Chukanov (see his PhD)

After JETSET tuning MC is well describing strange particles in NOMAD → ready for polarization study!
Polarization Analysis

- 2 MC based methods for polarization extraction:
  - correct real data angular distributions for detector acceptance and fit with a straight line: $A_i(1 + \alpha P_i \cos \theta_i)$
  - advanced 3D fit taking into account smearing of the angular variables and the detector acceptance
- MC independent method for transverse polarization
  - Use right-left symmetry of the detector

All methods give similar results!
General Results

Λ polarization

\[ P_x = -0.07 \pm 0.12 \text{ (stat)} \pm 0.09 \text{ (syst)} \]
\[ P_y = 0.09 \pm 0.13 \text{ (stat)} \pm 0.10 \text{ (syst)} \]
\[ P_z = 0.10 \pm 0.13 \text{ (stat)} \pm 0.07 \text{ (syst)} \]

Λ polarization vector is consistent with zero

NOMAD results with respect to previous bubble chamber measurements

- WA21 (\( \nu_e - p \))
- WA21 (\( \nu_x - p \))
- WA59 (\( \nu_x - Ne \))
- E632 (\( \nu_x - Ne \))
- NOMAD (\( \nu_x - C \))

- Observed negative longitudinal polarization
- For the first time in neutrino experiments observed transverse polarization
- \( P_z \) is consistent with zero
Lambda Polarization Vector in Target and "Current" Fragmentation Regions

Target fragmentation region: $x_F < 0$

- $N_{Au} = 5608$
- $<x_F> = -0.36$
- $P_{z} = -0.21 \pm 0.04$
- $P_{y} = -0.26 \pm 0.04$
- $P_{x} = -0.08 \pm 0.04$

Current fragmentation region: $x_F > 0$

- $N_{Au} = 2479$
- $<x_F> = 0.21$
- $P_{z} = -0.09 \pm 0.06$
- $P_{y} = -0.10 \pm 0.06$
- $P_{x} = 0.02 \pm 0.06$
Strong dependence on $W^2$

Controversial theoretical descriptions at $x_F > 0$ ...

**Longitudinal polarization: $x_F > 0$**

- B.Ma, I.Schmidt, J.Soffer and J.Yang, hep-ph/0001259 (right)
Longitudinal Lambda Polarization – Theoretical Description

J. Ellis et al. model

Negatively polarized \( \Lambda \)

Current direction

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\[
P^{lN}_\Lambda(B) = \frac{\sum_M P_s(B(J, M)) | \langle B(J, M) | \text{di-quark remnant + s quark} \rangle |^2}{\sum_M | \langle B(J, M) | \text{di-quark remnant + s quark} \rangle |^2}.
\]

- \( P_s(B(J, M)) \) is the polarization of the strange quark in the baryon \( B \) with the spin state \( | B(J, M) \rangle \).
- \( | \text{di-quark remnant + s quark} \rangle \) is the product of the wave function of the remnant di-quark and the wave function of polarized \( s \) quark.

The remnant di-quark wave functions are:

\[
|p \otimes d^\uparrow\rangle = \frac{1}{\sqrt{36}}[-\sqrt{2}(wu)_{1,0} + 2(wu)_{1,-1}],
\]

\[
|n \otimes d^\uparrow\rangle = \frac{1}{\sqrt{36}}[3(ud)_{0,0} + (ud)_{1,0} - \sqrt{2}(ud)_{1,-1}],
\]

The wave function of polarized \( s \) quark is:

\[
|s\rangle_{\text{pol}} = \frac{1}{\sqrt{2}} \left( \sqrt{(1 + C_{sq})} s^\uparrow + \sqrt{(1 - C_{sq})} s^\downarrow \right)
\]

Finally, the \( \Lambda^0 \) polarization in \( lN \) DIS is:

\[
P^{lN}_\Lambda = \sum_B \xi_B P^{lN}_\Lambda(B), \text{ where } \xi_B \text{ is the fraction of } \Lambda^0 \text{ produced via } B.
\]
Tagging scheme for a hyperon
Which contains:

<table>
<thead>
<tr>
<th>Struck quark</th>
<th>Remnant diquark</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_q = 1$</td>
<td>$R_{qq} = 1$</td>
</tr>
<tr>
<td>$R_q \geq 1$ &amp; $R_{qq} \neq 1$</td>
<td>$R_{qq} = 1$ &amp; $R_q \neq 1$</td>
</tr>
</tbody>
</table>

Figure 1: Left: $\nu_\mu$ CC, $E_\nu = 43.8$ GeV, Right: $\mu^+$, $E_\mu = 160$ GeV. $x_F$ distribution of all $\Lambda^0$ hyperons (solid line), of those originated from the diquark fragmentation and of those originated from the quark fragmentation for two models A and B (see the legend on the plots).

Our observations:
$\Lambda^0$ hyperons produced in the quark fragmentation have mostly $x_F > 0$ distribution as expected BUT their fraction is small compared to other origins!

A possible explanation: the beam energy is too small... let us increase it and see ⇒
Conclusion:

Current energies of all experiments in game today are too low to access quark fragmentation to hyperons...

The diquark fragmentation is dominant...
Fixing free parameters of the model

We vary two correlation coefficients ($C'_{sq_{aut}}$ and $C'_{sq_{ase}}$) in order to fit our models A and B to the NOMAD $\Lambda$ polarization data. Scattering of the exchange $W$ boson on the sea quark can be enhanced within a sample of $\Lambda^0$ hyperons with low $x_{Bj}$ or high $W^2$. A strong target nucleon effect was found by the NOMAD as well. Therefore we fit to the following 4 NOMAD points to find our free parameters:

- $np$: $P^\Lambda_{g}\approx -0.26 \pm 0.05(stat)$,
- $nn$: $P^\Lambda_{g}\approx -0.09 \pm 0.04(stat)$,
- $W^2 < 15$ GeV$^2$: $P^\Lambda_{g}(W^2 < 15) = -0.34 \pm 0.06(stat)$,
- $W^2 > 15$ GeV$^2$: $P^\Lambda_{g}(W^2 > 15) = -0.06 \pm 0.04(stat)$.

As a result of these fits we find:

**model A:** $C'_{sq_{aut}} = -0.35 \pm 0.03$ and $C'_{sq_{ase}} = -0.95 \pm 0.03$.

**model B:** $C'_{sq_{aut}} = -0.25 \pm 0.03$ and $C'_{sq_{ase}} = 0.15 \pm 0.03$.

The coefficients found are considerably different for models A and B that is related to different descriptions of the strange hadrons origin in these models. Fortunately both fragmentation models give similar predictions for the $\Lambda^0$ hyperons polarization produced in various lepton nucleon experiments.
Compare to NOMAD data:

- ✔ Absolute value OK
- ✔ Functional Dependencies OK
- ✗ Proton/neutron targets No

<table>
<thead>
<tr>
<th>$P_A$ (%)</th>
<th>Target nucleon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>isoscalar</td>
</tr>
<tr>
<td>model A</td>
<td>-17.4</td>
</tr>
<tr>
<td>model B</td>
<td>-19.3</td>
</tr>
<tr>
<td>NOMAD</td>
<td>-15.0±3</td>
</tr>
</tbody>
</table>

Alushta, Crimea, September 2003

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Compare to HERMES (ep @27.5 GeV)

Compare to E665 (μp @470 GeV)

Small statistics yet…

…Waiting new data by COMPAS, HERMES, NOMAD

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Transverse Polarization

unpolarized hadron-hadron experiments:
(plot NA 48)

NOMAD $\nu_{\mu}N \rightarrow \mu^{-}\Lambda X$:
($x_F < 0$)

- where $p_T$ is the transverse momentum of the $\Lambda$ with respect to the beam direction
- similar dependence on $p_T$
- absolute value grows linearly with $p_T$

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Transverse Polarization

$W^2$ dependence ($x_F < 0$):

$E_\nu$ dependence ($x_F < 0$):

- no statistically significant effect found in both $x_F < 0$ and $x_F > 0$
- transverse polarization likely originates in the fragmentation process

We can check for $P_y$ vs $E_\nu$ dependence in one experiment due to a wide energy spectrum!

- no statistically significant effect found in both $x_F < 0$ and $x_F > 0$

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A qualitative picture for polarization vs $P_T$
Before my conclusions...

Starting from a hypothetical particle by Pauli, passing through an almost undetectable particle by Bethe and Pierls nowadays neutrinos provide a precise and powerful tool for Particle physics.

NOMAD worked on:
1. Neutrino oscillation exclusion region
2. Strange particles production and polarization
3. Charm particles production, $m_c$ measurement
4. Diffractive physics
5. Others...

NOMAD is still working on:
1. $\sin \Theta_W$ measurement
2. Quasi Elastic cross section and $M_A$ measurement
3. $K^*$ spin alignment
4. Strange Particles and Spin Physics in Neutral Currents ($Z^0$ boson exchange)

Laboratory of Nuclear Problems JINR is heavily participating in most of these analyses

Alushta, Crimea, September 2003

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Conclusions

1. Measurement of hyperon's and meson's yields is a milestone for Monte Carlo generators tuning...

2. Spin Problem of the Proton is still not resolved finally while much more better understood today.
   1. COMPAS (CERN) and HERMES (DESY) attack this problem
   2. NOMAD data favors that $s$ quarks in the nucleon sea are negatively polarized... shadowing the valence quark spin of the nucleon

3. The transverse polarization of strange hyperons is clearly observed in NOMAD (for the first time in neutrino experiments).
   1. the polarization originates in the string fragmentation
   2. There is no good theory of this polarization

4. Many other exciting and top level things can be done within neutrino detector like the NOMAD and some of them are under investigation