EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EPS95 Ref. **EPS-0400**
Submitted to **Pa-08 Pa-14**
Pl-04 Pl-11

Measurement of the Λ_b polarisation in Z decays

The ALEPH Collaboration

Abstract

The Λ_b polarisation in hadronic Z decays is measured using the average energies of the charged lepton and the neutrino in Λ_b semileptonic decays. In a data sample of approximately 3 million hadronic Z decays collected by the ALEPH detector at LEP, 462 ± 20 Λ_b candidates are selected using a $(\Lambda\pi^+)$ lepton correlation technique. From this event sample, the Λ_b polarisation is measured to be:

$$\mathcal{P}_{\Lambda_b} = -0.26^{+0.23}_{-0.20}(stat.)^{+0.13}_{-0.12}(sys.)$$

Contribution to the International Europhysics Conference on High Energy Physics,
Brussels, Belgium, July 27 - August 2, 1995

1 Introduction

In the standard model of electroweak interaction, quarks are produced in Z decays with high longitudinal polarisation due to parity violation in the decay. At the Z peak, the quark mean longitudinal polarisation is given by:

$$\mathcal{P}_q = \frac{-2v_q a_q}{v_q^2 + a_q^2} \tag{1}$$

where v_q and a_q are respectively the vectorial and the axial coupling constants.

For $sin^2\theta_W = 0.23$, the b-quark mean longitudinal polarisation is $\mathcal{P}_b = -0.936$ which is 6.5 times higher than the τ polarisation ($\mathcal{P}_\tau = -0.143 \pm 0.023$ [1]). In the absence of hard gluon emission, the initial b-quark polarisation is expected to be present at the time of hadron formation. However in the hadronisation process part or whole of the initial b-quark polarisation might be lost in the final hadron state due to spin-spin forces within the b-hadron.

In Hadronisation to b-mesons, the meson always cascade down to spin zero pseudoscalar states which do not retain any polarisation information [2, 3]. Hadronisation to b-baryons might preserve a large fraction of the initial b-quark polarisation in the lowest lying b-baryon state (Λ_b state) which carries entirely the b-quark spin and where the light quarks are arranged in a spin-0, isospin-0 singlet. Higher mass baryonic states (Σ_b and Σ_b^*) are expected to lose most of their polarisation in their hadronic decays into a Λ_b ((Σ_b, Σ_b^*) $\to \Lambda_b\pi$), implying that the Λ_b net polarisation in the full Λ_b sample in Z decay is reduced. From the prediction of reference [3], Λ_b polarisation is expected to be 72% of the initial b-quark polarisation [1].

The measurement of the Λ_b polarisation sign will determine unambiguously the chirality of the b-quark coupling to the weak charged current [4]. Furthermore the measurement of the magnitude of the Λ_b polarisation will provide an indirect measurement of the fraction of b-baryon states where a Λ_b is produced directly.

The measurement of the Λ_b polarisation is based on approximately 3 million hadronic Z decays recorded with the ALEPH detector from 1991 to 1994. The selection of hadronic events is based on charged tracks and has been described in reference [5].

2 The ALEPH detector

The ALEPH detector is described in detail in reference [6]. Only a sketch of its main components is presented here. Surrounding the beam pipe, two concentric layers of a double sided silicon vertex detector (VDET), positioned at average radii of 6.5 and 11.3 cm, cover respectively 85% and 69% of the solid angle. The intrinsic spatial resolution of the VDET is 12μm for the $r\phi$ coordinate and between 11 and 22μm for the z coordinate, depending on the polar angle of the track. The VDET

---

[1] this prediction relies on the assumption that Σ_b, Σ_b^* mass spliting due to spin-spin interaction is greater than the width of their hadronic decay to Λ_b and that their proportion is 30% of the non-strange b-baryons. In the heavy quark limit $m_b \to \infty$, Σ_b and Σ_b^* are degenerate and the initial b-quark polarisation should be completely transfered to the final Λ_b state.

is surrounded by two cylindrical drift chambers, the Inner Tracking Chamber (ITC) and the Time Projection Chamber (TPC), which measure charged tracks over the range $|cos\theta| < 0.95$, where θ is the polar angle. The ITC, at radii from 16 to 26 cm, provides up to 8 coordinates per track in the $r\phi$ view. The TPC measures up to 21 three-dimentional points per track at radii between 30 and 180 cm and provides up to 338 measurements of the specific ionization ($\mathrm{d}E/\mathrm{d}x$) of the track. The three detectors are immersed in an axial magnetic field of 1.5 Tesla and together provide a transverse momentum resolution of $\sigma_p/p = 6 \times 10^{-4} p$ (p in GeV/c) at 45 GeV/c. The TPC is surrounded by an electromagnetic calorimeter (ECAL) with energy resolution of $\sigma_E = 0.18/\sqrt{E} + 0.009$ (E in GeV). It is made of lead and proportional chambers, segmented into 15 mrad × 15 mrad projective towers read out in three sections in depth. Arround the coil of the superconducting solenoid, the hadron calorimeter (HCAL) with a thickness of over 7 interaction lengths, is composed of the iron return yoke of the magnet interleaved with 23 layers of streamer tubes. Two additional double layers of streamer tubes for muon identification surround the HCAL. Combining the measurements from the different detector components, an algorithm provides a determination of the visible energy in the detector with a precision of $\sigma_E = 0.59\sqrt{E} + 0.6$ (E in GeV).

3 Λ_b selection and analysis procedure

The fraction of the initial b-quark polarisation that survives b hadronisation into a Λ_b state, can be estimated from the inclusive semileptonic decay $\Lambda_b \to X_c l^- \overline{\nu_l}$, where X_c is any charmed hadron state. This decay channel, sensitive to Λ_b polarisation, has the advantage of being copiously produced and easy to tag. From the theoretical point of view, the inclusive Λ_b semileptonic decay, is remarkably simple and can be treated in the heavy-quark limit as a free quark decay $b \to c\, l^- \overline{\nu_l}$ [7]. The lepton and neutrino energy spectra contain information on the Λ_b polarisation. Figure 1 shows the dependence of the average lepton energy and the average neutrino energy on the Λ_b polarisation in the laboratory frame. The neutrino energy is much more sensitive to Λ_b polarisation than the charged lepton energy and unlike the latter its average energy decreases with polarisation.

To study Λ_b polarisation from inclusive Λ_b semileptonic decays, the method proposed in reference [8] is adopted, where using the variable $y = \frac{\langle E_l \rangle}{\langle E_{\bar\nu} \rangle}$, with $\langle E_l \rangle$ and $\langle E_{\bar\nu} \rangle$ respectively the average charged lepton and neutrino energies, optimizes the sensitivity to the Λ_b polarisation. This variable has a simple and large dependence on the Λ_b polarisation $\mathcal{P}_{\Lambda_b}$:

$$y \;=\; \frac{\langle E_l \rangle}{\langle E_{\bar\nu} \rangle} = \frac{7 - \mathcal{P}_{\Lambda_b}}{6 + 2\mathcal{P}_{\Lambda_b}} - \epsilon(0.6 + 1.3\mathcal{P}_{\Lambda_b}) \qquad (2)$$

The term proportional to $\epsilon = (m_c^2/m_b^2)$ is a small kinematic correction known to 1% precision. This method is more sensitive to Λ_b polarisation, compared to other methods proposed in the literature [9], and is almost free of theoretical uncertainties including fragmentation.

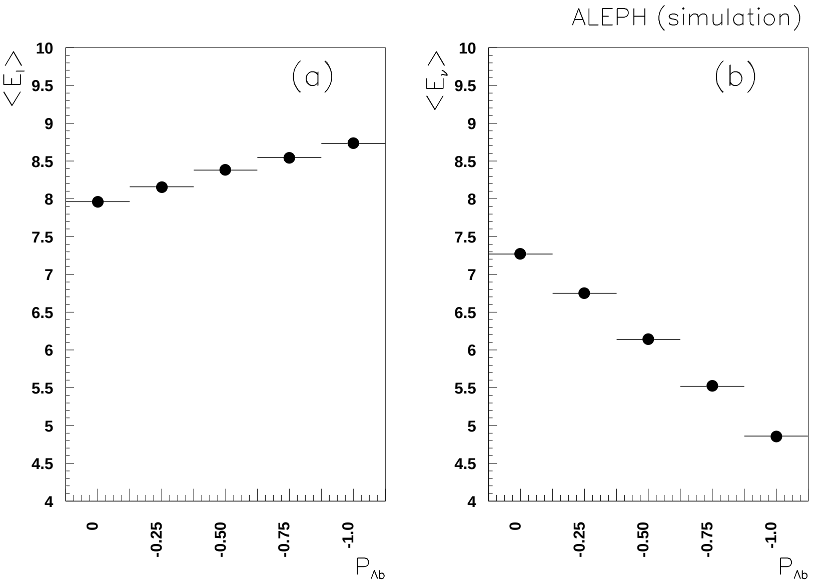

Figure 1: The average charged lepton (a) and neutrino (b) energies as a function of the Λ_b polarisation.

3.1 Λ_b selection

Semileptonic Λ_b decay candidates are selected in hadronic Z events using the charge correlation between the $\Lambda\pi^+$ system and the lepton in the same hemisphere with respect to the thrust axis. Through out this paper, ”lepton” refers to either electrons or muons, and charge conjugate reactions are always implied. Before any particle identification and in order to start with well contained events in the detector, each hadronic event is required to have $|cos\theta_{thrust}| < 0.85$, where θ_{thrust} is the polar angle of the thrust axis.

Leptons are identified by matching a charged track measured in the inner tracking detectors with either an energy deposit consistent with an electron in the ECAL, or a pattern of hits consistent with a muon in the HCAL and muon chambers. Lepton identification in ALEPH is described in detail in reference [6]. In this paper the $\mathrm{d}E/\mathrm{d}x$ requirement for electron is used only when available.

Candidates Λ are reconstructed, in the channel $\Lambda \to p\pi^-$, using an algorithm which fits two oppositely charged tracks to a common vertex. To reduce combinatorial background, Λ candidates are required to have a momentum greater than 3 GeV/c and a decay length of at least 5 cm with respect to the interaction point. To reduce the contamination from other decays, candidates with invariant mass consistent with either K^0_S or γ mass hypotheses are rejected. The TPC $\mathrm{d}E/\mathrm{d}x$ measurements for the two Λ daughter tracks are required, when available, to be within three standard deviations of that expected for a proton and a pion.

Selected Λ candidates are combined with pions with momentum $P_\pi > 0.2$ GeV/c. Events with a Λ_c^+ semileptonic decay may contribute to the missing energy in the tagged hemisphere, and these events are removed by requiring that the pion candidates does not to satisfy the lepton identification cuts. The invariant mass of the $\Lambda\pi^+$ system is required to be less than 2.35 GeV/c^2 and the χ^2 probability of the $\Lambda\pi^+$ vertex fit must be larger than 1%. Selected $\Lambda\pi^+$ candidates are combined with identified leptons with momentum $P_l > 3$ GeV/c and transverse momentum[2] $p_T >$ 1 GeV/c. Finally the $(\Lambda\pi^+)l$ system is required to have an invariant mass less than 5.8 GeV/c^2, the χ^2 probability of the $(\Lambda\pi^+)l$ vertex fit must be larger than 1%, the angle between the Λ and the lepton is required to be less than 45 degrees, and the distance joining the $(\Lambda\pi^+)l$ vertex and the primary vertex, projected onto the $(\Lambda\pi^+)l$ direction must be positive.

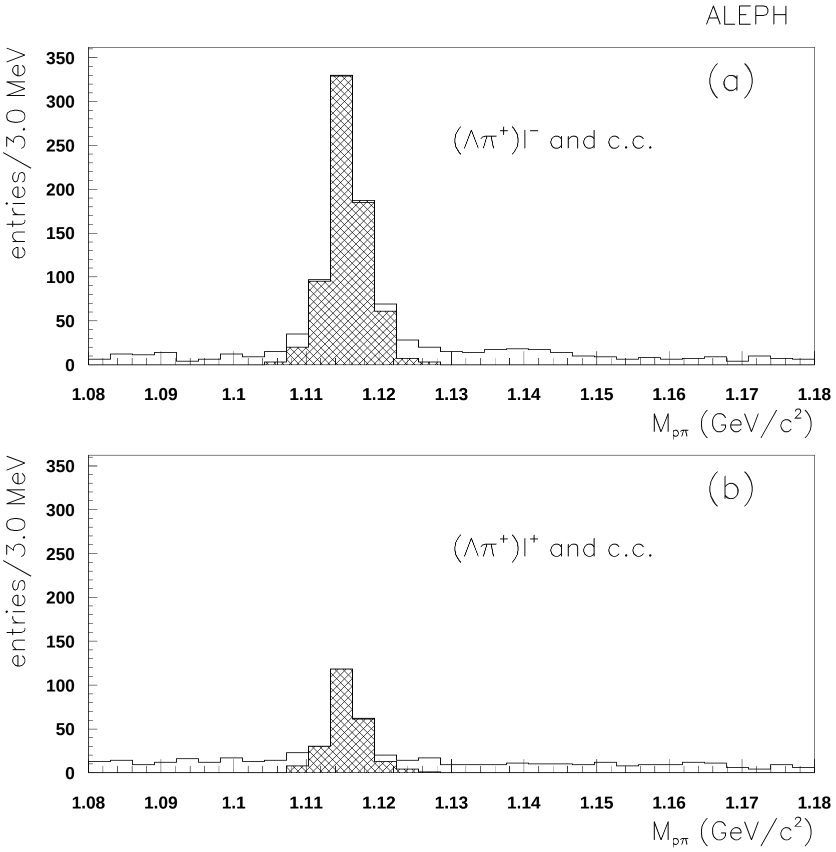

Figure 2: The $p\pi^-$ invariant mass distributions of the right-sign $(\Lambda\pi^+)l^-$ combinations (a) and the wrong-sign $(\Lambda\pi^+)l^+$ combinations (b) in the 1991-1994 data. The shaded area shows the momentum dependent mass window used to select Λ_b candidates.

Figure 2 shows, the $p\pi^-$ invariant mass distributions of the $(\Lambda\pi^+)l^-$ (right-sign) and the $(\Lambda\pi^+)l^+$ (wrong-sign) combinations after all requirements. The excess of $(\Lambda\pi^+)l^-$ events over $(\Lambda\pi^+)l^+$ is attributed to Λ_b semileptonic decays. Right-sign and wrong-sign $(\Lambda\pi^+)l$ candidates are selected using a momentum dependent mass window of $\pm 2.5\,\sigma(p)$ around the nominal Λ mass where $\sigma(p)$ is the mass error for the particular Λ event of momentum p. The shaded area corresponds to the mass

---

[2] The p_T is calculated with respect to the jet containing the lepton.

window for selected events. The raw excess of $(\Lambda\pi^+)l^-$ combinations over $(\Lambda\pi^+)l^+$ is 462 ± 22.

The right-sign $(\Lambda\pi^+)l^-$ candidates consist of two components, a component originating from Λ_b semileptonic decays and a background component which is due mainly to accidental combinations of real or fake $(\Lambda\pi^+)$ in association with real or fake leptons. Contributions from physics background processes [10] are negligible. Wrong-sign $(\Lambda\pi^+)l^+$ combinations consist mainly of accidental combinations. There is a small fraction of signal component in the wrong-sign events consisting of a combination between a lepton from Λ_b semileptonic decay and a Λ from fragmentation.

The selection efficiency is determined from a Monte Carlo simulation [12] of semileptonic Λ_b decays containing a Λ in the hadronic decay sequence. The average efficiency is 8.5% and is independent of the Λ_b polarisation. For Λ_b events originating from the decay of Σ_b or Σ_b^*, the selection efficiency is $(8.22 \pm 0.15)\%$, while prompt Λ_b events (originating directly from the b-quark fragmentation) are selected with an efficiency of $(8.78 \pm 0.16)\%$. This small difference leads to a Λ_b selected sample with a slightly higher polarisation than the initial sample if one considers that direct Λ_b are fully polarised while those from Σ_b decay are completely depolarised.

3.2 Neutrino energy measurement

The neutrino energy is measured from the missing energy in the $(\Lambda\pi^+)$ lepton hemisphere :

$$E_\nu = E_{tot} - E_{vis} \tag{3}$$

where E_{vis} is the visible energy in the $(\Lambda\pi^+)l$ hemisphere, defined as the sum of the charged tracks, the gammas and the neutral hadronic energies :

$$E_{vis} = E_{charged} + E_\gamma + E_{neut.\,had.}, \tag{4}$$

and E_{tot} is the total energy in the hemisphere calculated from the beam energy and energy-momentum conservation, defined as follows [11]:

$$E_{tot} = \frac{\sqrt{s}}{2} + \frac{M_{same}^2 - M_{oppo}^2}{2\sqrt{s}} \tag{5}$$

M_{same} is the invariant mass of the $(\Lambda\pi^+)l$ hemisphere and M_{oppo} is the mass of the opposite hemisphere.

From Monte Carlo simulation of the Λ_b semileptonic decays, the neutrino energy resolution obtained with this method is $\sigma_{E_\nu} = 3.1$ GeV.

3.3 Analysis procedure and method

The selection cuts and neutrino energy reconstruction discussed above, introduce a shift in the y variable. These effects can be corrected for using Monte Carlo with the variable:

$$R_y = \frac{y_{data}}{y_{MC}} \tag{6}$$

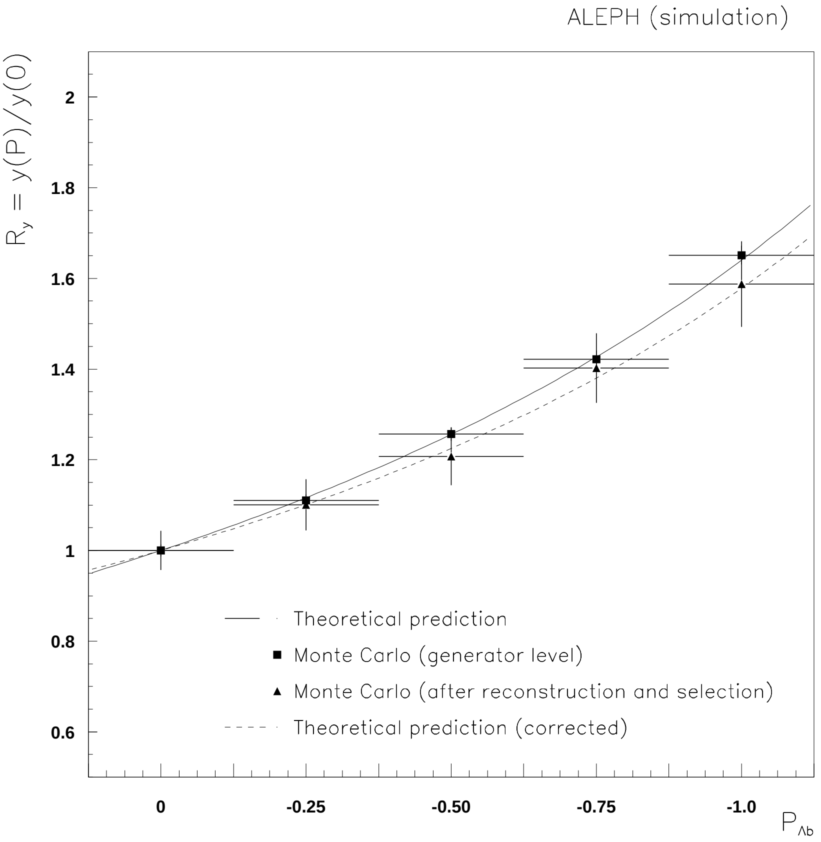

Figure 3: The variation of the R_y observable as a function of the Λ_b polarisation. The solid line represents the theoretical prediction, the square points are the simulated R_y values for different Λ_b polarisation, the triangle points correspond to the R_y values after Monte Carlo events reconstruction and selection cuts and the dashed line is the theoretical prediction corrected for the reconstruction and acceptance effects.

The value of y_{MC} is extracted from a fully reconstructed unpolarised Λ_b semileptonic Monte Carlo sample using the same selection cuts. If both charged lepton energy and missing neutrino energy measurements agree well in data and Monte Carlo, the R_y value for an unpolarised Λ_b sample should be equal to unity. Any significant deviation of R_y from unity in the Λ_b sample will be considered as an evidence for Λ_b polarisation. To measure the Λ_b polarisation we need to know how R_y varies with Λ_b polarisation and figure 3 shows this before and after reconstruction and selection cuts. At the generator level, the theoretical prediction and Monte Carlo simulation agree very well. After reconstruction and selection cuts, there is a small shift which is taken into account using the following parametrization:

$$R^{corr}(\mathcal{P}_{\Lambda_b}) = R^{th}(\mathcal{P}_{\Lambda_b}) - 0.058 \times \mathcal{P}_{\Lambda_b} \tag{7}$$

obtained from Monte Carlo events samples produced with five different polarisation values (-1.0, -0.75, -0.5, -0.25, 0.0).

4 Background subtraction

Figure 4 shows the charged lepton and the neutrino energy distributions of the selected right-sign and wrong-sign $(\Lambda\pi^+)l$ combinations. To extract the average charged lepton energy and the average neutrino energy originating from the Λ_b semileptonic decays, one needs to know what is the fraction and the average charged lepton and neutrino energies of the background component in the right-sign $(\Lambda\pi^+)l^-$ combinations. These quantities can be determined by comparing the wrong-sign $(\Lambda\pi^+)l^+$ combinations with the background component in $q\overline{q}$ Monte Carlo events and both with the wrong-sign combinations in data.

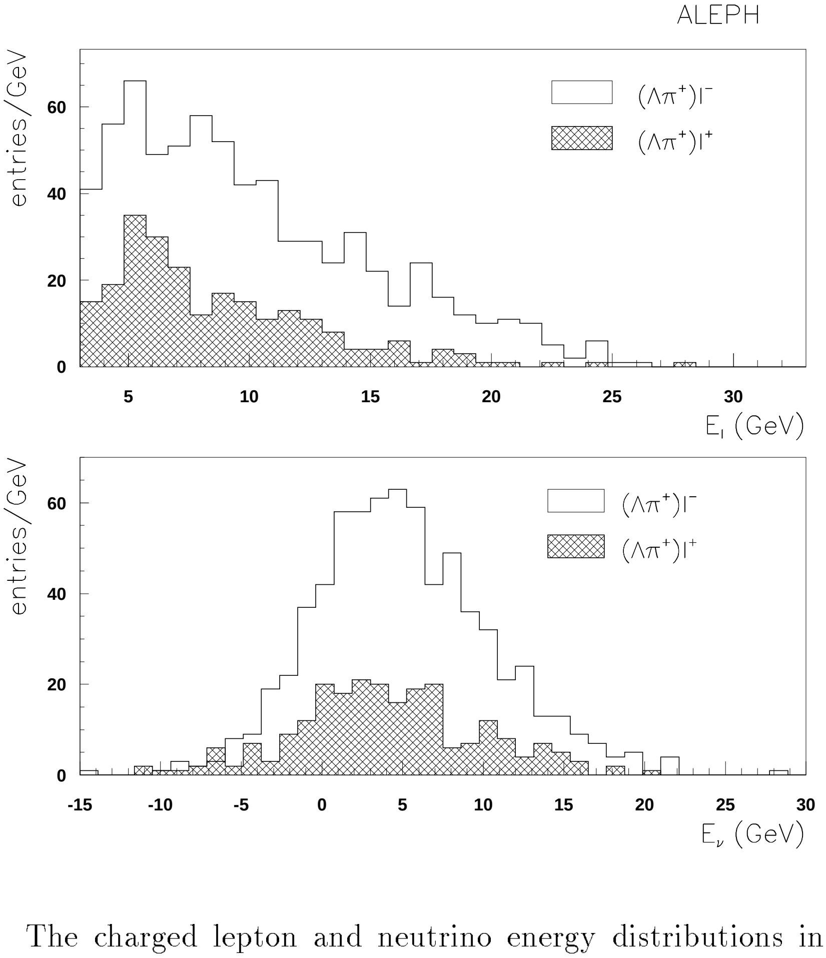

Figure 4: The charged lepton and neutrino energy distributions in the data for the selected right-sign (open histograms) and wrong-sign combinations (dashed histograms).

Table 1 shows the sample composition of the wrong and right-sign combinations selected from a sample of 3.8 million $q\overline{q}$ Monte Carlo events. The fractions of combinatorial background components in the right and wrong-sign combinations are

lepton sources	**right-sign**	**wrong-sign**
$b - baryons$	$66.8 \pm 1.9\%$	$14.3 \pm 1.4\%$
$b - mesons$	$21.7 \pm 1.5\%$	$19.9 \pm 1.5\%$
$c - baryons$	$0.6 \pm 0.3\%$	$1.9 \pm 0.5\%$
$c - mesons$	$7.1 \pm 1.0\%$	$7.2 \pm 1.1\%$
$others(K, \gamma)$	$0.5 \pm 0.2\%$	$0.5 \pm 0.2\%$
$fake$	$4.8 \pm 0.7\%$	$4.2 \pm 0.7\%$

Table 1: Monte Carlo sample composition of wrong and right-sign combination after Λ_b selection cuts. The fractions of the wrong-sign components are normalised to the total number of right-sign combinations.

wrong-sign	N_{events}	$\langle E_l \rangle$ (GeV)	$\langle E_\nu \rangle$ (GeV)
Data	233.0 ± 15.3	8.68 ± 0.28	3.89 ± 0.39
Monte Carlo	282.0 ± 16.8	8.67 ± 0.39	4.1 ± 0.29

Table 2: Comparison of the number of wrong-sign events and their average charged lepton and neutrino energies in data and in Monte Carlo. The selected wrong-sign Monte Carlo sample is normalized to 3 million $q\bar{q}$ events corresponding to the data.

basically the same. The fraction of b-baryon events in the wrong sign combinations is due to a combination between a lepton originating from Λ_b semileptonic decay and a Λ from fragmentation. Such a combination is suppressed in the right-sign sample, because the fragmentation Λ in the Λ_b semileptonic decay has a baryon number opposite to the one from the Λ_b cascade decay.

The comparison of the wrong-sign samples in data and Monte Carlo (table 2) shows that the numbers of wrong-sign combinations are equivalent within 2 σ and that the average charged lepton and neutrino energies are compatible. Furthermore, table 3 shows that the number of background events in the wrong-sign sample is equivalent, within errors, to the number of background events in the right-sign combinations and that their corresponding average charged lepton and neutrino energies are compatible within 1 σ.

Given that the fraction of signal events in the wrong-sign sample has the same average charged lepton and neutrino energies as the signal component in the right-sign sample, the average charged lepton energy and the average neutrino energy

Monte Carlo background	N_{events}	$\langle E_l \rangle$ (GeV)	$\langle E_\nu \rangle$ (GeV)
right-sign	258.0 ± 16.1	8.68 ± 0.26	3.81 ± 0.35
wrong-sign	244.0 ± 18.7	8.50 ± 0.27	3.53 ± 0.32

Table 3: Comparison of the number of background events in the right and wrong-sign events and their respective average charged lepton and neutrino energies in the Monte Carlo.

Sample	$\langle E_l \rangle$ (GeV)	$\langle E_\nu \rangle$ (GeV)	y
91-94	10.94 ± 0.34	5.59 ± 0.38	1.957 ± 0.145
Monte Carlo $q\bar{q}$	11.07 ± 0.41	6.47 ± 0.51	1.710 ± 0.150
Monte Carlo signal	10.55 ± 0.14	6.03 ± 0.16	1.752 ± 0.052

Table 4: The average charged lepton and neutrino energies of the selected Λ_b semileptonic decays in data and Monte Carlo and their corresponding y values.

originating from the Λ_b semileptonic decays can be extracted from the right-sign sample using the following background subtraction :

$$\langle E_{l,\nu} \rangle = \frac{1}{1 - f_{bck}} \left(\langle E_{l,\nu}^{RS} \rangle - f_{bck} \langle E_{l,\nu}^{WS} \rangle \right) \tag{8}$$

where $\langle E_{l,\nu}^{RS} \rangle$ and $\langle E_{l,\nu}^{WS} \rangle$ are the average charged lepton or neutrino energies in the right-sign and the wrong-sign samples respectively, and f_{bck} is the background fraction in the right-sign sample :

$$f_{bck} = \frac{N_{WS}}{N_{RS}}$$

N_{WS} and N_{RS} are the number of selected wrong-sign and right-sign events respectively. In data $f_{bck} = 0.33 \pm 0.02$.

5 Results

The y observable is determined from the average charged lepton $\langle E_l \rangle$ and neutrino $\langle E_\nu \rangle$ energies for both data and Monte Carlo events. For the latter an unpolarised Λ_b Monte Carlo sample is used. For comparison $q\bar{q}$ Monte Carlo events with unpolarised Λ_b events are also used. The results are presented in table 4. The y value from the $q\bar{q}$ Monte Carlo sample is similar to the one extracted from the background free Λ_b Monte Carlo signal. This shows that the background subtraction described in the previous section is well justified. The value of R_y is obtained from the ratio of y values in data and Monte Carlo signal. The result is :

$$R_y = \frac{y_{data}}{y_{MC}} = 1.119 \pm 0.088$$

The Λ_b polarisation is extracted from the comparison between the measured R_y value above and that expected for different Λ_b polarisation values as shown in figure 5. The result is : $\mathcal{P}_{\Lambda_b} = -0.28^{+0.20}_{-0.17}$, where the errors are statistical only.

A correlation exists between the statistical errors of the average charged lepton and neutrino energies and this has been studied using a fast Monte Carlo which reproduces the kinematic distributions of the final state particles in the Λ_b semileptonic decays. The correlation coefficients for the charm quark, the lepton and the neutrino momenta, as obtained from the fast Monte Carlo, show that there is a negative

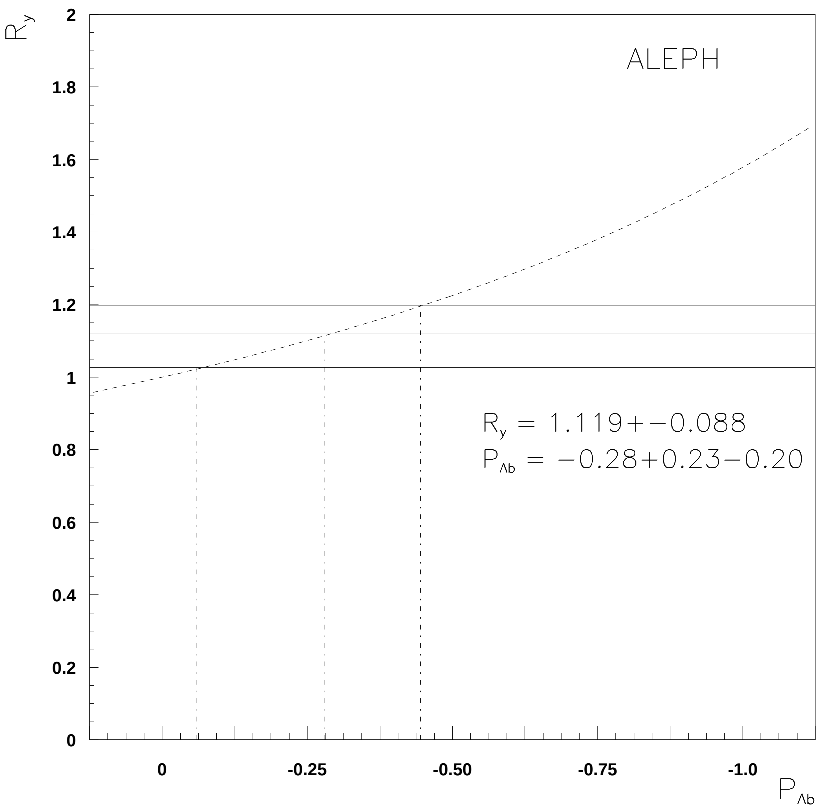

Figure 5: The method used to extract the Λ_b polarisation value. Comparison between the measured R_y value and the theoretical prediction.

correlation between any two Λ_b daughters, in the range of -12% to -28% depending on cuts. A negative correlation coefficient will reflect a positive fluctuation in the lepton sample into a negative fluctuation in the neutrino sample, resulting in a higher-than-statistical error for y. To determine the exact size of the error, the fast Monte Carlo was run for 500 samples of 500 events each, and a polarisation of 0, -0.25, -0.5, -0.75 and -1.0. The conclusion is that the statistical error needs to be multiplied by a factor of 1.15 ± 0.03 to take into account correlations between lepton and neutrino energies. Taking into account this correction factor, the measured Λ_b polarisation is :

$$\mathcal{P}_{\Lambda_b} = -0.28^{+0.23}_{-0.20}$$

6 Systematic checks

The Λ_b polarisation is determined from R_y which relies on a comparison of the average charged lepton energy and the average neutrino energy measurements in real data with that in the Monte Carlo. It is therefore crucial to have a good agreement

$\langle E_{lepton} \rangle$ (GeV)	**L1**	**L2**
Data	8.34 ± 0.02	10.26 ± 0.03
Monte Carlo ($q\bar{q}$)	8.26 ± 0.03	10.27 ± 0.05

Table 5: The average charged lepton energy in the two inclusive lepton control samples **L1** and **L2**.

between data and Monte Carlo for the charged lepton energy and the missing neutrino energy measurements.

6.1 Charged lepton energy

Charged leptons are well identified in the ALEPH detector and their momenta are well measured by the tracking system. The agreement of the charged lepton energy measurement in Monte Carlo and real data has been studied using two control samples selected from hadronic events :

- a sample **L1** with a $b\bar{b}$ tagged events [3] and a lepton selection (b-purity $\sim$ 96%).
- a sample **L2** with inclusive lepton selection and a lepton transverse momentum $p_T > 1$ GeV/c (b-purity $\sim$ 90%)

Table 5 compares the average lepton energy in Monte Carlo and real data from the two control samples. They agree within 100 MeV.

6.2 Neutrino energy

To study how well the missing energy measurement in Monte Carlo reproduces the one in data, four control samples selected in hadronic events were used:

- **A** : $b\bar{b}$ tagged events and lepton selection (b-purity $\sim$ 96%)
- **B** : light quarks tagged events[4] and lepton selection (b-purity $\sim$ 21%)
- **C** : $b\bar{b}$ tagged events and veto lepton selection (b-purity $\sim$ 90%)
- **D** : light quarks tagged events and veto lepton selection (b-purity $\sim$ 4%)

These four control samples are independent by construction. They allow an estimation of the possible bias in the missing energy measurement due to imperfection in the Monte Carlo simulation.

---

[3] the $b\bar{b}$ event selection makes use of the relatively long b lifetime and the precision of the VDET. The selection procedure is described in reference [13]

[4] the light quarks events selection uses the same algorithm as for $b\bar{b}$ events selection. The selection procedure is also described in ref. [13]

$\langle E_{miss} \rangle$ (GeV)	**A**(96% b)	**B**(21% b)	**C**(90% b)	**D**(4% b)
Data 1991-1994	6.100 ± 0.029	3.090 ± 0.024	1.033 ± 0.035	0.701 ± 0.012
Monte Carlo ($q\bar{q}$)	6.163 ± 0.033	3.267 ± 0.023	1.104 ± 0.036	1.003 ± 0.012

Table 6: The average missing energy in four control samples with different b-purity for data and $q\bar{q}$ Monte Carlo.

Table 6 shows the average missing energy in the four control samples for data and Monte Carlo. In the $b\bar{b}$ tagged samples, the data and Monte Carlo agree to within 70 MeV. In the lepton sample, which corresponds to our analysis sample, the agreement is at the 60 MeV level. For light quarks samples the shift in missing energy between data and Monte Carlo is in the $250 - 300$ MeV range.

The dependence of the average missing energy on the p_T cut on the lepton has also been studied. The difference $\Delta \langle E_{miss} \rangle$ between the average missing energies in data and in Monte Carlo for an inclusive lepton sample vary from 140 MeV (no p_T cut) to 220 MeV ($p_T < 1.$ GeV/c^2). The average missing energy in the Monte Carlo is at most 250 MeV higher than in the data.

As a supplementary check and in order to study the influence of particle identification on the missing energy, events containing identified protons, $K^{\pm}$, Λ or K_s^0 were selected in the tagged or the anti-tagged lepton hemisphere. The shifts between the average missing energies in data and Monte Carlo are in agreement with the inclusive samples.

Complementary checks on the missing energy measurements in data and Monte Carlo were performed using Monte Carlo events with different physics inputs such as the B^{**} fraction and the $b \to c \to l$ branching ratio. The agreement between real data and Monte Carlo is within ±300 MeV.

7 Systematic uncertainties

Several sources of systematic uncertainties have been considered. Their contributions to the total systematic error on the Λ_b polarisation measurement are summarized in table 7. They are listed and discussed below.

Lepton and neutrino energy measurements :

The missing energy measurement discussed in section 5 shows that the agreement between data and Monte Carlo is at the level of ± 300 MeV. Varying the average missing energy in the Λ_b semileptonic decay Monte Carlo sample within ± 300 MeV, leads to a systematic error of $^{+0.12}_{-0.11}$ on the measured Λ_b polarisation.

Similarly, varying the average charged lepton energy within the estimated ± 100 MeV difference between data and Monte Carlo, leads to a Λ_b polarisation error of ±0.02.

Background fraction :

The fraction of background events enters in the determination of the average charged lepton and neutrino energies. The difference between data and Monte Carlo in the number of wrong sign events is of the order of 20%, this corresponds to an error of ±7% with respect to the right-sign combinations. This error corresponds to a systematic uncertainty of $^{+0.03}_{-0.02}$ on the Λ_b polarisation.

Corrections due to reconstruction and selection cuts:

The theoretical curve which reproduces the variation of R_y with respect to the Λ_b polarisation, is used to extract the Λ_b polarisation. To take into account the effects of the reconstruction and the selection cuts on R_y, a correction has been introduced (see section 3.3). Varying this correction within its estimated error, leads to an uncertainty on Λ_b polarisation of ± 0.016.

Λ_c^+ polarisation :

The Λ_c^+ polarisation in Λ_b polarised events can affect the results of the present analysis because the cuts on the Λ momentum (at 3 GeV/c) and on the angle between the Λ and the charged lepton (45^o) can introduce biases due to the topological correlation between the spin states of the Λ_b and the Λ_c^+. A dedicated Monte Carlo was used to produce the decay chain :

$$\begin{array}{llll} \Lambda_b \longrightarrow & \Lambda_c^+ & l^- & \bar{\nu}_l \\ & \hookrightarrow & \Lambda & \pi^+ \end{array}$$

where both Λ_b and Λ_c^+ were considered polarised. The Λ_c^+ decay is weighed using the weighing function :

$$W(\cos\theta_\Lambda) = 1 + \alpha_{\Lambda_c}\mathcal{P}_{\Lambda_c}\cos\theta_\Lambda \tag{9}$$

where θ_Λ is the angle between the Λ and Λ_c^+ momenta in the Λ_c^+ rest system , $\mathcal{P}_{\Lambda_c}$ is the Λ_c^+ polarisation and α_{Λ_c} is the analysing power of the decay measured by CLEO and ARGUS experiments [14]:

$$\begin{array}{ll} \alpha_{\Lambda_c} = -1.0^{+0.4}_{-0.0} & (ARGUS) \\ \alpha_{\Lambda_c} = -0.98 \pm 0.42 & (CLEO) \end{array}$$

Varying the Λ_c^+ polarisation from 0. to -1.0, leads to a systematic uncertainty on the measured Λ_b polarisation of 0.04. Half this value is quoted as a systematic error and the central value is shifted by $+0.02$.

Theoretical errors :

Theoretical errors arise from three sources:

One is the unknown ratio of the charm and beauty masses which enter in the determination of y. Varying $(m_c/m_b)^2$ between 0.06 and 0.13, leads to a Λ_b polarisation change of 0.004.

Non perturbative corrections are known to appear only to $O(\Lambda_{QCD}/m_b)^2$ [7], which is a quantity of order 1% and is neglected.

Perturbative QCD corrections turn a small percentage of the decays into four body decays, due to the presence of a gluon, and produce a small degradation in

Source		$\sigma_{\mathcal{P}_{\Lambda_b}}$
Missing energy	±300 MeV	${}^{+0.12}_{-0.11}$
Lepton energy	±100 MeV	±0.02
Background fraction f_{bck}	33 ± 7%	${}^{+0.03}_{-0.02}$
Reconstruction and acceptance		±0.016
Λ_c^+ polarisation		±0.02
Theory (m_b/m_c, QCD)		±0.015
Total		${}^{+0.13}_{-0.12}$

Table 7: Systematic uncertainties

sensitivity. These corrections have been calculated in reference [15]. Varying α_s between 0.10 and 0.30 leads to an uncertainty on the Λ_b polarisation of ${}^{+0.011}_{-0.012}$.

8 Conclusions

The polarisation of Λ_b is measured using semileptonic decay events selected from a data sample of approximately 3 million hadronic Z decays collected with the ALEPH detector in 1991-1994. The Λ_b semileptonic decay events are selected using the correlation of the $(\Lambda\pi^+)$ system and the lepton in the same hemisphere of a hadronic Z decay. The final sample consists of 462 ± 22 Λ_b candidates. The ratio between the average charged lepton energy and average neutrino energy of these events is used to measure the Λ_b polarisation. This ratio is normalized to the one extracted from an unpolarised sample of Λ_b semileptonic Monte Carlo events.

The Λ_b polarisation is measured to be :

$$\mathcal{P}_{\Lambda_b} = -0.26^{+0.23}_{-0.20}(stat.)^{+0.13}_{-0.12}(sys.)$$

This result confirms the negative polarisation of the Λ_b sample produced at the Z peak. It corresponds to a lose of (73 ± 25)% of the initial b-quark polarisation in the process of fragmentation down to Λ_b. In the case where the lose of polarisation is due to Λ_b from Σ_b or Σ_b^* decays, this result suggests that the fraction of Λ_b originating from these two states is (73 ± 25)%.

Acknowledgements

We whish to thank our colleagues from the accelerator divisions for the successful operation of LEP. We are indebted to the engineers and technicians at CERN and our home institutes for their contribution to the good performance of ALEPH. Those of us from non member countries thank CERN for its hospitality.

References

[1] D. Buskulic *et al.*, (Aleph Collab.), Z. Phys. **C 59**, (1993), 369.

[2] F.E. Close, J. Korner, R.J.N. Phillips and D.J. Summers, J. Phys. **G 18**, (1992), 1716.

[3] A.F. Falk and M.E. Peskin, Phys. Rev. **D 49**,(1994),3320.

[4] M. Gronau, in *B decays* 2nd edition, ed. by S.Stone, p. 644, World Scientific, Singapore (1994).

[5] D. Decamp *et al.*, (Aleph Collab.), Z. Phys. **C 53**, (1992), 1.

[6] D. Decamp *et al.*, (Aleph Collab.), Nucl. Inst. and Meth. **A294**, (1990), 121; D. Buskulic *et al.*, (Aleph Collab.), Nucl. Inst. and Meth. **A346**, (1994), 461; D. Buskulic *et al.*, (Aleph Collab.), preprint CERN-PPE/94-170, submitted to Nucl. Inst. and Meth. **A**.

[7] J. Chay, H. Georgi and B. Grinstein, Phys. Lett. **B 247**, (1990), 399; A.V. Manohar and M.B. Wise, Phys. Rev. **D 49**, (1994), 1310.

[8] G. Bonvicini and L. Randall, Phys. Rev. Lett. **73**, (1994), 392.

[9] J. G. Korner and M. Kramer, Phys. Lett. **B 275**, (1992), 495; T. Mannel and G.A. Schuler, Phys. Lett. **B 279**, (1992), 194; G. Altarelli and B. Mele, Phys. Lett. **B 299**, (1993), 345; J.F. Amundson, J.L. Rosner, M. Worah and M.B. Wise, Phys. Rev. **D 47**, (1993), 1260.

[10] D. Decamp *et al.*, (Aleph Collab.), Phys. Lett. **B 257**, (1991), 492; B. Adeva *et al.*, (L3 Collab.), Phys. Lett. **B 270**, (1991) 111; P. Abreu *et al.*, (Delphi Collab.), Zeit. Phys. **C 53**, (1991), 567; P.D. Acton *et al.*, (Opal Collab.), Phys. Lett. **B 274**, (1992), 513.

[11] D. Buskulic *et al.*, (Aleph Collab.), Phys. Lett. **B 322**, (1994), 275.

[12] T. Sjostrand, Comp. Phys. Com. **82**, (1994), 74. Throught this analysis, a modified version of the JETSET 7.3 program was used to generate both $Z \to q\overline{q}$ events and Λ_b semileptonic decays. The generated Monte Carlo events are processed through a full simulation of the performance characteristics of the ALEPH detector.

[13] D. Buskulic *et al.*, (Aleph Collab.), Phys. Lett. **B 298**, (1993), 479.

[14] P. Avery *et al.*, (Cleo Collab.), Phys. Rev. Lett. **65**, (1990), 2842; H. Albrecht *et al.*, (Argus Collab.), Phys. Lett. **B 274**, (1992), 239.

[15] A. Czarnecki, M. Jezabek, J. Korner, and J. Kuhn, TTP 93-332, MZ-TH/**93-35**, hep-ph 9312249.