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Λ and $\overline{\Lambda}$ polarization in lepton induced processes

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Abstract. The study of the longitudinal polarization of Λ and $\overline{\Lambda}$ hyperons produced in polarized deep inelastic scattering, neutrino scattering, and in Z^0 decays allows one to access the spin dynamics of the quark fragmentation process. Different phenomenological spin transfer mechanisms are considered and predictions for the Λ and $\overline{\Lambda}$ longitudinal polarization in various processes using unpolarized and polarized targets are made. Current and future semi-inclusive deep inelastic scattering experiments will soon provide accurate enough data to study these phenomena and distinguish between various models for the spin transfer mechanisms.

1 Introduction

Sensitive tests of strong interaction dynamic models are provided by polarization measurements. The largest amount of discussions have been stimulated by the polarized deep inelastic lepton nucleon scattering (DIS) measurements [1]. These results suggest that the angular momentum of the nucleon is not distributed among its parton constituents in the way expected in naïve quark models. New information on the non-perturbative dynamics of strong interactions can be obtained by investigating semi-inclusive deep inelastic processes which, in addition to the nucleon parton distribution functions, depend also on fragmentation functions.

To investigate the spin transfer phenomenon in quark fragmentation one needs a *source* of polarized quarks. The simplest processes involving polarized quark fragmentation are the e^+e^- annihilation, the DIS of polarized charged leptons off unpolarized and polarized targets, and neutrino (anti-neutrino) DIS. The self-analyzing decay properties of the $\Lambda/\overline{\Lambda}$ hyperon make this particle particularly interesting for spin physics. A first theoretical study of the Λ polarization in hard processes

$$l + N \to l' + \Lambda/\overline{\Lambda} + X \tag{1}$$

and

$$e^+ + e^- \to \Lambda/\overline{\Lambda} + X \tag{2}$$

to investigate the longitudinal spin transfer from polarized quarks (di-quarks) to $\Lambda/\overline{\Lambda}$'s was made by Bigi [2]. The idea of using $\Lambda/\overline{\Lambda}$'s as a quark transverse-spin polarimeter in reaction (1) was originally proposed by Baldracchini et al. [3], and later rediscovered by Artru and Mekhfi [4]. The $\Lambda/\overline{\Lambda}$ polarization in reactions (1) and (2) has been discussed in several recent works [5]–[15], which show a considerable interest for this problem. Some $\Lambda/\overline{\Lambda}$ polarization data already exist for the reaction (1) from neutrino (anti-neutrino) beam experiments [16] and for the reaction (2) at the Z^0 pole [17]. New high statistics data are expected soon from several experiments [18–21].

The longitudinal polarization transfer mechanism from a polarized lepton to the final hadron in reaction (1) is based on the idea [2], that the exchanged polarized virtual boson will strike preferentially one quark polarization state inside the target nucleon, and that the fragment left behind will contain some memory of the angular momentum removed from the target nucleon, thus resulting in a non-trivial longitudinal polarization of Λ hyperons produced in the target fragmentation region ($x_F < 0$, x_F is the Feynman x) [7]. The fragmenting struck quark in turn can transfer its polarization to a $\Lambda/\overline{\Lambda}$ hyperon produced in the current fragmentation region ($x_F > 0$). In both cases the underlying dynamics of the hyperon production and polarization cannot be described by perturbative QCD and some phenomenological models have to be considered.

A phenomenological study of the Λ and $\overline{\Lambda}$ longitudinal polarization in the reaction $\mu^+ + N \to \mu^{+\prime} + \Lambda/\overline{\Lambda} + X$ has been already presented by us in the *COMPASS* proposal [21]. Here we present a more detailed and complete study of the $\Lambda/\overline{\Lambda}$ polarization in DIS of charged leptons and neutrinos in the current fragmentation region and in e^+e^- annihilation at the Z^0 pole. The measurement of the $\Lambda/\overline{\Lambda}$ polarization in these processes can help us to distinguish between different mechanisms of the spin transfer in the quark fragmentation. In Sect. 2 we describe some models for the spin transfer mechanism that we consider in our studies. In Sects. 3 and 4 we present predictions for the $\Lambda/\overline{\Lambda}$ polarization in electro-production with polarized leptons on unpolarized and polarized targets, in Sect. 5

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for neutrino and anti-neutrino scattering, and in Sect. 6 at the Z^0 pole. Section 7 contains a discussions of the results presented in this work.

2 Models for spin transfer in quark fragmentation

The quark fragmentation functions as well as the parton distribution functions of the nucleon are well defined objects in quantum field theory. The spin, twist, and chirality structure of the quark fragmentation functions, integrated over the transverse momentum, are discussed and classified in [22]. The leading twist unpolarized ($D_q^\Lambda(z)$) and polarized ($\Delta D_q^\Lambda(z)$) quark fragmentation functions to a Λ hyperon are defined as:

$$D_q^\Lambda(z) = D_q^{+\,\Lambda}(z) + D_q^{-\,\Lambda}(z) \tag{3}$$

$$\Delta D_q^\Lambda(z) = D_q^{+\,\Lambda}(z) - D_q^{-\,\Lambda}(z) \tag{4}$$

where $D_q^{+\,\Lambda}(z)$ ($D_q^{-\,\Lambda}(z)$) is the spin dependent quark fragmentation functions for the Λ spin parallel (anti-parallel) to that of the initial quark q, and z is the quark energy fraction carried by the Λ hyperon.

We will parametrize the polarized quark fragmentation functions as

$$\Delta D_q^\Lambda(z) = C_q^\Lambda(z) \cdot D_q^\Lambda(z) \tag{5}$$

where $C_q^\Lambda(z)$ are the spin transfer coefficients. Since much is still unknown on polarized fragmentation functions, we do not consider explicitly their Q^2 evolution in this work (see for instance [12]). In the literature there exists some models [13,14] for the spin dependent fragmentation functions in which a z dependence of the spin transfer coefficients can be found. For example, in the jet fragmentation model of [13], $C_q^\Lambda(z) \sim z$ at small z and $C_q^\Lambda(z) \to 1$ at $z \to 1$. In the covariant quark – di-quark model of [14] $C_u^\Lambda(z) \sim z$ at small z, whereas $C_s^\Lambda(z) \sim const$. We will not present here predictions for the $\Lambda/\overline{\Lambda}$ polarization obtained with these models, since they contain many free parameters which are not well tuned with existing data.

To get quantitative predictions for the $\Lambda/\overline{\Lambda}$ polarization in processes (1) and (2) we used a phenomenological approach similar to that of [5]. We consider two different descriptions of the spin transfer mechanism in the quark fragmentation to a $\Lambda/\overline{\Lambda}$ hyperon. The first one is based on the non-relativistic quark model SU(6) wave functions, where the Λ spin is carried only by its constituent s quark. Therefore, the polarization of directly produced Λ's is determined by that of the s quark only, while Λ's coming from decays of heavier hyperons inherit a fraction of the parent's polarization, which might originate also from other quark flavors (namely u and d). In this scheme the spin transfer is discussed in terms of *constituent quarks*. Table 1 shows the spin transfer coefficients C_q^Λ for this case [2,5]. As discussed in Sect. 6 and shown in [17], this model reproduces fairly well the $\Lambda/\overline{\Lambda}$ longitudinal polarization measured at the Z^0 pole and at large z. However, the interpretation of these data is not unique. A particular case is given by a simpler assumption that the Λ hyperon gets its polarization from s quarks only. In the following we will refer to the former description as *BGH* (*for* Bigi, Gustafson, and Häkkinen) and the latter as *NQM* (*for* naïve quark model).

Table 1. Spin transfer coefficients according to non-relativistic SU(6) quark model

Λ's parent	C_u^Λ	C_d^Λ	C_s^Λ	$C_{\bar{q}}^\Lambda$
Quark	0	0	+1	0
Σ^0	−2/9	−2/9	+1/9	0
$\Sigma(1385)$	+5/9	+5/9	+5/9	0
Ξ	−0.3	−0.3	+0.6	0

Table 2. Spin transfer coefficients according to the Burkardt-Jaffe g_1^Λ sum rule

	C_u^Λ	C_d^Λ	C_s^Λ	$C_{\bar{q}}^\Lambda$
BJ-I	−0.20	−0.20	+0.60	0.0
BJ-II	−0.14	−0.14	+0.66	−0.06

The second approach is based on the g_1^Λ *sum rule* for the first moment of the polarized quark distribution functions in a polarized Λ hyperon, which was derived by Burkardt and Jaffe [6] in the same fashion as for the proton one (g_1^p). We assume that the spin transfer from a polarized quark q to a Λ is proportional to the Λ spin carried by that flavor, *i.e.* to g_1^Λ. Table 2 contains the spin transfer coefficients C_q^Λ, which were evaluated using the experimental values for g_1^p. Two cases are considered [15]: in the first one only valence quarks are polarized; in the second case also sea quarks and anti-quarks contribute to the Λ spin. In the following we will refer to the first one as *BJ-I* and the second one as *BJ-II*. In this description, Λ's originating from strong decays of hyperon resonances are absorbed in the Λ fragmentation function. A similar description for Σ^0's and cascades is not yet available; therefore Λ's originating from decays of these hyperons have to be excluded in this description. As our calculations have shown, the exclusion of these Λ's has a small effect on the final polarization result (contained to within a few%).

In the g_1^Λ *sum rule* scheme a negative spin transfer from u and d quarks to a Λ hyperon is predicted. A negative spin transfer from u and d quarks of -0.09 was also predicted in [8] using an effective QCD Lagrangian, and in the covariant quark – di-quark model of [14]. This effect can be understood qualitatively even if the spin of the Λ is determined by its constituent s quark only: in some cases the fragmenting u or d quark will become a sea quark of the constituent s quark, and the spin of the constituent s quark will be anti-correlated to the spin of the fragmenting quark [24,7]. Another possibility occurs when the Λ is produced as a second rank particle in the fragmentation of a u or d quark. If the first rank particle was a pseudoscalar strange meson, then the spin of the $\bar{\mathsf{s}}$ quark has to be opposite to that of the u (d) quark, and

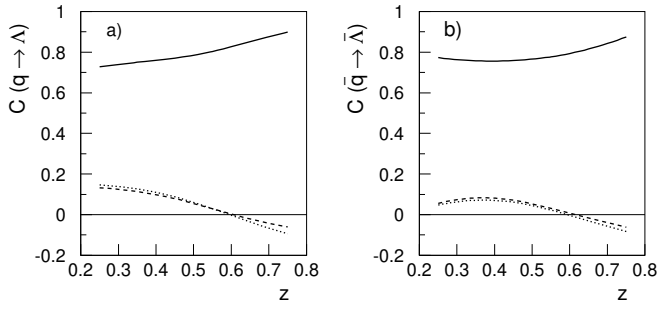

Fig. 1. *z dependence* of the spin transfer coefficients C_q^Λ in the *BGH* spin transfer mechanism. **a** Λ: *solid line* - s quark, *dashed* - u, and *dotted* - d; **b** $\overline{\Lambda}$: *solid line* - $\bar{\mathrm{s}}$ quark, *dashed* - $\bar{\mathrm{u}}$, *dotted* - $\bar{\mathrm{d}}$

since the $\mathrm{s\bar{s}}$ pair created from the vacuum in the string breaking is assumed to be in a $^3P_0$ state [25], the s quark is also oppositely polarized to the u or d quark. This last mechanism of the spin transfer can be checked by measuring the Λ polarization for a sample of events containing fast K mesons.

We implemented the spin transfer coefficients C_q^Λ given in Tables 1 and 2 in appropriate Monte Carlo event generators for different processes on the basis of the program information on the flavor of the fragmenting quark and the Λ production process (directly produced or originating from decays). For the simulation of DIS events (charged leptons and neutrinos) we used the `LEPTO v.6.3 - JETSET v.7.4` [26,27] event generator, and for the e^+e^- annihilation at the Z^0 pole the `PYTHIA v.5.7 - JETSET v.7.4` [27] event generator. With a suitable choice of input parameters these event generators reproduce well the distributions of various measured physical observables and the particle yields. The quark hadronization is described by the LUND string fragmentation model [28]. We used the LUND modified symmetric fragmentation function with default parameter settings [27]. Different fragmentation schemes were also considered, like the independent fragmentation options in `JETSET` [27]. They lead to similar results and conclusions. We set the strangeness suppression factor to 0.20 in agreement with recent experimental data [29].

In the *BGH* approach the spin transfer coefficients for individual channels are z independent. However, the effective spin transfer coefficient for a given quark flavor, obtained by summing over all Λ production channels appears to have a z dependence. Thus using the C_q^Λ from Table 1 together with appropriate weights for different Λ production channels, as obtained from the event generators, we automatically introduce a z dependence in $C_q^\Lambda(z)$ (see Fig. 1). For the g_1^Λ *sum rule* spin transfer mechanism we make the simplest assumption, in which the spin transfer coefficients are z independent. If we choose a z dependence for C_q^Λ similar to the one proposed in [13], we will obtain smaller (larger) values of the Λ polarization at small (large) z.

3 Λ and $\overline{\Lambda}$ polarization in charged lepton DIS off an unpolarized target

The complete twist-three level description of spin-1/2 baryons production in polarized DIS is given in [23]. Here we will consider this process at leading order integrated over the final hadron transverse momentum. In this approximation the magnitude of the Λ longitudinal polarization is given by the simple parton model expression [21,7]

$$P_\Lambda(x,y,z) = P_\Lambda^{\parallel}(x,y,z) = \frac{\sum_q e_q^2 \left[P_B D(y) q(x) + P_T \Delta q(x)\right] \Delta D_q^\Lambda(z)}{\sum_q e_q^2 \left[q(x) + P_B D(y) P_T \Delta q(x)\right] D_q^\Lambda(z)}, \quad (6)$$

where P_B and P_T are the beam and target longitudinal polarizations, e_q is the quark charge, $q(x)$ and $\Delta q(x)$ are the unpolarized and polarized quark distribution functions, and $D_q^\Lambda(z)$ and $\Delta D_q^\Lambda(z)$ are the unpolarized and polarized fragmentation functions.

$$D(y) = \frac{1-(1-y)^2}{1+(1-y)^2} \quad (7)$$

is commonly referred to as the longitudinal depolarization factor of the virtual photon with respect to the parent lepton, where y is the energy fraction of the incident lepton carried by the virtual photon [1].

For scattering off an unpolarized target (6) reduces to

$$P_\Lambda(x,y,z) = P_B D(y) \frac{\sum_q e_q^2\, q(x)\, \Delta D_q^\Lambda(z)}{\sum_q e_q^2\, q(x)\, D_q^\Lambda(z)}. \quad (8)$$

This expression is intuitively easy to understand since the final quark polarization, $P_{q'}$, in polarized lepton-unpolarized quark scattering is given by the QED expression

$$P_{q'} = P_B D(y). \quad (9)$$

We implemented (8) and the spin transfer coefficients C_q^Λ from Tables 1 and 2 into the `LEPTO` code to predict the $\Lambda/\overline{\Lambda}$ polarization for different models of the spin transfer mechanism. Our calculations have been performed in experimental conditions similar to that of the proposed *COMPASS* experiment [21]: hard DIS ($Q^2 > 4$ GeV^2) of negatively polarized μ^+'s ($P_\mu = -0.80$) at $E_\mu = 200$ GeV [2] off an unpolarized isoscalar target (^{6}LiD). To select Λ's produced in the current fragmentation region we require $x_F > 0$ and $z > 0.2$ [3]. Additionally, to enrich the sample

[1] Here and in the following the sign of the Λ polarization is given with respect to the direction of the momentum transfer (*i.e.* along the axis of the exchanged virtual boson in DIS)

[2] The beam energy chosen in the *COMPASS* proposal [21] is 100 GeV. No big differences are expected for $E_\mu = 100$ GeV compared to $E_\mu = 200$ GeV

[3] A different selection of the current fragmentation region was proposed by Berger [31] - *Berger criterium*. Basically, to each W^2 value it corresponds a range in z, $z_{min} < z < 1$, where it should be possible to measure the fragmentation functions: for instance for $W^2 > 55\,(> 23)$ GeV^2, $z > 0.1\,(> 0.2)$. In our kinematical conditions this criterium is satisfied automatically by all selected events

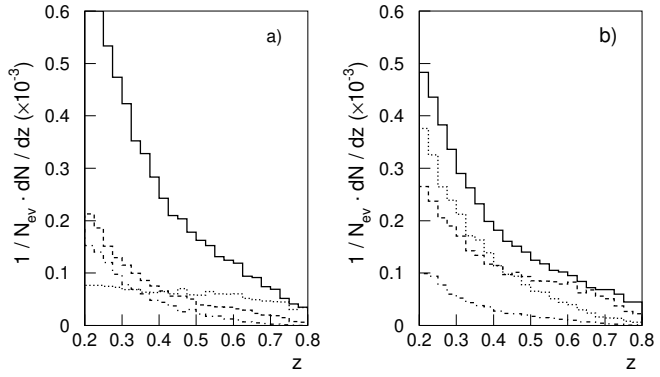

Fig. 2. a normalized z distribution of Λ's produced in μ^+–DIS originating from the fragmentation of different quark flavors: *solid line* - u quark, *dashed* - d, *dotted* - s, and *dot-dashed* - $\bar{u}$; **b** normalized z distribution of directly produced Λ's (*solid line*), Λ's coming from $\Sigma(1385)$ resonances (*dotted*), Σ^0 decays (*dashed*), and cascades (*dot-dashed*)

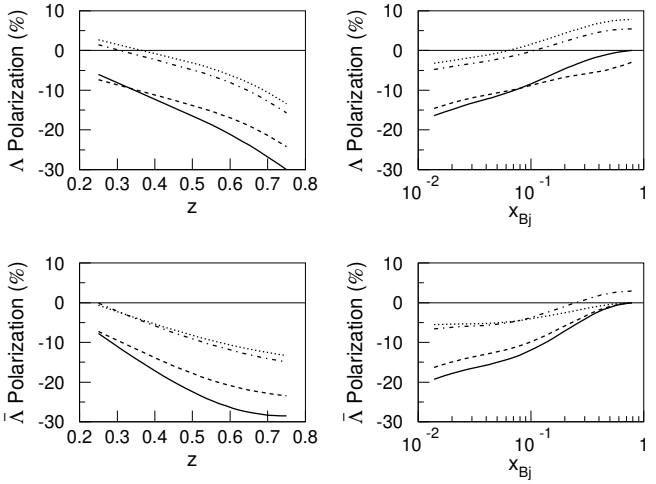

Fig. 3. Λ and $\overline{\Lambda}$ longitudinal polarization in the current fragmentation region for DIS of polarized μ^+'s on an unpolarized target for different mechanisms of spin transfer: *solid line* - *NQM*, *dashed* - *BGH*, *dotted* - *BJ-I*, and *dot-dashed* - *BJ-II*

with events with a large spin transfer in lepton – quark scattering, we restrict the virtual photon energy range to $0.5 < y < 0.9$, which gives $\langle D(y)\rangle \sim 0.8$. In these studies we used the recent $MRSA'$ unpolarized parton distribution functions [30]. In the selected kinematical region the yields of Λ's and $\overline{\Lambda}$'s are similar as is their kinematical spectra. Roughly 10% of all produced Λ's and one third of $\overline{\Lambda}$'s survive the x_F and z cuts. This sample represents about 1% of the total DIS cross section ($\sigma \sim 10$ nb in these conditions).

In Fig. 2a we show the normalized z distribution (to the total number of generated events) of Λ's created in the fragmentation of different quark and anti-quark flavors as obtained from the LEPTO code. Figure 2b shows the z distribution of directly produced Λ's, as well as Λ's coming from Σ^0 decays, higher spin resonances $\Sigma(1385)$, and cascades. Almost half of the total Λ sample is produced directly.

In Fig. 3 we present our results for the Λ and $\overline{\Lambda}$ longitudinal polarization separately. The differences in the $\Lambda/\overline{\Lambda}$ polarizations are quite significant between the two schemes for the spin transfer mechanism (the *constituent quark* on one hand and the g_Λ^1 *sum rule* on the other), while they appear to be small (only a few%) within the same scheme. Integrating in z for $z > 0.2$ we expect a polarization of about $-12\%\,(-14\%)$ for Λ's ($\overline{\Lambda}$'s) for the first scheme, and $-2\%\,(-5\%)$ for the second one [4]. No significant variations were observed for the $\Lambda/\overline{\Lambda}$ polarization values, when performing the same analysis for a proton or neutron target in the same kinematical region.

Already at low values of z, the *constituent quark* scheme predicts a sizeable negative Λ polarization, while the g_Λ^1 *sum rule* a slightly positive one. At high z both reach large negative values. This behaviour of the Λ polarization is easily understood, given that at low z ($z < 0.5$) Λ production is dominated by scattering off u quarks (see Fig. 2a), which in the two schemes contributes to the Λ polarization with opposite signs (see Table 1 and Table 2). At high z ($z > 0.5$) the relative contribution of s quarks, which contributes with the same sign but different magnitudes, increases significantly, and eventually dominates at large z. In the same way the x dependence of the polarization can also be understood: in the low x region scattering off both u and s quarks contribute to the Λ production and polarization, while at high x only u quarks contribute. A similar analysis applies to the $\overline{\Lambda}$ polarization results.

A high luminosity experiment, like *COMPASS* [21], might collect with these kinematical conditions a fully reconstructed sample of $\Lambda/\overline{\Lambda}$ in excess of 10^5. This will allow a precise determination of the $\Lambda/\overline{\Lambda}$ polarization in several bins over a wide z range with a precision of a few% for each bin and to distinguish between the two descriptions of the spin transfer mechanism discussed above.

We performed similar calculations also for different beam energies, like the *HERMES* experiment [18] with the 30 GeV polarized electron beam, and the *E665* experiment [19] with the 500 GeV polarized muon beam. Table 3 summarizes these results for $x_F > 0$ and $z > 0.2$. In Figure 4 we compare the $\Lambda/\overline{\Lambda}$ polarization predictions for these three different beam energies using the *BGH* and the *BJ-I* spin transfer mechanism. We always assume a beam polarization $P_B = -0.80$, an isoscalar target, $Q^2 > 4$ GeV^2, and $0.5 < y < 0.9$. The conclusions are similar to the ones above, except that at each different beam energy a different x interval is covered (the higher the energy, the lower the accessible x). In particular, at 30 GeV (and $Q^2 > 4$ GeV^2) Λ production is dominated by scattering off u quarks even at large z, and the Λ polarization varies weakly with z in the whole z interval for the *constituent quark* spin transfer mechanism, since the accessible x range hardly extends into the low x region, where s quarks are abundant.

[4] These results were obtained for a negative beam polarization of $P_B = -0.80$. For different beam polarizations these results can be rescaled accordingly

Table 3. $\Lambda/\overline{\Lambda}$ longitudinal polarization for different lepton beam energies and an unpolarized deuterium target, $x_F > 0$ and $z > 0.2$

E_{beam} (GeV)	NQM	BGH	$BJ-I$	$BJ-II$
30 – Λ	−5.8	−12.0	4.9	2.4
30 – $\overline{\Lambda}$	−12.8	−10.4	−5.2	−4.3
200 – Λ	−12.4	−11.5	−1.1	−2.6
200 – $\overline{\Lambda}$	−15.8	−13.1	−5.1	−5.4
500 – Λ	−15.9	−14.1	−3.4	−4.8
500 – $\overline{\Lambda}$	−17.8	−14.7	−5.6	−6.3

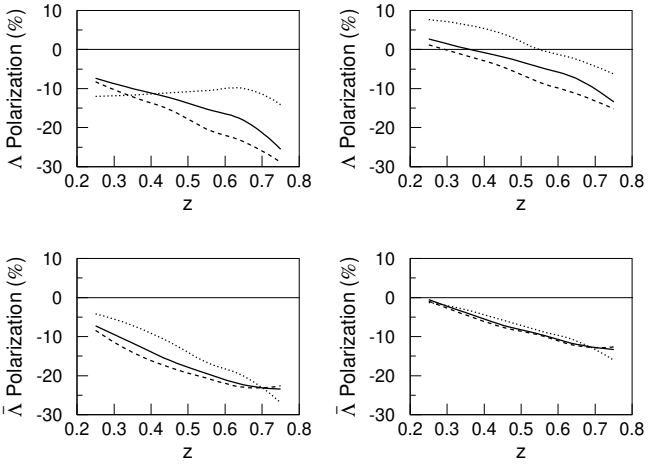

Fig. 4. Λ and $\overline{\Lambda}$ longitudinal polarization for three different beam energies using the *BGH* (*left plots*) and the *BJ-I* (*right plots*) spin transfer mechanism: *solid line* - $E_\mu = 200$ GeV, *dashed* - $E_\mu = 500$ GeV, and *dotted* - $E_{el} = 30$ GeV

4 $\Lambda/\overline{\Lambda}$ polarization in DIS off a polarized target

For a polarized target and polarized lepton beam (see (6)) there are two *sources* for the fragmenting quarks polarization: the spin transfer from the polarized lepton and from the struck polarized quark in the target. We studied the polarization difference between the $\Lambda/\overline{\Lambda}$ polarization for positive (parallel to the beam polarization) and negative target polarization (anti-parallel to the beam polarization)

$$\Delta P_\Lambda \;=\; P_\Lambda\,(+P_T) \;-\; P_\Lambda\,(-P_T)\,. \qquad (10)$$

By reversing the target polarization, the fragmenting quark polarization, $P_{q'}$, changes by

$$\Delta P_{q'}(x,y) = 2\,P_q(x)\,\frac{1-(P_B\,D(y))^2}{1-(P_B\,D(y)\,P_q(x))^2} \qquad (11)$$

where

$$P_q(x) = P_T\frac{\Delta q(x)}{q(x)} \qquad (12)$$

is the polarization of the quark in the polarized nucleon.

In our calculations we use a polarized proton target of $P_T = 0.80$ and a 200 GeV polarized μ^+ beam of $P_B = -0.80$. In most experiments complex target materials are used and the effective nucleon polarization is significantly diluted (for instance for a polarized ^{6}LiD target $\langle P_N\rangle \sim 25\%$). For such targets a smaller sensitivity on the nucleon polarization is therefore expected (roughly $3\times$ smaller). The covered kinematical range is similar to the one in the previous section. To reduce the effects related to the beam polarization, we extend our analysis to the whole accessible y range, $0.1 \le y \le 0.9$, to which corresponds a photon beam with smaller polarization ($\langle D(y)\rangle \sim 0.4$). In ΔP_Λ ($\Delta P_{\overline{\Lambda}}$) the beam polarization ($P_B\langle D(y)\rangle$) enters quadratically, and therefore affects little the final result (typically $(P_B\langle D(y)\rangle)^2 < 0.1$). The total DIS cross section for this sample is about 35 nb. Figure 5 shows the normalized x distribution of different quark and anti-qaurk flavors fragmenting to the selected Λ's and $\overline{\Lambda}$'s.

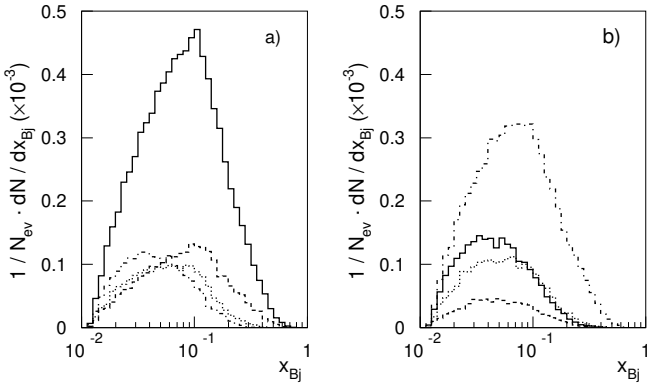

Fig. 5. a normalized x distribution of Λ's produced in μ^+–DIS from the fragmentation of different quark flavors: *solid line* - u quark, *dashed* - d, *dotted* - s, and *dot-dashed* - ū; **b** same as **a** for $\overline{\Lambda}$'s: *solid line* - ū quark, *dashed* - d̄, *dotted* - s̄, and *dot-dashed* - u ($x_F > 0$ and $z > 0.2$)

In Fig. 6 we present our predictions for the Λ ($\overline{\Lambda}$) polarization difference ΔP_Λ ($\Delta P_{\overline{\Lambda}}$). As input for the polarized quark distribution functions we used the Brodsky, Burkardt, and Schmidt parametrization [32], which predicts a large negative sea quark polarization ($\Delta \mathsf{s} = -0.10$, and $\Delta s(x)/s(x) \sim -0.20$ at $x \sim 0.1$ and input scale of $Q_0^2 = 4$ GeV^2). Different polarized parton densities were also considered (see Fig. 7).

All the different spin transfer models lead to similar predictions for ΔP_Λ ($\Delta P_{\overline{\Lambda}}$) within a few%, except for Λ's produced at high x. This effect is easily understood, given that at high x, Λ production is dominated by scattering off polarized u quarks, which transfer their polarization to the Λ's in different ways and with opposite signs (see Table 1 and Table 2). The *dip* in the $\Lambda/\overline{\Lambda}$ polarization distributions just below $x \sim 0.1$ originates from the large negative s/s̄ polarization in this x interval correlated with a large positive spin transfer coefficient C_s^Λ, and the positive u/ū polarization with a negative spin transfer coefficient C_u^Λ; therefore both quarks contribute with the same sign. These results were obtained with the polarized parton density parametrization of Brodsky, Burkardt, and Schmidt [32].

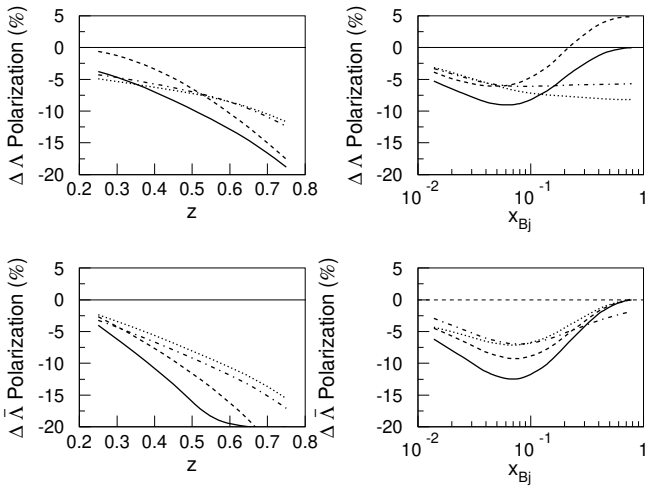

Fig. 6. ΔP_Λ and $\Delta P_{\overline{\Lambda}}$ (10) for DIS of polarized μ^+'s off a polarized proton target: *solid line* - *NQM*, *dashed* - *BGH*, *dotted* - *BJ-I*, and *dot-dashed* - *BJ-II*

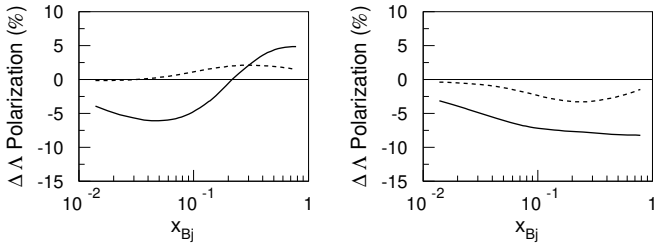

Fig. 7. Comparison of ΔP_Λ for two different polarized parton densities (*solid line* - Brodsky, Burkardt, and Schmidt [32] and *dashed* - Gehrmann and Stirling [33]) for the *BGH* (*left plot*) and the *BJ-I* (*right plot*) spin transfer mechanism

For comparison we also used different parametrizations of the polarized quark distributions, like the Gehrmann and Stirling one [33] with a zero sea quark polarization at the input scale ($Q_0^2 = 4$ GeV^2). With this parametrization we obtained considerably smaller results. Near zero values for the polarization difference ΔP_Λ ($\Delta P_{\overline{\Lambda}}$) were obtained using the polarized parton densities of Glück, Reya, Stratman, and Vogelsang [34]. Table 4 summarizes the $\Lambda/\overline{\Lambda}$ longitudinal polarization results, integrated in z for $x_F > 0$ and $z > 0.2$, using these three different polarized parton densities. Figure 7 compares the ΔP_Λ expectations for the first two polarized parton densities using the *BGH* and the *BJ-I* spin transfer mechanism.

The longitudinal polarization of $\Lambda/\overline{\Lambda}$'s produced in the scattering off a polarized nucleon, should allow, at least in principle, to access the polarized quark densities in the nucleon, once the spin transfer mechanism for the $\Lambda/\overline{\Lambda}$ production is understood. From the study with an unpolarized target (previous Section), the ΔD_q^Λ which best describes the data can be determined, and then used for the polarized target case. However, our studies have shown that typically one would expect at most $|\Delta P_\Lambda| \sim 6\%$: for a solid target, like in most fixed target experiments, $|\Delta P_\Lambda|$ reduces to only 1–2%. In addition, one can determine, realistically, the $\Lambda/\overline{\Lambda}$ longitudinal polarization with a precision not higher than a percent, because of experimental systematic uncertainties in the measurement of this quantity. These facts indicate a relatively small sensitivity of the $\Lambda/\overline{\Lambda}$ polarization to the target polarization, contrary to what is expected for instance in [11]. Therefore, only a crude estimate of the polarized parton densities can be obtained through the study of the $\Lambda/\overline{\Lambda}$ polarization. Nevertheless, a sizeable (negative) $\Lambda/\overline{\Lambda}$ polarization would indicate a large (negative) *strange* sea polarization.

Table 4. ΔP_Λ (upper lines) and $\Delta P_{\overline{\Lambda}}$ (lower lines) for three different polarized parton densities and different spin transfer mechanisms

Pol. part. dens.	*NQM*	*BGH*	*BJ − I*	*BJ − II*
BBS	−7.2	−4.0	−6.5	−6.0
[32]	−10.3	−7.7	−5.5	−6.5
*GS*94	0.1	1.1	−2.0	−1.4
[33]	0.1	0.1	0.0	−0.4
GRSV	0.0	0.3	−0.5	−0.3
[34]	0.0	0.0	0.0	−0.1

5 Λ polarization in neutrino and anti-neutrino production

Particularly interesting conditions for the measurement of polarized fragmentation functions are provided by Λ production in neutrino and anti-neutrino DIS. In neutrino scattering the flavor changing charged current weak interaction selects left-handed quarks (right-handed anti-quarks), giving 100% polarized fragmenting quarks. For this process (8) reads

$$P_\Lambda(x,z) = \frac{\sum_{q,q'} \epsilon_q w_{qq'}\ q(x)\ \Delta D_{q'}^\Lambda(z)}{\sum_{q,q'} w_{qq'}\ q(x)\ D_{q'}^\Lambda(z)}. \qquad (13)$$

where the $w_{qq'}$ are the W^+q (W^-q) weak charge couplings (for instance $w_{su} = \sin\theta_C$ where θ_C is the Cabibbo angle), $\epsilon_q = -1$ ($\epsilon_{\bar{q}} = +1$) for scattering off (anti-)quarks, q is the struck quark, and q' is the fragmenting quark (of different flavor).

Using the LEPTO event generator we have performed calculations for the $\Lambda/\overline{\Lambda}$ polarization in neutrino and anti-neutrino DIS in the current fragmentation region ($x_F > 0$ and $z > 0.2$) in the same fashion as for the electroproduction DIS case by implementing 13 into the event generator code. In our calculations we used a neutrino and an anti-neutrino beam of $E_{\nu(\overline{\nu})} = 50$ GeV incident on an isoscalar target.

In Fig. 8a we show the normalized z distribution (to the total number of generated events) of Λ's created in the fragmentation of different quark and anti-quark flavors as obtained from the LEPTO code. Figure 8b shows the z distribution of directly produced Λ's, as well as Λ's coming from Σ^0 decays, higher spin resonances $\Sigma(1385)$, and cascades. These distributions (Fig. 8b) are similar to the ones obtained with a muon beam (see Fig. 2b).

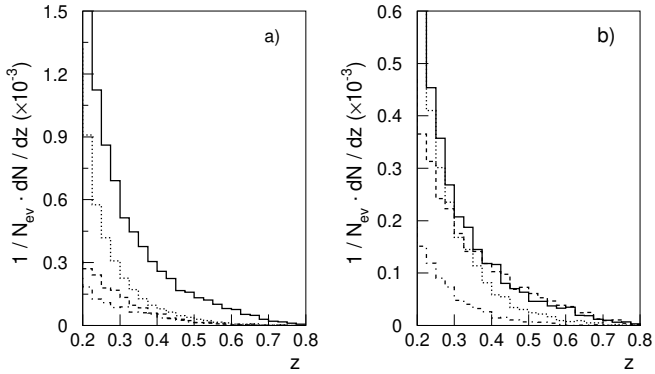

Fig. 8. a normalized z distribution of Λ's originating from the fragmentation of different quark flavors produced in ν–DIS: *solid line* - u quark, *dashed* - c, and Λ's produced in $\overline{\nu}$–DIS: *dotted* - d, and *dot-dashed* - s; **b** normalized z distribution of directly produced Λ's (*solid line*), Λ's coming from $\Sigma(1385)$ resonances (*dotted*), Σ^0 decays (*dashed*), and charmed hadrons (*dot-dashed*) in ν–DIS

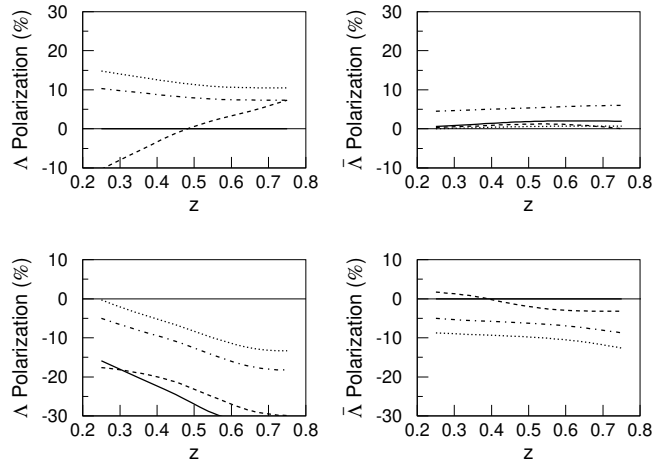

Fig. 9. $\Lambda/\overline{\Lambda}$ polarization in the current fragmentation region in ν–DIS (*upper plots*) and $\overline{\nu}$–DIS (*lower plots*): *solid line* - *NQM*, *dashed* - *BGH*, *dotted* - *BJ-I*, and *dot-dashed* - *BJ-II*

The results for the $\Lambda/\overline{\Lambda}$ polarization as a function of z are presented in Fig. 9. In neutrino scattering, Λ production is dominated by fully polarized fragmenting u quarks (see Fig. 8), with a small contribution of c quarks ($\sim 10\%$) at this energy (at a lower energy the contribution of c quarks is smaller). In $\overline{\nu}$–DIS both d and s quark fragmentation contributes to Λ production and the latter dominates at large z. Note that the polarization of d and s quarks is opposite compared to that of u quarks in ν–DIS. This easily explains the observed behavior of the Λ polarization for the considered mechanisms of the spin transfer shown in Fig. 9.

The difference between the *constituent quark* and the g_1^Λ *sum rule* spin transfer mechanism are quite significant in neutrino scattering. These two schemes lead to different signs for the Λ polarization, contrary to what was found in the μ–beam case (Sect. 3) and at the Z^0 pole (next Section). This effect is mainly due to the different signs in the spin transfer from u quarks, which in this reaction dominate the Λ production. The *NQM* gives zero polarization, since no s quarks are involved, while the *BGH* increases with z from negative values to slightly positive values at large z, which is correlated with the relative abundances of Σ^* hyperons. The *BJ-I* and *BJ-II* prescriptions give almost constant (in z) positive values for the Λ polarization.

The longitudinal Λ polarization in anti-neutrino scattering has been measured by the *WA59* experiment [16] in the current fragmentation region and kinematical conditions similar to our analysis. However, the result obtained $P_\Lambda = -0.11 \pm 0.45$ has a large uncertainty and it is inconclusive as far as this analysis is concerned. New data on $\Lambda/\overline{\Lambda}$ production with a neutrino beam at a mean beam energy of 30 GeV will be soon available from the *NOMAD* experiment [20]. At 30 GeV we expect similar Λ polarization results as those shown in Fig. 9. This experiment might collect a sample of several thousands Λ's, giving a relatively accurate measurement of the Λ polarization within a few% and thus allowing one to distinguish between the models considered here and to measure directly the polarized fragmentation function $\Delta D_{\mathsf{u}}^{\Lambda}$ for u quarks in *clean* conditions.

6 $\Lambda/\overline{\Lambda}$ polarization at the Z^0 pole

The Standard Model predicts a high degree of longitudinal polarizations for quarks and anti-quarks produced in Z^0 decays: $P_s = P_d = -0.91$, $P_u = P_c = -0.67$ [35]. Thus, reaction (2) is a source of polarized quarks which can be exploited to investigate the spin transfer dynamics in polarized quark fragmentation.

A large $\Lambda/\overline{\Lambda}$ longitudinal polarization ($P_\Lambda = -0.32 \pm 0.06$ for $z > 0.3$) has been recently reported by the *ALEPH* collaboration [17]. The authors concluded that the measured $\Lambda/\overline{\Lambda}$ longitudinal polarization is well described by the *constituent quark* model predictions of Gustafson and Häkkinen [5]. However, as our study shows, the interpretation of this data is not unique.

In Fig. 10a we present our predictions for different spin transfer mechanisms for the $\Lambda/\overline{\Lambda}$ polarization at the Z^0 pole. These predictions are compared with experimental data from [17]. At high z both models, the *BGH* and g_1^Λ *sum rule*, describe the experimental data fairly well, while the *NQM* mechanism gives too large values for the $\Lambda/\overline{\Lambda}$ polarization. At small z the data even favors the g_1^Λ *sum rule* mechanism. Also in this case more precise experimental data are needed to distinguish between the various models of the spin transfer mechanism in quark fragmentation.

Our analysis differs from that of [17] in two main points. The authors of [17] assume in their analysis (similarly as in [5]) that only fragmenting polarized s quarks contribute to the Λ polarization (*i.e.* $C_u^\Lambda = C_d^\Lambda = 0$ in Table 1). Additionally, they separate between first and lower rank Λ's produced in the string fragmentation, and they assume that lower rank Λ's do not inherit any polarization from the fragmenting quark. Their argument that s quarks produced in the fragmentation process have no longitudinal polarization due to parity conservation is

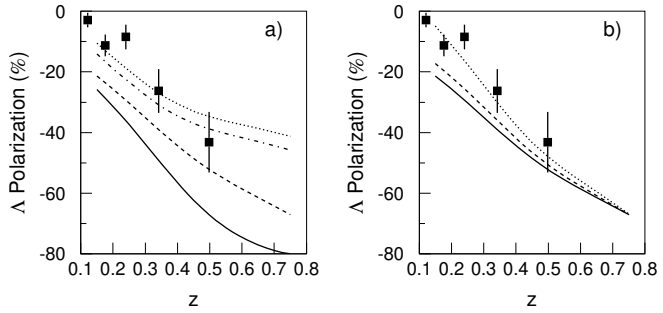

Fig. 10. a $\Lambda/\overline{\Lambda}$ polarization at the Z^0 pole for different mechanisms of spin transfer: *solid line - NQM*, *dashed - BGH*, *dotted - BJ-I*, and *dot-dashed - BJ-II*. The experimental data (*full squares*) are from [17]. **b** comparison between predictions using the *BGH* model for the Λ polarization in our analysis (*solid line*) and the analysis of [17] assuming that only s quarks contribute to Λ polarization (*dashed*), and additionally that only first rank Λ's inherit a fraction of the fragmenting quark polarization (*dotted*)

not applicable to polarized quarks fragmentation. In our study, instead, all quark flavors contribute to the Λ polarization (according to Table 1), and we also do not separate between first and lower rank Λ's. For comparison we also performed the analysis of [17]. Figure 10b compares the results thus obtained for the *BGH* spin transfer mechanism. These two different approaches give similar results in the high z region, where Λ production is dominated by fragmenting s quarks and the Λ polarization is directly correlated to that of the fragmenting s quark (first rank particle), while at lower z our analysis predicts larger values for the Λ polarization.

7 Conclusions

In this work we have studied several lepton induced processes, where the longitudinal spin transfer in polarized quark fragmentation can be investigated through the measurement of the $\Lambda/\overline{\Lambda}$ longitudinal polarization produced in these processes. Two different scenarios for the spin transfer mechanism, the *constituent quark* and the g_1^Λ *sum rule*, were used for numerical estimates of the $\Lambda/\overline{\Lambda}$ longitudinal polarization. To distinguish between various spin transfer mechanisms, it is important to measure the $\Lambda/\overline{\Lambda}$ polarization in different processes, since different quark flavors are involved in the fragmentation to a $\Lambda/\overline{\Lambda}$ hyperon with different weights. For instance, the largest effects are expected in neutrino DIS, where mainly u quarks fragment to a Λ, and the two scenarios predict also different signs for the polarization. Typically, the *constituent quark* spin transfer mechanism predicts, in magnitude, larger values for the $\Lambda/\overline{\Lambda}$ polarization, while the g_1^Λ *sum rule* mechanism predicts smaller values. The existing experimental data have large uncertainties on the polarization measurements [5] and cannot separate between these models. Current and future semi inclusive DIS experiments will soon provide accurate enough data to study these phenomena.

Our studies have shown that the $\Lambda/\overline{\Lambda}$ polarization in electro-production is less sensitive to the target polarization (in general) and to Δs as expected in [11]. The main physics reason behind this is that Λ production is dominated by scattering off u quarks even in the low x region. The production of Λ's from scattering off s quarks can be enhanced by selecting events in the high z region. However, in this region the $\Lambda/\overline{\Lambda}$ yields drop significantly, and measurements will be limited by small statistics. The small sensitivity is also due to the experimental difficulties in measuring the longitudinal $\Lambda/\overline{\Lambda}$ polarization to very high accuracy and in the realization of proton targets with a high effective polarization. Nevertheless, a sizeable (negative) Λ polarization (*i.e.* ΔP_Λ) will indicate a large (negative) polarization of sea quarks in the polarized nucleon.

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