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Λ-polarization in e^+e^--annihilation at the Z^0-pole

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Abstract:

Strange quarks produced in e^+e^--annihilation at the Z^0-pole are very strongly polarized. To study to which extent this polarization is transferred to the observable hadrons would give interesting information on the hadronization mechanism. Λ-particles produced with relatively large x-values are expected to frequently contain an originally produced s-quark. We estimate that Λ-particles with $x > 0.3$ should have a longitudinal polarization of about 30%.

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Strange quarks produced in e^+e^--annihilation at the Z^0-pole are very strongly polarized. This is a result of interference between the vector and axial vector couplings in the standard model for electroweak interaction. To study to which extent this polarization is transferred to the observable hadrons would give interesting information on the hadronization mechanism.

In hadronic reactions strange particles often show polarization effects transversely to the scattering plane [1]. The polarization is most easily observed experimentally in Λ-particles, which are easy to identify and have a particularly large decay asymmetry. In the non-relativistic quark model a Λ-particle consists of a strange quark together with a ud quark pair with spin and isospin zero. Thus in this model the spin of the Λ equals the spin of the s-quark. Various models attempting to explain the polarization of Λ-particles are also generally based on the assumption that the spin of the Λ is determined by the spin of the s-quark [2].

Fast Λ-particles in e^+e^--annihilation are expected to often contain a initial s-quark, produced at the electroweak vertex, together with an ud spin 0 diquark system produced in the hadronization process. Consequently these Λ's are expected to reveal the longitudinal polarization of the initial s-quark. In this note we attempt to estimate how much this polarization effect is diluted because many Λ contain s-quarks which are produced in the hadronization process or are the decay products of heavier resonances.

Before discussing the hadronization process we first want to study the polarization of the initial s-quark. At the Z^0-pole we can neglect the contribution from an intermediate photon. In the standard electroweak theory the longitudinal polarization of the strange quarks (or charge $-\frac{1}{3}$ quarks in general) is given by the following expression, valid for unpolarized electron and positron beams (see eg. ref [3])

$$P = \frac{a(1+\cos^2\theta) + b\cos\theta}{c(1+\cos^2\theta) + d\cos\theta}. \qquad (1)$$

$$\begin{aligned}
a &= -2(v_e^2 + a_e^2)v_d a_d & \qquad v_e &= -1 + 4\sin^2\theta_W \\
b &= -4v_e a_e(v_d^2 + a_d^2) & a_e &= -1 \\
c &= (v_e^2 + a_e^2)(v_d^2 + a_d^2) & v_d &= -1 + \frac{4}{3}\sin^2\theta_W \\
d &= 8v_e a_e v_d a_d & a_d &= -1
\end{aligned}$$

Here θ is the CMS angle between the electron and the s-quark and v_e, a_e, v_d, a_d are the vector and axial vector couplings of the electron and a down-type quark.

Because $\sin^2\theta_W$ is close to $\frac{1}{4}$ the polarization is only slowly varying with the angle θ. For $\sin^2\theta_W = \frac{1}{4}$ we would have obtained $b = d = 0$ and

$$P = \frac{a}{c} = -2\frac{a_d v_d}{a_d^2 + v_d^2} = -\frac{12}{13} \approx -0.92 \qquad (\sin^2\theta_W = \frac{1}{4}) \qquad (2)$$

For the real value $\sin^2\theta_W = 0.22$–0.23 the polarization is slowly varying as shown in Fig 1. The angular variation of the unpolarized cross section is determined by the expression

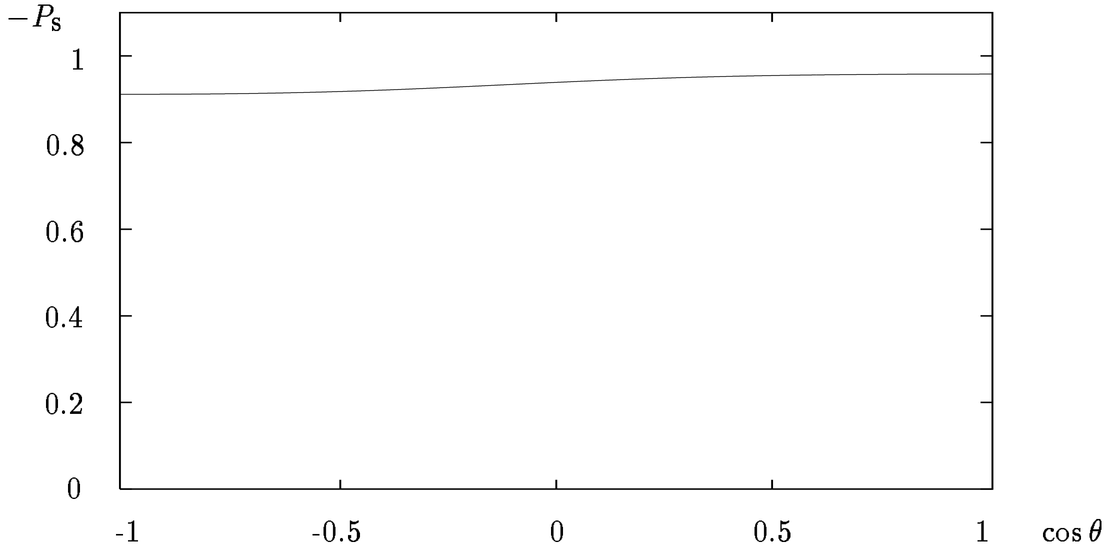

Figure 1: Polarization of the s-quark as a function of $\cos\theta$

$\sigma^0 = c(1+\cos^2\theta) + d\cos\theta$ in the denominator of Eq (1). Thus the polarization weighted by the cross section, $< P >$, is also given by the same ratio $\frac{a}{c}$:

$$< P >= \frac{\int P\sigma^0 \mathrm{d}(\cos\theta)}{\int \sigma^0 \mathrm{d}(\cos\theta)} = \frac{a}{c} \approx -0.94 \qquad (\sin^2\theta_{\mathrm{W}} \approx 0.225) \tag{3}$$

Our conclusions are that the polarization of the s-quarks is varying very little with the angle θ, and the average polarization is approximately 94%. Of course the $\bar{\mathrm{s}}$-quarks have the same degree of polarization, however with *opposite* helicity.

We now want to study how the polarization of the s-quarks is reflected in the polarization of Λ-particles. We will use the Lund string fragmentation model [4], implemented in the JETSET MC program [5], to estimate the contributions to Λ-production from different sources. The model parameters are adjusted to fit the experimental data on strange baryon production from OPAL [6].

We distinguish between directly produced Λ's and Λ's which are decay products of heavier resonances, and we also distinguish between Λ's which contain an initial strange quark and those which contain an s-quark produced in the hadronization process. To estimate the polarization in these different categories we use the following assumptions:

i) As mentioned above strange baryons produced in high energy reactions show strong polarization effects transversely to the scattering plane. There are however very little polarization in the longitudinal direction. For this reason we assume that quarks produced in the hadronization process are only very weakly polarized longitudinally.

ii) If the Λ contains an initially produced u- or d-quark, this quark is part of a spin 0 ud quark pair. Therefore we assume that the initial polarization of this u- or d-quark is lost in the formation of the Λ.

iii) Because the ud pair in a Λ has spin 0, the Λ spin is determined by the s-quark spin. Thus a directly produced Λ, which contains an initial s-quark, ought to be polarized in the same way as the strange quark.

iv) Some Λ's contain an initial s-quark but are decay products of heavier resonances. These Λ-particles are assumed to inherit part of their parent's polarization. We assume again that the polarization of the parent is determined by the initial s-quark, while those quarks of the parent, which are produced in the hadronization process, are not longitudinally polarized.

From these assumptions follows that the polarization of the Λ should be negligible if it does not contain an initially produced s-quark. If it, however, does contain an initial s-quark the polarization depends on the type of parent in the following way:

Directly produced Λ: For these Λ's we have

$$P_\Lambda = P_{\rm S} \tag{4}$$

where P_Λ and $P_{\rm S}$ are the polarization of the Λ-particles and the s-quarks respectively.

$\Sigma^0 \to \Lambda\gamma$: The ud quark pair in Σ^0 has isospin and spin 1. Thus in the non-relativistic quark model we have $P_{\Sigma^0} = -\frac{1}{3}P_{\rm S}$. In the electromagnetic decay $\Sigma^0 \to \Lambda\gamma$, the spin-isospin 1 ud-diquark is changed to a spin-isospin 0 ud-diquark. In the simple quark model the s-quark is not affected by this process, which implies that

$$P_\Lambda \approx -\frac{1}{3}P_{\Sigma^0} = +\frac{1}{9}P_{\rm S}. \tag{5}$$

$\Sigma(1385) \to \Lambda\pi$: $\Sigma(1385)$ has spin $\frac{3}{2}$, and if the non strange diquark is randomly polarized we will get $P_{\Sigma(1385)} = \frac{5}{9}P_{\rm S}$. In the P-wave decay to $\Lambda\pi$ the Λ will get the same polarization as the parent $\Sigma(1385)$. Thus we find

$$P_\Lambda = P_{\Sigma(1385)} = \frac{5}{9}P_{\rm S}. \tag{6}$$

$\Xi \to \Lambda\pi$: The quark model wave function of the Ξ implies that $P_\Xi = \frac{2}{3}P_{\rm S}$. The parity non-conserving decay into a $\Lambda\pi$ system is dominantly an S-wave decay. Averaged over decay angles the Λ polarization is given by $P_\Lambda = (\frac{1}{3} + \frac{2}{3}\gamma)P_\Xi$, where $\gamma \approx 0.87$ [7]. Consequently

$$P_\Lambda \approx 0.9P_\Xi = 0.6P_{\rm S}. \tag{7}$$

$\Xi(1530) \to \Xi\pi \to \Lambda\pi\pi$: In the same way as for $\Sigma(1385)$ we find $P_\Xi = P_{\Xi(1530)} = \frac{5}{9}P_{\rm S}$. From $P_\Lambda \approx 0.9P_\Xi$ then follows

$$P_\Lambda \approx 0.9\frac{5}{9}P_{\rm S} = 0.5P_{\rm S}. \tag{8}$$

The contributions from other possible decays, $\Sigma(1385) \to \Sigma^0\pi \to \Lambda\gamma\pi$, $\Omega^- \to \Lambda K^-$, and $\Omega^- \to \Xi\pi \to \Lambda\pi\pi$ give very small contributions which can be neglected.

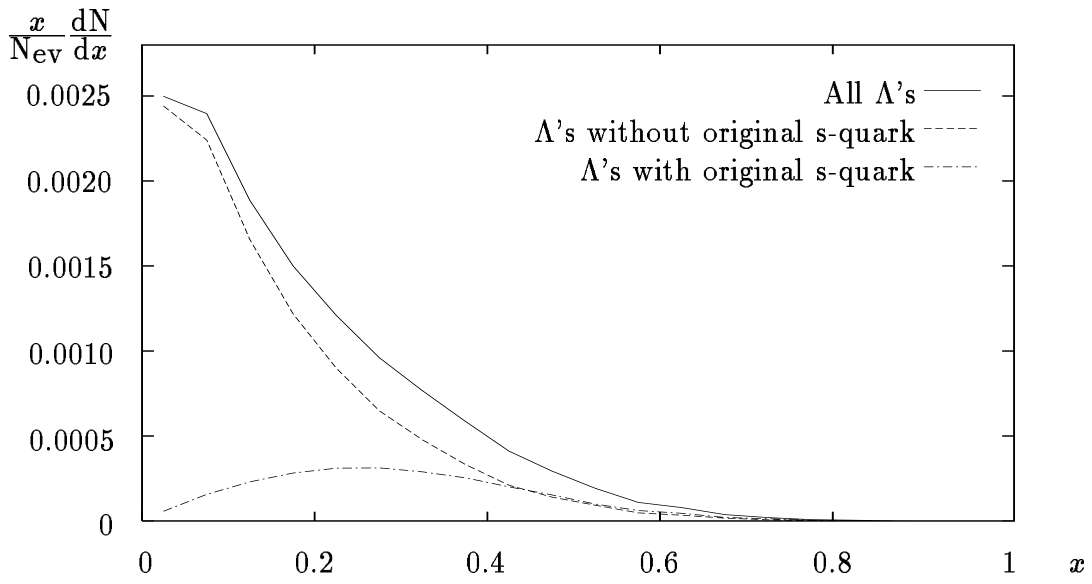

Figure 2: The contributions to the production of Λ's

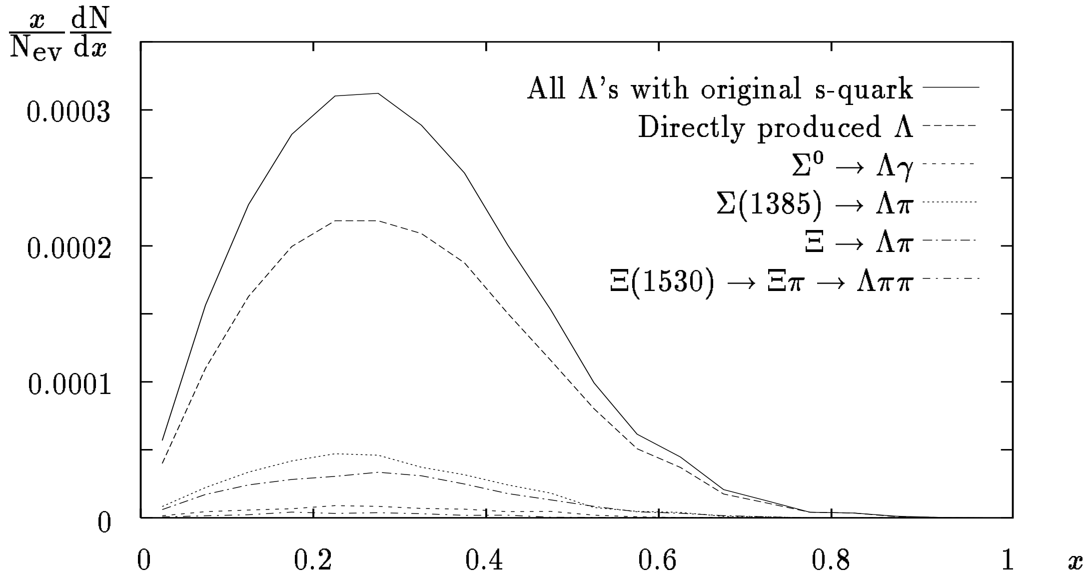

Figure 3: The contributions to the production of Λ's containing an initial s-quark

The contributions to the Λ-production from the different sources are shown in Fig 2 and Fig 3. In Fig 2 we show the contributions to the production from Λ's with and without the original s-quark, together with the total yield of Λ's. Fig 3 shows how the Λ's, which do contain an initial s-quark, can be separated into contributions from directly produced Λ's and decay products from different baryon resonances. We see that the probability that the Λ contains an initial s-quark is relatively large for $x > 0.3$, but, as expected, rapidly decreasing for smaller x-values. (We note that the largest resonance contribution comes from Σ(1385). For this reason we have used the hadronization parameter set, determined by the OPAL Coll., which fits the Σ(1385) production [6].)

The polarization expected is shown in Fig 4. The dashed curve is the fraction of the Λ's, which is directly produced with an initial s-quark, multiplied with the factor 0.94, corresponding to the s-quark polarization. The solid line is the result after adding the

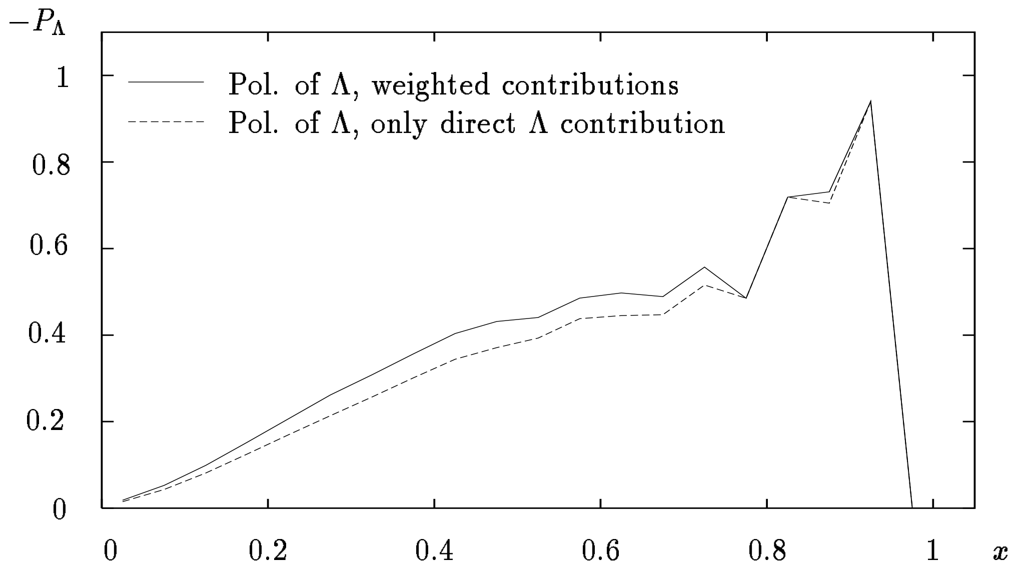

Figure 4: Expected longitudinal polarization of Λ as a function of x

contribution from resonance decays in accordance with Eqs (5–8). We see that this only gives a small correction. A minor dilution of the polarization of the direct Λ's may be expected from the hadronization process. We also note that with default values for the hadronization parameters, the polarization would be decreased by about 0.07 units. This is due to to a smaller fraction of directly produced Λ's and a larger production of strange baryon resonances.

Our conclusion is that the estimated longitudinal Λ-polarization is about 25-30% for $x > 0.3$. (Note that for larger x-values, where the polarization is larger, the rate is also rapidly decreasing.) In $\frac{1}{4}$ million events we expect (with 100% detection efficiency) about 3000 Λ or $\bar{\Lambda}$ in this x-range, which should be sufficient for a determination of the polarization with a statistical uncertainty of about 0.05. This estimate is based on the non-relativistic quark model, and to see whether it agrees or disagrees with experimental results will give interesting information on the hadronization process. We also note that, given enough statistics, it would be interesting to study how the polarization varies off the Z^0-pole due to Z^0-γ interference.

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