A measurement of the semileptonic branching ratio Br(b-baryon $\rightarrow \mathrm{p} l \bar{\nu} X$) and a study of inclusive π, K, proton production in Z decays

The ALEPH collaboration

Abstract

The inclusive π, K, and proton production has been investigated using data recorded by the ALEPH detector between 1992 and 1994. Using an algorithm on statistical base the momentum spectra and multiplicities have been measured in $\mathrm{Z} \rightarrow \mathrm{b\bar{b}}$, $\mathrm{Z} \rightarrow \mathrm{c\bar{c}}$ and $\mathrm{Z} \rightarrow \mathrm{u\bar{u}}, \mathrm{d\bar{d}}, \mathrm{s\bar{s}}$ decays separately. The number of protons found in b – hadron decays has been used to estimate the fraction of b baryons in b events to be $(12.1 \pm 0.9 \pm 3.1)\,\%$. From a study of proton – lepton correlations in b events Br(b – baryon $\rightarrow$ $\mathrm{p}l^- X$) $= (3.90 \pm 0.62 \pm 0.85)\,\%$ is obtained. The ratio Br(b – baryon $\rightarrow$ $\mathrm{p}l^- X$)/Br(b – baryon $\rightarrow \mathrm{p}X$) is found to be $0.078 \pm 0.012 \pm 0.014$.

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1 Introduction

The long pending discrepancy between theoretical predictions and measurements of the semileptonic branching ratio of heavy hadrons [1] was recently explained by calculations including higher order corrections [2]. However, the puzzle of the different lifetimes of b – mesons and b – baryons has remained. Theory predicts the ratio $\tau_{\mathrm{b-baryon}}/\tau_{\mathrm{B^0}}$ not to be smaller than approximately 0.9 [3] while present measurements yield a value of 0.73 ± 0.08 [4]. Under the assumption that the semileptonic widths of all b – hadrons are comparable this ratio can be probed independently by a measurement of the semileptonic branching ratios of b – baryons and mesons. If the different lifetimes would be real, a significant smaller semileptonic branching ratio is expected for b – baryons than for b – mesons.

Here the first measurement of the branching ratio $\mathrm{Br}(\mathrm{b-baryon} \to \mathrm{p}l^- X)$ is presented[1]. The evaluation of the absolute ratio required the knowledge of the overall number of b – baryons and hence also an estimate of the b – baryon fraction f_{Λ_b} (the probability of a b – quark to form a baryon during hadronization) is presented. It has been derived from the proton production in b – hadron decays.

Most of this paper concerns the evaluation of f_{Λ_b} and its main problem: to distinguish protons produced in b – hadron decays from other particles. The method used here is based on the impact parameter of the tracks and their angle with the thrust axis. The two variables are independent and display good separation power between leading and non – leading particles. Together with the specific energy loss in the TPC and a b tagging of events a statistical discrimination between protons from b – hadron decays and other particles has been achieved.

In parallel to the search for proton from b decays charged particle production has been studied in $\mathrm{Z} \to \mathrm{b\bar{b}}$, $\mathrm{Z} \to \mathrm{c\bar{c}}$ and $\mathrm{Z} \to \mathrm{u\bar{u}}, \mathrm{d\bar{d}}, \mathrm{s\bar{s}}$ events separately. The momentum spectra have been measured for pions, kaons and protons and the corresponding mean multiplicities have been calculated. These measurements are important for an understanding of the fragmentation of quarks and gluons into hadrons. At the same time the measurement of the rates and momentum spectra of particles produced in b – hadron decays helps to assure a correct description of the weak decay of b – hadrons in the Monte Carlo simulation.

The outline of the paper is the following: A brief description of the detector and its performance is given in section two. Event and track selection is described in section three. Section four discusses the particle identification with dE/dx and section five explains the selection of b decay particles. Section six deals with proton – lepton correlations. In section seven the systematic uncertainties of the analysis are discussed. Conclusions summarizing the results are presented in section eight.

[1] Charge conjugated modes are always included if not stated otherwise.

2 The detector

The ALEPH detector has been described in detail elsewhere [5],[6] and only a brief overview of the most relevant parts for this analysis is given here.
The momentum of charged particles is measured in three concentric tracking chambers. The most inner is the vertex detector consisting of two layers of double sided silicon microstrips with radii of 6.5 cm and 11.3 cm respectively. The spatial resolution for the $r\phi$ and z projections is 12μm at normal incidence. The vertex detector is surrounded by the inner drift chamber (ITC) with eight coaxial wire layers. Outside the ITC lies the time projection chamber (TPC) with an inner radius of 30 cm and outer radius of 180 cm. The TPC is 2.2 m long and measures up to 21 threedimensional space points per track. The three tracking detectors lie within a superconductive solenoid providing a magnetic field of 1.5 T, and together give a momentum resolution of $\sigma(p)/p = 6 \times 10^{-4} p_T \oplus 0.005$ (p_T in GeV/c).
The TPC also provides up to 338 measurements of the ionization loss of a track from the wires placed in the MWPC at the TPC end plates and is therefore essential for the identification of charged particles. A more detailed description of the ALEPH dE/dx measurement can be found in [6] and [7].
The TPC is surrounded by a lead/proportional-chamber electromagnetic calorimeter segmented into $0.9^\circ \times 0.9^\circ$ projective towers and read out in three sections in depth with an energy resolution of $\sigma(E)/E = 0.18/\sqrt{E} + 0.009$ (E in GeV). Among other things the electromagnetic calorimeter identifies electrons and photons by their characteristic longitudinal and transverse shower developments. Outside the electromagnetic calorimeter lies the iron return yoke of the magnet which is instrumented with streamer tubes to form a hadron calorimeter surrounded by two additional double layers of streamer tubes to aid in muon identification.
The selection of hadronic events is based on charged tracks and is described elsewhere [8]. The interaction point is reconstructed on an event-by-event basis using the constraint of the average beam spot position [6] resulting in an average resolution of 85 μm for $\to b\bar{b}$ events, projected along the sphericity axis of the event.

3 Event and track selection

The data have been recorded by the ALEPH detector during the years 1992 – 1994. Only events with a thrust axis fulfilling $|\cos\theta_{thrust}| < 0.85$ have been used. About 2.3 million hadronic Z decays have been selected. Further cuts have been applied on the quality of the tracks. Each track has at least four measured track points in the TPC and at least 125 single dE/dx wire measurements. The tracks have to originate from within a cylinder of radius 2 cm and length 10 cm centred on the nominal interaction point. The polar angle of the tracks has to fulfill $|\cos\theta_{track}| < 0.85$ and a minimum momentum of 300 MeV/c is required. To avoid the sizeable excess of protons over antiprotons due to interactions with the detector material only negatively charged tracks are selected for momenta lower than 2.8 GeV/c. These cuts result in more than 30 millions selected

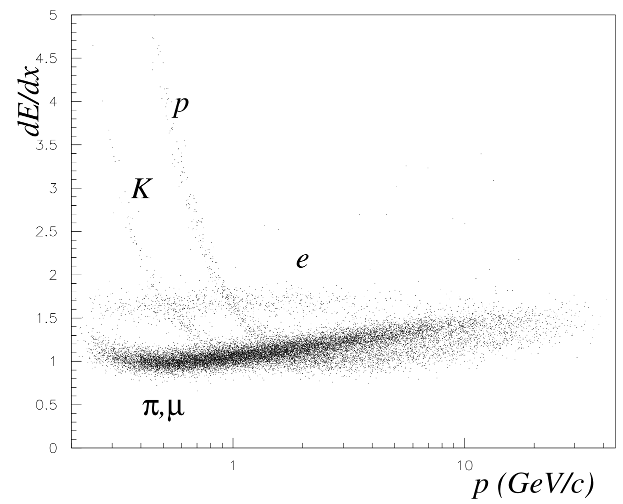

Figure 1: *The mean dE/dx of a sample of 20 000 tracks as a function of their momentum*

tracks.

4 Particle identification

Charged particles are identified by their specific energy loss in the TPC. Figure 1 shows the truncated mean dE/dx as a function of the momentum for selected tracks from hadronic events. From the dE/dx distribution an extended maximum likelihood fit is used to extract the number of pions, kaons and protons. The parametrization of the dE/dx probability density is similar to the one given in [7] but uses a 'bifurcated' Gaussian instead of a Gaussian (formula 2). The complete likelihood function is:

$$\mathcal{L} = \frac{e^{-\phi}\phi^N}{N!} \prod_{i=1}^{N} (\sum_j f_j G_i^j (dE/dx_{meas}^i, \langle dE/dx \rangle_{exp}^{ji}, \sigma_{ji}, \ldots)) \quad (1)$$

where the product runs over all tracks in each momentum bin. The different particle fraction are represented by f_j ($j = \pi, \mathrm{K}, \mathrm{p}, \mathrm{e}, \mu$ with the constraint $\sum_j f_j = 1$) and G_i^j is the individual dE/dx probability density for track i under the particle hypothesis j and depends on the measured mean dE/dx, the expected dE/dx $\langle dE/dx \rangle_{exp}^{ji}$ and the expected resolution σ_{ji}. The Poisson factor in front represents the probability of obtaining a sample of size N from a distribution of mean ϕ where ϕ is an additional free parameter in the fit. The dE/dx probability density has been parametrized as follows:

$$G^j(dE/dx) = \frac{2}{\sqrt{2\pi}(\sigma_1 + \sigma_2)} exp(-\frac{(dE/dx_{meas} - \langle dE/dx \rangle_{exp}^j)^2}{2\sigma_j^2}) \quad (2)$$

$$\text{with} \quad \sigma_j = \sigma_1 \quad \text{for} \quad dE/dx_{meas} < \langle dE/dx \rangle_{exp}^j$$

$$\text{and} \;\; \sigma_j = \sigma_2 \;\; \text{for} \;\; dE/dx_{meas} \geq \langle dE/dx \rangle_{exp}^j$$

σ_1 and σ_2 are defined as:

$$\sigma_2 / \langle dE/dx_{exp} \rangle = a \cdot \sigma_1 / dE/dx_{exp} = \sigma_0 {n_s}^{P_1} l^{P_2} \langle dE/dx \rangle_{exp})^{P_3} \qquad (3)$$

with a being a free parameter in the fit (which in general is found to be close to one). n_s stands for the number of single wire dE/dx measurements and l is the normalized mean sample length per wire measurement. The exponents P have been determined to be $P_1 = -0.5$ and $P_2 = P_3 = -0.4$ [9]. The expected energy loss per unit length is given by the Bethe – Bloch formula [10], a parametrization has been fit to the ALEPH data from all particles in the low β region and from pions at higher momenta. Muons are not distinguished in the fit. Their fraction is small with respect to the pions and hence it is fixed to the Monte Carlo prediction. The induced uncertainties, mainly on the pion rate, are minor.

Some examples of the likelihood fit are shown in figure 2 to illustrate its quality.

5 π, K, proton production

5.1 Decomposition of the track samples

All selected events have been divided into two hemispheres, defined by the plane perpendicular to the thrust axis. On each hemisphere a b tag has been applied. The performance of the b tag has been described in detail in [11]. Five b tag intervals have been defined and all tracks have been selected into one of these intervals according to the b tag result of the opposite hemisphere in the same event. Using the result of the opposite hemisphere is crucial to minimize a possible bias invoked by the b tag. Using the tracks in each subsample the likelihood fit results in the number of pion, kaons and protons for 50 different momentum bins. The composition of the particles regarding their origin can be described for each of the five samples i by:

$$N^i_{\pi,\mathrm{K,p}} = \epsilon^i_{\mathrm{b}} N^{\mathrm{b}}_{\pi,\mathrm{K,p}} + \epsilon^i_{\mathrm{c}} N^{\mathrm{c}}_{\pi,\mathrm{K,p}} + \epsilon^i_{\mathrm{uds}} N^{\mathrm{uds}}_{\pi,\mathrm{K,p}} \qquad (4)$$

where $N^{\mathrm{b}}_{\pi,\mathrm{K,p}}$, $N^{\mathrm{c}}_{\pi,\mathrm{K,p}}$ and $N^{\mathrm{uds}}_{\pi,\mathrm{K,p}}$ are the (unknown) number of pions, kaons or protons in b, c, and uds hemipheres. ϵ^i_{b}, ϵ^i_{c} and $\epsilon^i_{\mathrm{uds}}$ are the fractions of b, c or uds hemispheres which fall in the b tag interval i. The fractions ϵ^i can almost completely be derived from data following closely the method described in [11]. The number of hemispheres N^{H^i} within a specific b tag interval i can be written as

$$N^{H^i} = \epsilon^i_{\mathrm{b}} \cdot R_{\mathrm{b}} \cdot N^H_{tot} + \epsilon^i_{\mathrm{c}} \cdot R_{\mathrm{c}} \cdot N^H_{tot} + \epsilon^i_{\mathrm{uds}} \cdot R_{\mathrm{uds}} \cdot N^H_{tot} \qquad (5)$$

N^H_{tot} is the total number of hemispheres, R_{b} the ratio of partial widths $\Gamma_{\mathrm{Z}\to\mathrm{b\bar{b}}}/\Gamma_{\mathrm{Z}\to hadrons}$. R_{c} and R_{uds} are defined analogously to R_{b} . The number of events with both hemispheres in the same interval i is given by

$$N^{E^i} = {\epsilon_{\mathrm{b}}^{D}}^{i} \cdot R_{\mathrm{b}} \cdot N^E_{tot} + {\epsilon_{\mathrm{c}}^{D}}^{i} \cdot R_{\mathrm{c}} \cdot N^E_{tot} + {\epsilon_{\mathrm{uds}}^{D}}^{i} \cdot R_{\mathrm{uds}} \cdot N^E_{tot} \qquad (6)$$

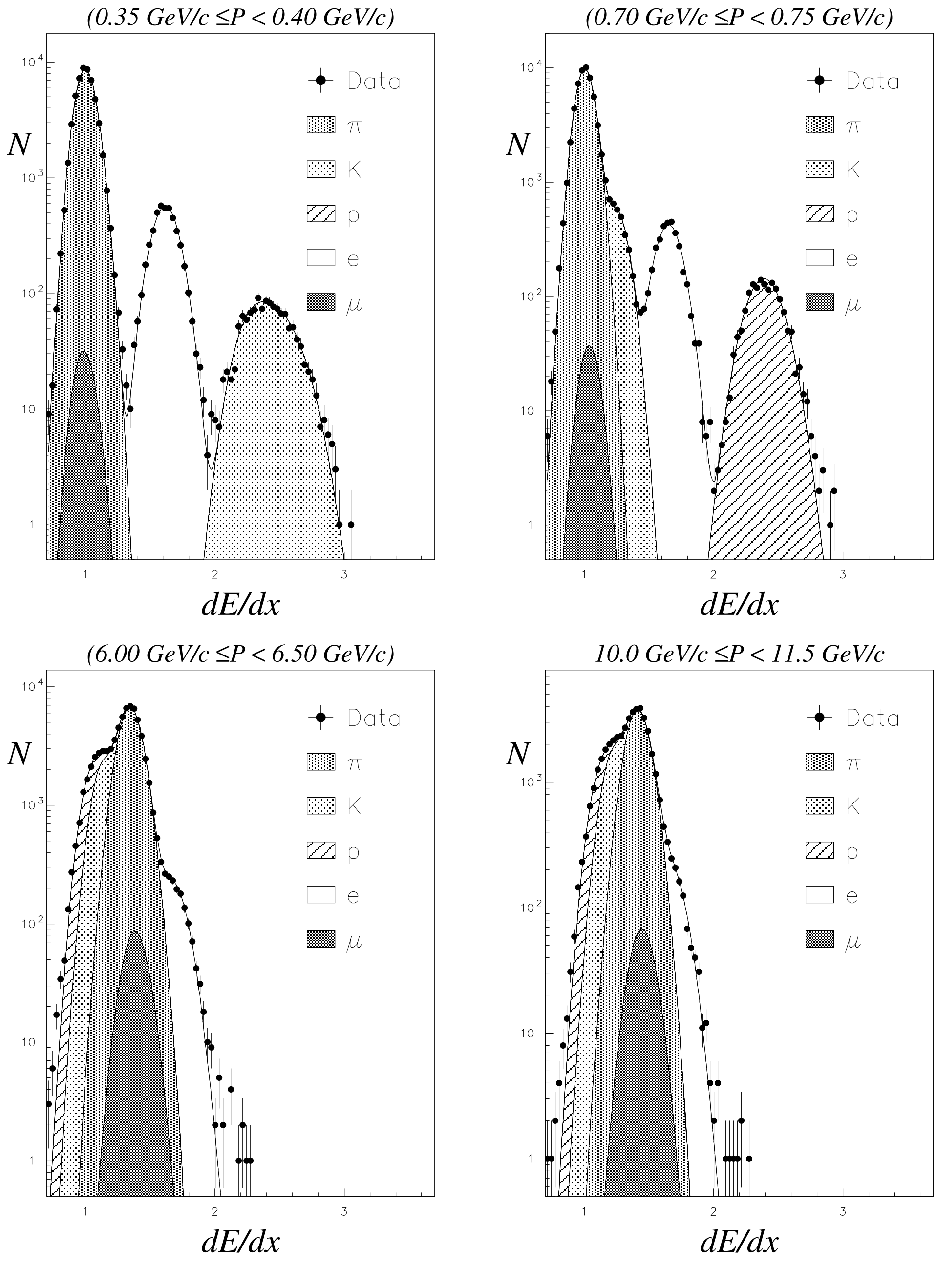

Figure 2: *Specific energy loss of selected particles together with the likelihood fit result in different momentum bins. The crosses represent the data, the hatched regions indicate the different particle fractions and the line is the overall fit function.*

$\epsilon^{D^i} = \lambda^i \epsilon^{i^2}$ with the factors λ^i taking account of the correlation between the two hemispheres (in the order of 10 %). The λ^i values have been taken from simulations. With the partial decay widths of the Z fixed to their Standard Model predictions and the constraint $\sum_i \epsilon^i_{flav} = 1$ (sum over the five b tag ranges, valid for all flavours separately) almost all fractions can be calculated from data. Only the three least significant values (of fifteen) have been fixed to their Monte Carlo predictions.

The number of pions, kaons and protons in $\mathrm{Z} \to \mathrm{b\bar{b}}$, $\mathrm{Z} \to \mathrm{c\bar{c}}$ and $\mathrm{Z} \to \mathrm{u\bar{u}, d\bar{d}, s\bar{s}}$ ($N^{\mathrm{b}}_{\pi,\mathrm{K,p}}$, $N^{\mathrm{c}}_{\pi,\mathrm{K,p}}$, $N^{\mathrm{uds}}_{\pi,\mathrm{K,p}}$) are now calculated from equation 4 in every momentum bin. The resulting momentum spectra are given in figures 7 to 9. They have been corrected for the effects of geometrical acceptance, track reconstruction efficiency and interactions in the material of the detector, using an event generator based on the DYMU [12] and JETSET 7.3 programs. The spectra have been normalized to the number of hadronic Z decays. The expectations of JETSET 7.3, which has been tuned to reproduce global event shape and charged particle inclusive distributions, are indicated by the overlaid curves. The 'holes' in the spectra correspond to those momentum regions where the dE/dx distributions of the different particle types overlap so heavily that the fit is no longer sensitive to the different particles fractions. These regions have been excluded from the analysis.

To measure the number of particles from b hadron decays the track samples have been further classified. Within each b tag interval the tracks have been divided into four classes: tracks with positive impact parameter, tracks with negative impact parameter, tracks with $|\cos\alpha| > 0.975$, where α is the angle between track and thrust axis, and tracks with $|\cos\alpha| < 0.975$. This leads to $5 \times 4 = 20$ different track samples and hence to 20 different equations per particle type, describing the particle composition in the different samples (the index $\pi, \mathrm{K, p}$ has been omitted):

$$\begin{aligned} N^i &= \epsilon^i_{\mathrm{b}}(\epsilon^{class}_{bdecay} \cdot N^{\mathrm{b}}_{decay} + \epsilon^{class}_{accomp} \cdot N^{\mathrm{b}}_{accomp}) \\ &\quad + \epsilon^i_{\mathrm{c}} \epsilon^{class}_{\mathrm{c}} N^{\mathrm{c}} \\ &\quad + \epsilon^i_{\mathrm{uds}} \epsilon^{class}_{\mathrm{uds}} N^{\mathrm{uds}} \end{aligned} \tag{7}$$

where N^i is the overall number of particles in the specific track sample. N^{b}_{decay}, N^{b}_{accomp}, N^{c} and N^{uds} are the number of particles from b decay, accompanying the b – hadron in a b event, from c events and from uds events. $\epsilon^{class}_{bdecay}$ is the fraction of particles from b decays fulfilling the criteria 'class' (positive/negative impact parameter, $|\cos\alpha| < 0.975 / > 0.975$). $\epsilon^{class}_{accomp}$, $\epsilon^{class}_{\mathrm{uds}}$ and $\epsilon^{class}_{\mathrm{c}}$ are defined analogously. All these fractions are taken from Monte Carlo simulations. As an example the fraction of protons with positive impact parameter from b – hadron decay is depicted in contrast to the accompanying protons in figure 3.

After performing the likelihood fit in each sample the numbers of pions, kaons and protons from b – hadron decays and accompanying the b – hadrons have been calculated from equation 7 for all momentum bins. Below 1 GeV/c the small number of protons from b decays is not accessible because of the high background of fragmentation protons.

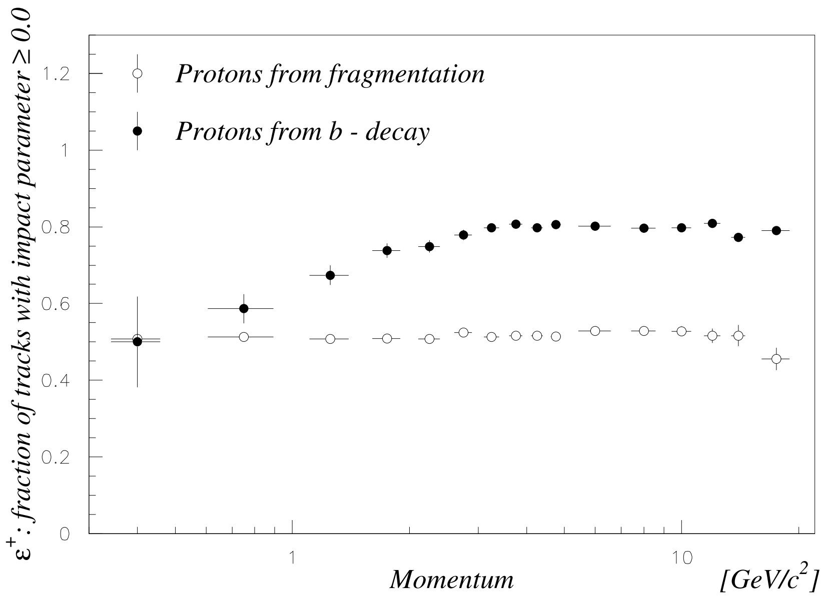

Figure 3: *Fraction ϵ^+ of protons with positive impact parameter depending on origin and momentum of the particle as predicted from Monte Carlo simulations.*

5.2 Multiplicities

The study of the particle production in different Z decays resulted in the momentum spectra of pion, kaons and protons in $Z \to b\bar{b}$, $Z \to c\bar{c}$, $Z \to u\bar{u}, d\bar{d}, s\bar{s}$ events, in b – hadron decays and of pion, kaons and protons accompanying the b – hadron in a b event. The spectra are shown at the end of the paper in figures 7 to 11, efficiency corrected and normalized to the number of hadronic Z decays. For comparison the JETSET 7.3 predictions are shown as well.
After extrapolating the spectra over the full kinematic range the corresponding mean multiplicities have been calculated. They can be found in the tables 1 to 3.

origin	$\pi^{\pm}$				
$Z \to q\bar{q}$	17.04	$\pm$	0.005_{stat}	$\pm$	0.31_{sys}
$Z \to uds$	16.86	$\pm$	0.02_{stat}	$\pm$	0.52_{sys}
$Z \to c\bar{c}$	15.93	$\pm$	0.07_{stat}	$\pm$	1.31_{sys}
$Z \to b\bar{b}$	18.44	$\pm$	0.03_{stat}	$\pm$	0.63_{sys}
b decay	3.97	$\pm$	0.02_{stat}	$\pm$	0.21_{sys}

Table 1: *Pion multiplicities in Z and b – hadron decays*

origin	$K^{\pm}$				
$Z \to q\bar{q}$	2.26	$\pm$	0.002_{stat}	$\pm$	0.12_{sys}
$Z \to uds$	2.14	$\pm$	0.008_{stat}	$\pm$	0.13_{sys}
$Z \to c\bar{c}$	2.44	$\pm$	0.03_{stat}	$\pm$	0.23_{sys}
$Z \to b\bar{b}$	2.63	$\pm$	0.008_{stat}	$\pm$	0.14_{sys}
b decay	0.72	$\pm$	0.020_{stat}	$\pm$	0.06_{sys}

Table 2: *Kaon multiplicities in Z and b – hadron decays*

origin	$p, \bar{p}$				
$Z \to q\bar{q}$	1.00	$\pm$	0.002_{stat}	$\pm$	0.07_{sys}
$Z \to uds$	1.04	$\pm$	0.006_{stat}	$\pm$	0.07_{sys}
$Z \to c\bar{c}$	0.87	$\pm$	0.02_{stat}	$\pm$	0.10_{sys}
$Z \to b\bar{b}$	1.00	$\pm$	0.007_{stat}	$\pm$	0.08_{sys}
b decay	.131	$\pm$	0.004_{stat}	$\pm$	0.011_{sys}

Table 3: *Proton multiplicities in Z and b – hadron decays*

Some multiplicities have been measured before by other LEP experiments. Comparisons with this analysis can be found in the tables 4, 5 and 6. In all cases the agreement is very good.

The proton production in b hadron decays as measured at LEP is found to differ significantly from the $\Upsilon(4S)$ value and is due to b – baryon production on the Z resonance.

Mean multiplicities in $Z \to q\bar{q}$			
	this analysis	DELPHI	OPAL
$\pi^{\pm}$	17.04 ± 0.31	—	17.05 ± 0.43
$K^{\pm}$	2.26 ± 0.12	2.26 ± 0.18	2.42 ± 0.13
$p, \bar{p}$	1.00 ± 0.07	1.07 ± 0.14	0.92 ± 0.11

Table 4: *Mean multiplicity of different particles in comparson with DELPHI [13] and OPAL [19].*

Mean multiplicities in $Z \to b\bar{b}$		
	this analysis	DELPHI
$\pi^{\pm}$	18.44 ± 0.63	—
$K^{\pm}$	2.63 ± 0.14	2.74 ± 0.50
$p, \bar{p}$	1.00 ± 0.08	1.13 ± 0.27

Table 5: *Mean multiplicities of different particles in $Z \to b\bar{b}$ in comparison with DELPHI results [13].*

Mean multiplicities in b – hadron decays			
	this analysis	DELPHI	ARGUS/CLEO
$\pi^{\pm}$	3.97 ± 0.21	—	4.11 ± 0.08
$K^{\pm}$	0.72 ± 0.06	0.88 ± 0.18	0.78 ± 0.03
$p, \bar{p}$	0.131 ± 0.011	0.141 ± 0.059	0.08 ± 0.004

Table 6: *Mean multiplicities of pions, kaons and protons in b – hadron decays in comparison to DELPHI measurements [13] and to measurements by ARGUS and CLEO in $\Upsilon(4S)$ decays [4]. In contrast to Z decays only $B^{\pm}$ and B^0 are produced there, leading to a significant lower proton production from b decays.*

5.3 The b – baryon fraction f_{Λ_b}

The overall number of protons from b – hadron decay has been used to estimate the b – baryon fraction f_{Λ_b}. The main idea is that Br(b-baryon $\to$ pX) is considerably bigger than Br(b-meson $\to$ pX) due to baryon conservation. Consequently even a small fraction of b – baryons should lead to a sizeable increase of protons in b – hadron decays with respect to pure meson sample as they are present e.g. in $\Upsilon(4S)$ decays.
The number of protons from b – hadron decays N_p is related to the b – baryon fraction as follows:

$$N_p = (f_{\Lambda_b} \cdot \mathrm{Br}(\text{b-baryon} \to \mathrm{p}X) + (1 - f_{\Lambda_b}) \cdot \mathrm{Br}(\mathrm{B} \to \mathrm{p}X)) \cdot N_b \tag{8}$$

N_b stands here for the number of b – hadron decays and is the number of events multiplied with two times R_b (using the Standard Model value for R_b). The equation can be resolved for f_{Λ_b}:

$$f_{\Lambda_b} = \frac{N_p/N_b - \mathrm{Br}(\mathrm{B} \to \mathrm{p}X)}{\mathrm{Br}(\text{b-baryon} \to \mathrm{p}X) - \mathrm{Br}(\mathrm{B} \to \mathrm{p}X)} \; . \tag{9}$$

To extract N_p the measured momentum spectra of b decay protons has been extrapolated from 3.75 GeV/c to zero using Monte Carlo prediction as indicated in figure

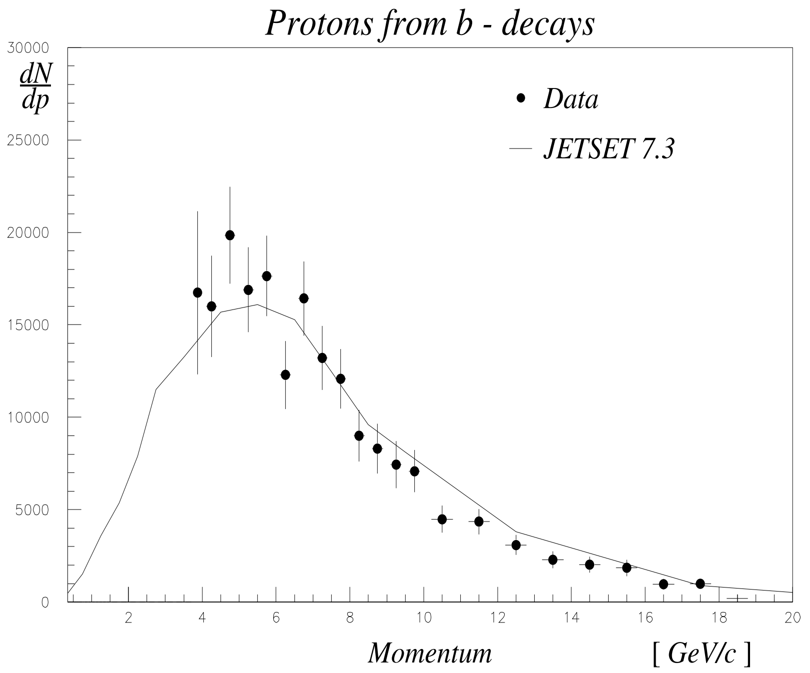

Figure 4: *Momentum spectra for protons from b decays: data and JETSET 7.3 prediction. The Monte Carlo has been normalized to the data.*

4. The branching ratio $\mathrm{Br}(\mathrm{B}^{\pm}, \mathrm{B}^0 \to \mathrm{p}X)$ has been measured on the $\Upsilon(4\mathrm{S})$ by ARGUS and CLEO to be $(8.0 \pm 0.4)\%$ but $\mathrm{Br}(\mathrm{B_s} \to \mathrm{p}X)$ is unknown. As a conservative estimate $\mathrm{Br}(\mathrm{B_s} \to \mathrm{p}X) = (8.0 \pm 4.0)\%$ has been assumed. The $\mathrm{B_s}$ fraction in b – events has been taken from [4]. Also Br(b-baryon $\to \mathrm{p}X$) has to be estimated because no measurements are available yet. Most naively Br(b-baryon $\to \mathrm{p}X$) is close to Br(b-baryon $\to \mathrm{n}X$) and hence about 50 %. But this assumption may not fully hold true, taking e.g. the decay via Λ or Σ particles into account which have different branching ratios into protons and neutrons. The branching ratio of b – baryons into Λ has been measured by DELPHI [13][2] and by OPAL [14] to be $0.17^{+0.11}_{-0.08}$ and 0.30 ± 0.10 respectively. The weighted average is 0.24 ± 0.08. Using Br(b-baryon $\to \Lambda X$) = 0.32 as an upper limit and assuming the other 67% of b – baryons to decay equally to protons and neutrons, Br(b-baryon $\to$ pX) would be 55 %. For a lower estimate Br(b-baryon $\to \Lambda X$) = Br(b-baryon $\to \Sigma^+ X$) = Br(b-baryon $\to \Sigma^0 X$) = Br(b-baryon $\to \Sigma^- X$) = 25 % and no direct protons production have been assumed. The outcome is Br(b-baryon $\to$ pX) = 45 %. Hence Br(b-baryon $\to$ pX) = (50 ± 5) % has been used for the calculation of the b – baryon fraction. The result is:

$$f_{\Lambda_\mathrm{b}} = (12.1 \pm 0.9_{stat} \pm 2.6_{sys1} \pm 1.8_{sys2})\,\% \qquad (10)$$

. Here the first systematic error represents uncertainties related to the analysis and the second uncertainties on the branching ratios. The systematic uncertainties of the measurement are discussed in section 7. The resulting baryon fraction can be compared

[2]The used number has not been taken from [13] but from [4] where it has been recalculated.

to the value $(13.2 \pm 4.1)\,\%$ calculated from the decay b-baryon $\rightarrow \Lambda_c l \bar{\nu} X$ and the b–baryon lifetime in [20][3] and is found to be in good agreement.

6 Proton – lepton correlation

For the search for proton lepton[4] pairs from b – baryon decays the analysis has been restricted to events containing a high momentum lepton candidate. (The selection of leptons within ALEPH is discussed in [15] and [16].) Some changes with respect to the analysis as described in the previous sections have been made: The angle between track and thrust axis has not beem used because of possible correlations with the transverse momentum of the lepton. The selection cuts for the tracks have been sightly released to gain efficiency. No b tag has been performed. The presence of a high momentum lepton candidate enriches sufficiently the event sample with b events.

The impact parameter of the proton candidates has again been used to measure their number in b decays while the p_T of the lepton was used to identify the proton lepton pairs from b – baryons and distinguish them from background processes. Possible background sources for proton lepton pairs are listed below:

1. Decay of the b – quark decay into $\bar{c}s$ with subsequent semileptonic c quark decay in $l^- X$. An example is the decay $\Lambda_b \rightarrow \bar{D}_s p X$, $\bar{D}_s \rightarrow l^- X$. Using Br(b $\rightarrow$ $c\bar{c}sX$, $\bar{c} \rightarrow lX$ = $(1.3 \pm 0.5)\,\%$ [17] and Br(b-baryon $\rightarrow$ pX) $\approx$ 50% about 0.7 % of all b – baryons are expected to contribute to this background. A similar assumption for mesons with Br(B $\rightarrow$ pX) = 0.08 leads to approximately 0.004 background events per b – baryon.

2. b-baryon $\rightarrow p\tau X$ with subsequent leptonic decay of the τ lepton. From the known branching ratio of $b \rightarrow \tau X$ one can conclude that about 0.17 % of all b – baryons contribute to this background source.

3. $B \rightarrow \Lambda_c \bar{p} X$ followed by a semileptonic decay of the Λ_c.

4. B $\rightarrow \bar{p} l X$ with a semileptonic decay of the b – quark.

5. The lepton is produced in pion or kaon decay, in photo conversion or is a misidentified hadron. These will be called 'fake leptons' in the following.

All background processes (which are summarized in table 7) show considerably softer lepton p_T spectra than the signal process.

Eight data sets have been selected: with the p_T of the lepton candidate between 0.0 and 0.5 GeV/c, 0.5 and 0.8 GeV/c, 0.8 and 1.2 GeV/c and with p_T greater than 1.2 GeV/c. Each set was divided into one sample containing tracks with positive impact parameters

[3] The quoted number has been taken from [4] where the result of [20] has been recalculated.
[4] 'lepton' stands for electron or muon

Composition of the proton lepton pair sample	
Source	number per b – baryon decay
b – baryon decays	free parameter
$\mathrm{b} \to \bar{\mathrm{c}}\mathrm{p}X, \bar{\mathrm{c}} \to l\nu X$	0.011
$\mathrm{b} \to \tau\nu\mathrm{p}X,\ \tau \to l\nu\nu$	0.002
$\mathrm{B} \to \Lambda_\mathrm{c}\bar{\mathrm{p}}X,\ \Lambda_\mathrm{c} \to l\nu X$	free parameter
$\mathrm{B} \to \bar{\mathrm{p}}l\nu X$	free parameter
$\mathrm{b} \to \mathrm{p}X+$ fake lepton	free parameter

Table 7: *Composition of the proton lepton sample where the protons come from b – hadron decay. As indicated two contributions have been fixed within the analysis, the rest have been left free.*

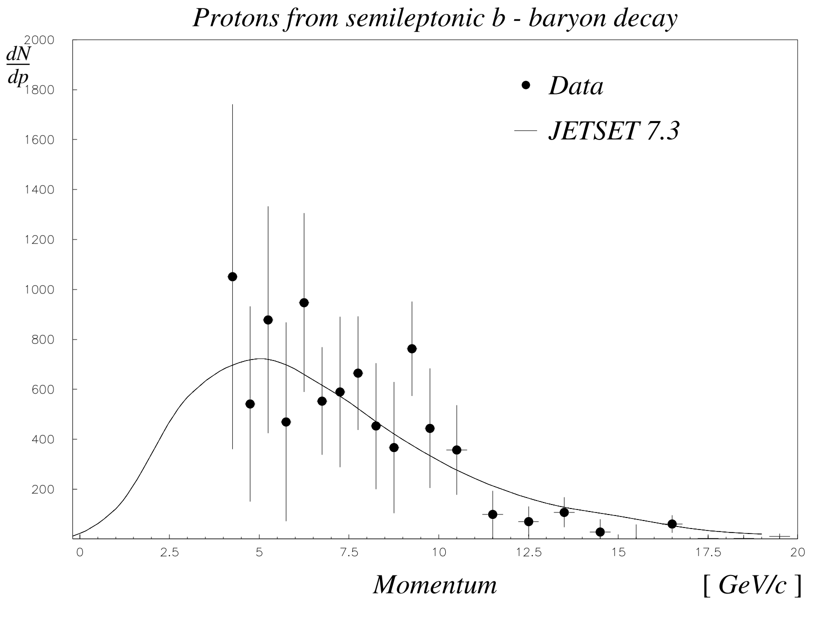

Figure 5: *The momentum spectrum of protons from semileptonic b – baryon decay (electrons and muons). The dots represent the data, the line the JETSET 7.3 prediction, normalized to the data*

and one containing tracks with negative impact parameters. The number of protons in each sample can be written as:

$$\begin{aligned} N^{pl}_{\hat{p_T},+} &= \epsilon^{+}_{\mathrm{b}} (\sum_x \epsilon^{x}_{\hat{p_T}} \cdot N^{x}_{\hat{p_T}}) + \epsilon^{+}_{non-b} N^{non-b}_{\hat{p_T}} \\ N^{pl}_{\hat{p_T},-} &= \epsilon^{-}_{\mathrm{b}} (\sum_x \epsilon^{x}_{\hat{p_T}} \cdot N^{x}_{\hat{p_T}}) + \epsilon^{-}_{non-b} N^{non-b}_{\hat{p_T}} \ . \end{aligned} \tag{11}$$

$N^{pl}_{\hat{p_T},+}$ is the measured number of proton – lepton pairs with a transverse momentum of the lepton in the p_T interval $\hat{p_T}$ and a proton with positive impact parameter. $N^{pl}_{\hat{p_T},-}$ is defined analogously but contains protons with negative impact parameter. $\epsilon^{x}_{\hat{p_T}}$ stands for the probability that a lepton from source x (b – baryon decay or one of the background processes described above) has a transverse momentum in the p_T interval $\hat{p_T}$. These numbers are taken from Monte Carlo. $\epsilon^{+}_{\mathrm{b}}$ stands for the fraction of protons from b – hadron decay having a positive impact parameter. ϵ^{+}_{non-b}, $\epsilon^{-}_{\mathrm{b}}$ and ϵ^{+}_{non-b} are defined analogously. To resolve the equations two background contributions had to be fixed to their expectation as indicated in table 7. The number of protons from b – baryon decays has then been calculated in different momentum bin. The result is given in figure 5. Extrapolating the spectrum to zero leads to

$$f_{\Lambda_\mathrm{b}} \cdot \mathrm{Br}(\text{b-baryon} \to \mathrm{p}l\nu X) = (4.72 \pm 0.66_{stat} \pm 0.44_{sys}) \cdot 10^{-3} \ . \tag{12}$$

This number is the average of $l = electron$ and $l = muon$ and can be compared with a measurement of DELPHI [21]: $f_{\Lambda_\mathrm{b}} \cdot \mathrm{Br}(\text{b-baryon} \to \mathrm{p}\mu X) = (4.9 \pm 1.1 \pm 1.3) \cdot 10^{-3}$. Together with $f_{\Lambda_\mathrm{b}} = (12.1 \pm 0.9 \pm 3.2)\,\%$ an absolute branching ratio can be calculated:

$$\mathrm{Br}(\text{b-baryon} \to \mathrm{p}l\nu X) = (3.90 \pm 0.62_{stat} \pm 0.59_{sys1} \pm 0.60_{sys2})\,\% \ . \tag{13}$$

One major uncertainty is $\mathrm{Br}(\text{b-baryon} \to \mathrm{p}X)$. However, the ratio $R_{pl} = \mathrm{Br}(\text{b-baryon} \to \mathrm{p}lX)/\mathrm{Br}(\text{b-baryon} \to \mathrm{p}X)$is only slightly dependent on this quantity as indicated in figure 6. If non – spectator amplitudes are small R_{pl} is close to $\mathrm{Br}(\text{b-baryon} \to lX)$. R_{pl} is found to be

$$R_{pl} = \frac{\mathrm{Br}(\text{b-baryon} \to \mathrm{p}lX)}{\mathrm{Br}(\text{b-baryon} \to \mathrm{p}X)} = 0.078 \pm 0.012_{stat} \pm 0.014_{sys} \ . \tag{14}$$

Within the spectator model R_{pl} can be compared with a recent OPAL measurement [14] of $R_{\Lambda l} = 0.070 \pm 0.012 \pm 0.007_{sys}$ with $R_{\Lambda l} = f_{\Lambda_\mathrm{b}} \cdot \mathrm{Br}(\text{b-baryon} \to \Lambda l X)/f_{\Lambda_\mathrm{b}} \cdot \mathrm{Br}(\text{b-baryon} \to \Lambda X)$ which is in very good agreement.

Assuming

$$\frac{\tau_{\text{b}-\text{baryon}}}{\tau_\mathrm{b}} \approx \frac{\mathrm{Br}(\text{b-baryon} \to lX)}{\mathrm{Br}(\mathrm{b} \to lX)} \tag{15}$$

one can compare the ratio of semileptonic branching ratios of b – baryons and all b – hadrons

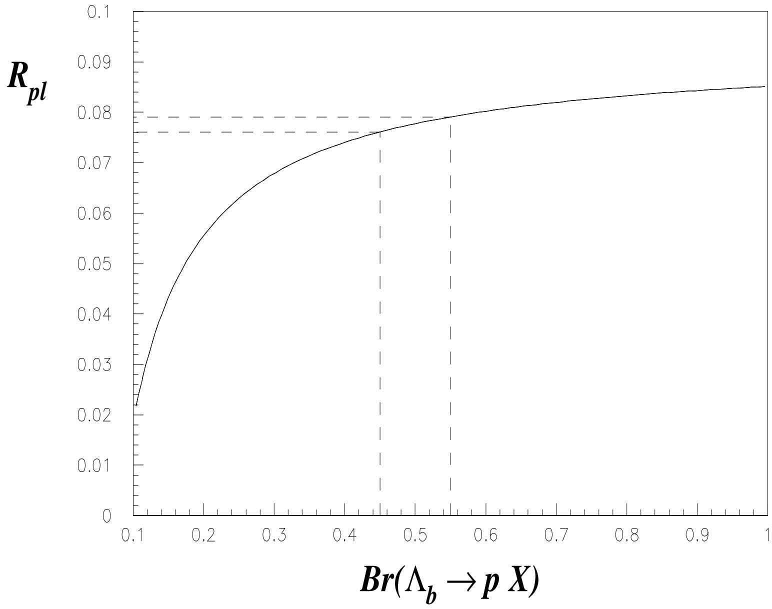

Figure 6: *The dependence of R_{pl} on $Br(b\text{-baryon} \to pX)$. R_{pl} varies only slightly with $Br(b\text{-baryon} \to pX)$ over a wide range. Allowing $Br(b\text{-baryon} \to pX)$ to vary between 0.45 and 0.55, R_{pl} changes only about 0.003. Towards smaller* $\mathrm{Br}(b\text{-baryon} \to pX)$ *the dependence increases significantly.*

$$\frac{R_{pl}}{\mathrm{Br}(\mathrm{b} \to lX)} = 0.70 \pm 0.16 \tag{16}$$

with $\mathrm{Br}(\mathrm{b} \to lX)$ taken from [4]. The corresponding ratio of lifetimes (taken from [4]) is:

$$\frac{\tau_{\mathrm{b-baryon}}}{\tau_{\mathrm{b}}} = 0.74 \pm 0.05\ . \tag{17}$$

The agreement is again very good.

7 Systematics

Several sources of systematic uncertainties affect the accuracy of the measurements. They are listed in table 8 and 9 together with the uncertainties due to the limited knowledge of the branching ratios Br(b-meson$\to pX$) and Br(b-baryon$\to pX$).

The fitted particle rates depend crucially on the expected dE/dx value and resolution entering the likelihood function. Therefore the expected dE/dx has been shifted within the uncertainties of the parametrization of the Bethe – Bloch formula (section 4). The resolution was rescaled and a Gaussian was used instead of a bifurcated Gaussian. In the overlap region the added uncertainties are 0.9 %, 4 % and 6.5 % for pions, kaons and protons respectively. The deviations of subsequent bins are correlated and

Composition of the systematic errors on f_{Λ_b}	
1. Systematic uncertainties from the analysis	
dE/dx	2.0 %
b tag	0.9 %
Imp. par. and $cos\alpha$.	1.0 %
Misc.	1.0 %
$\sum$	2.6 %
2. Systematic uncertainties from branching ratios	
Br(B $\rightarrow$ pX)	1.2 %
Br(b-baryon $\rightarrow$ pX)	1.4 %
$\sum$	1.8 %

Table 8: *The different contributions to the two systematic errors on f_{Λ_b}. The quoted errors are absolute.*

conservatively all momentum bins within the overlap region have been taken as 100 % correlated.

The sign of a track's impact parameter and its angle with the thrust axis have been used to distinguish particles from b – hadron decay from accompanying particles. Hence the result relies on the correct simulation of these two quantities in the Monte Carlo. Two checks have been performed: If one does not distinguish between decay and fragmentation particles the equation system 7 can be reduced to:

$$\begin{aligned} N_{all,i} &= \epsilon^i_\mathrm{b} N_\mathrm{b} + \epsilon^i_\mathrm{c} N_\mathrm{c} + \epsilon^i_\mathrm{uds} N_\mathrm{uds} \\ N^{class}_{all,i} &= \epsilon^{class}_\mathrm{b} \epsilon^i_\mathrm{b} N_\mathrm{b} + \epsilon^{class}_\mathrm{c} \epsilon^i_\mathrm{c} N_\mathrm{c} + \epsilon^{class}_{uds} \epsilon^i_\mathrm{uds} N_\mathrm{uds} \ . \end{aligned} \tag{18}$$

The fractions ϵ^{class} can be measured directly from the data and then be compared with the predictions. At very low and very high momentum ϵ^{class} is very close to $\epsilon^{class}_{accomp}$ and $\epsilon^{class}_{bdecay}$ respectively.

For the second check the number of particles from b – hadron decay has been calculated from the positive impact parameter alone and the result has been used to calculate the fraction fulfilling $|\cos\alpha| < 0.975$. In both cases the agreement between data and simulation is good and the maximum deviation has been taken as systematic uncertainty. This procedure takes automatically discrepancies between data and Monte Carlo into account which arises from different branching ratios or different decay chains of the b – hadrons.

The fraction of tracks from b decays having a positive impact parameter depends on the lifetime of the parent b – hadron. Because one of the motivations of this measurement was to test the difference in lifetimes between b – baryons and b – mesons consequently the found difference in the impact parameter distribution at different lifetimes has been taken into account in the systematic uncertainties but is not found to dominate them.

Several other sources of minor systematic uncertainties have been investigated: the b tag efficiencies, the reconstruction efficiencies, the muon fraction fixed in the likelihood

Overview over the systematic uncertainties on Br(b-baryon $\to plX$)	
1. Systematic uncertainties from the analysis	
dE/dx	0.39 %
b tag	0.29 %
Impact parameter	0.20 %
p_T spectra	0.16 %
lepton selection	0.08 %
Misc.	0.20 %
$\sum$	0.59 %
2. Systematic uncertainties from branching ratios	
Br(B $\to$ pX)	0.39 %
Br(b-baryon $\to$ pX)	0.46 %
$\sum$	0.60 %

Table 9: *The different contributions to the two systematic uncertainties on $Br(b - baryon \to plX)$. The errors are absolute.*

fit, the efficiency correction of particles from nuclear interactions and the extrapolation of the measured momentum spectra over the whole momentum range.

Most of the uncertainties discussed above are also present in the proton lepton analysis and partly cancel when the ratio $f_{\Lambda_b} \cdot$ Br(b-baryon $\to$ p$l\nu X)/f_{\Lambda_b}$ is built. Additional uncertainties are due to lepton identification and to the simulation of the lepton p_T spectra [15], [16]. The impact of the fixed branching ratios (b $\to$ c$\bar{\text{c}}$s with semileptonic $\bar{\text{c}}$ decay and b-baryon $\to \tau$pX) is small. Variations of 50% lead to a negligible effects. The modelling of the p_T lepton spectra of the background processes is of minor importance compared to the modelling of the signal distribution. The uncertainty was estimated from the divergence between different theoretical predictions for b – meson decay as described e.g. in [16]. In addition the rate of four body semileptonic b – baryon decays has been varied from 0 % to 40 % and the Λ_b polarization as measured by ALEPH in [18] was considered. The systematic uncertainties on Br(b-baryon $\to$ p$l\nu X$) are listed in table 9.

8 Conclusions

The momentum spectra and mean multiplicities have been measured for pions, kaons and protons in Z $\to$ b$\bar{\text{b}}$, Z $\to$ c$\bar{\text{c}}$ and Z $\to$ u$\bar{\text{u}}$, d$\bar{\text{d}}$, s$\bar{\text{s}}$ separately. In b events particles from b – hadron decay have been distinguished from non – leading particles. The b – baryon fraction and the absolute semileptonic branching ratio Br(b-baryon $\to$ pl$\bar{\nu}$X) have been evaluated from a study of proton and proton lepton production in b – hadron decays. The b – baryon fraction has been derived from the overall number of protons from b decays and has been found to be

$$f_{\Lambda_b} = (12.1 \pm 0.9_{stat} \pm 2.7_{sys_1} \pm 1.9_{sys_2})\% \ . \tag{19}$$

This result led to the measurement of the absolute branching ratio of the decay $\mathrm{b-baryon} \rightarrow \mathrm{pl}\bar{\nu}$.

$$\mathrm{Br(b\text{-}baryon} \rightarrow \mathrm{p}lX) = (3.90 \pm 0.62_{stat} \pm 0.59_{sys1} \pm 0.60_{sys2})\% \ . \tag{20}$$

The ratio R_{pl} =Br(b – baryon $\rightarrow$ pl^-X)/Br(b – baryon $\rightarrow$ pX) has been found to be

$$R_{pl} = 0.078 \pm 0.012_{stat} \pm 0.014_{sys} \ . \tag{21}$$

The relatively small semileptonic branching ratio supports the small lifetime of b – baryons with respect to b – mesons as measured at LEP.

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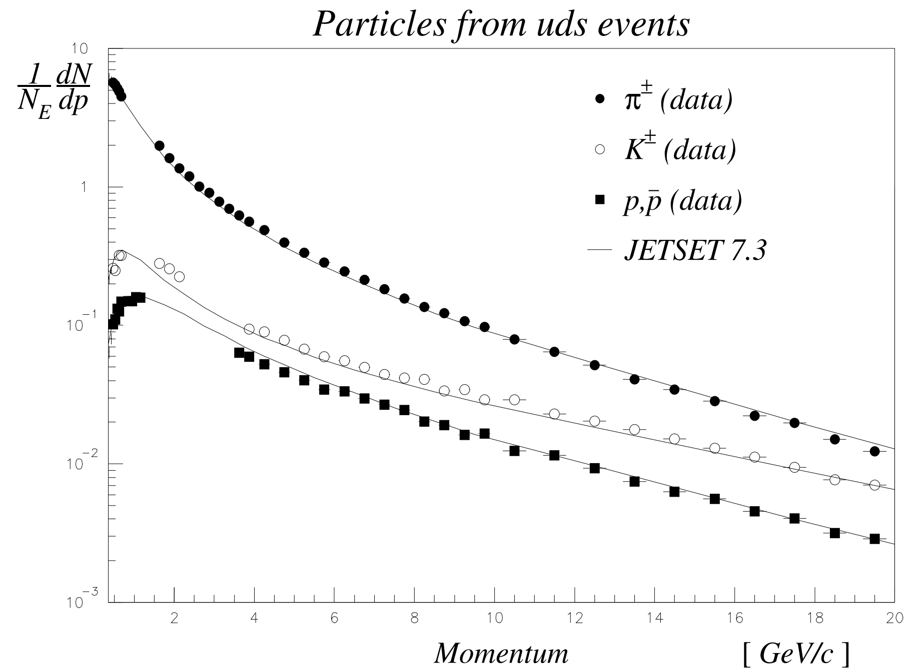

Figure 7: *Momentum spectra from pions, kaons and protons in uds events together with the JETSET predictions. The errors shown are the quadratic sum of statistical and systematic errors.*

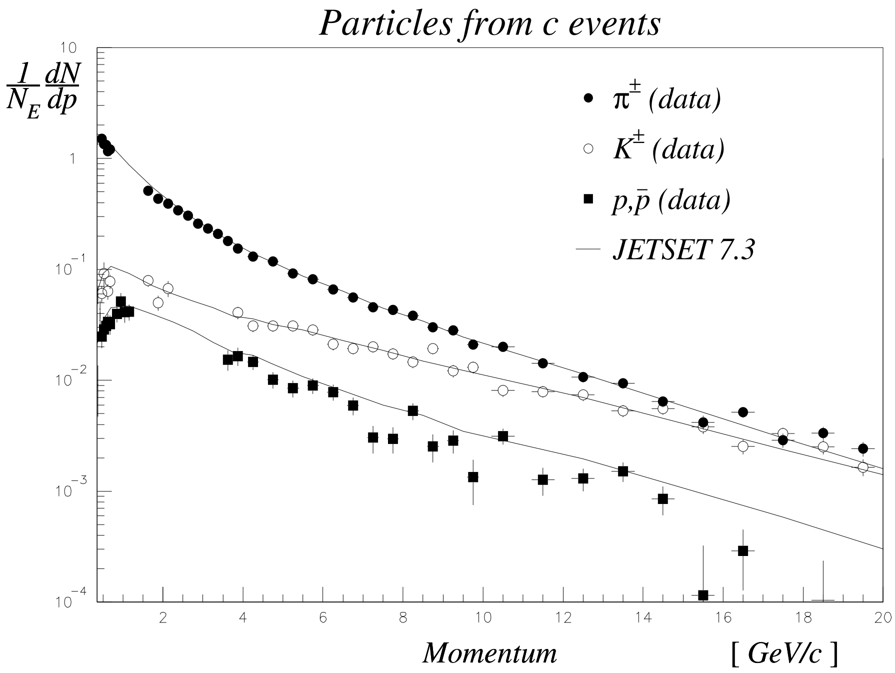

Figure 8: *Momentum spectra from pions, kaons and protons in c events together with the JETSET predictions. The errors shown are the quadratic sum of statistical and systematic errors.*

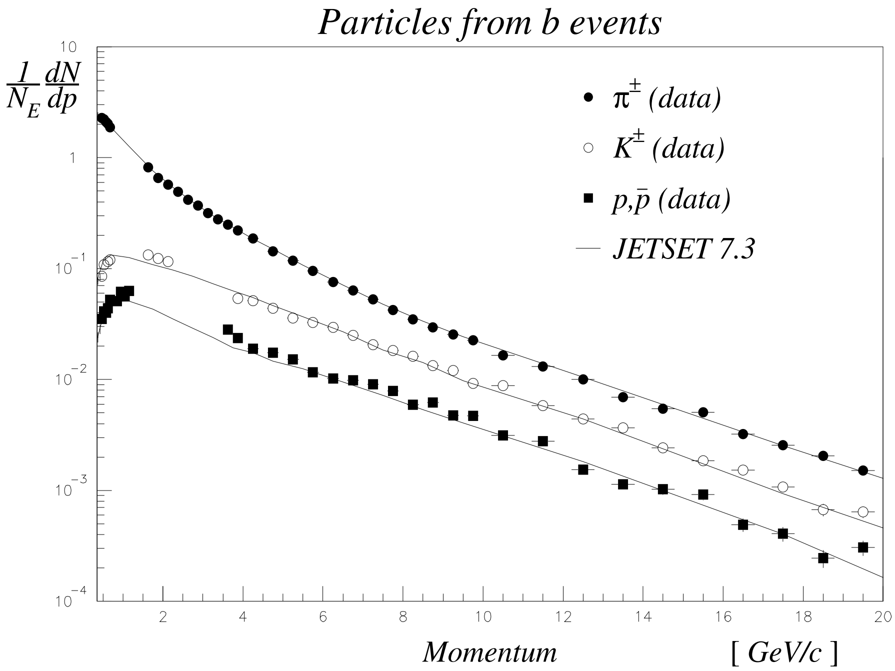

Figure 9: *Momentum spectra from pions, kaons and protons in b events together with the JETSET predictions. The errors shown are the quadratic sum of statistical and systematic errors.*

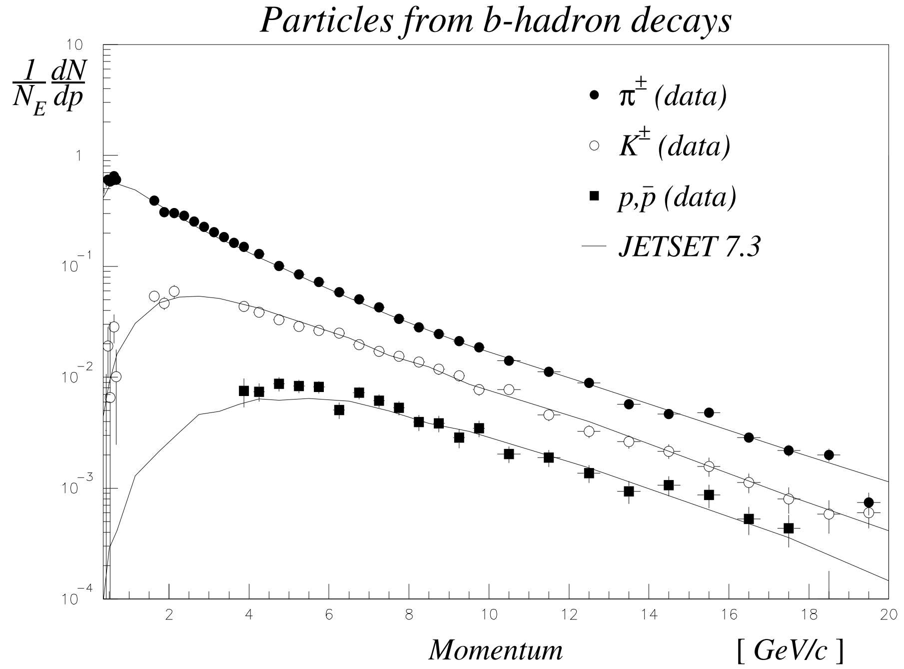

Figure 10: *Momentum spectra from pions, kaons and protons from $b-$hadron decays together with the JETSET predictions. The errors shown are the quadratic sum of statistical and systematic errors.*

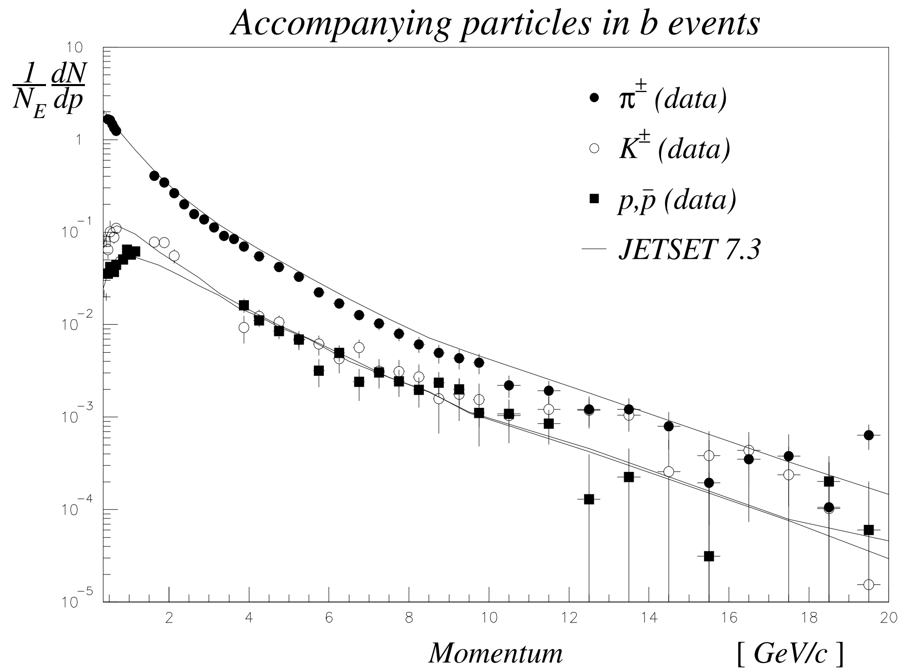

Figure 11: *Momentum spectra of pions, kaons and protons accompanying $b-$hadrons in b events together with the JETSET predictions. The errors shown are the quadratic sum of statistical and systematic errors.*

References

[1] I.I.Bigi, B.Blok, M.Shifman, A.Vainshtein, CERN – TH.7082/93

[2] E.Bagan, P.Ball, V.M.Braun, P.Gosdzinsky, Nucl.Phys. B432 (1994) 3; Phys.Lett. B342, (1995) 362 E.Bagan, P.Ball, B.Fiol, P.Gosdzinsky, Phys.Lett B351 (1995) 546

[3] M.Neubert, CERN-TH/96 – 55 (1996), to appear in International Journal of Modern Physics A

[4] Particle Data Group, *Review of Particle Physics*, Phys.Rev. D54 (1996) 1

[5] ALEPH collaboration, NIM A294 (1990) 121

[6] ALEPH collaboration, NIM A360 (1995) 481

[7] ALEPH collaboration, Z.Phys C66 (1995) 355

[8] ALEPH collaboration, Z.Phys C60 (1993) 71

[9] R.Assmann, R.Johnson, Z.Feng, ALEPH – 94 – 116 (1994)

[10] H.A.Bethe, Ann.Phys 5 (1930) 324
F.Bloch, Z.Phys 81 (1933) 363

[11] ALEPH collaboration, Phys.Lett.B313 (1993) 535

[12] J.E.Campagnea and R.Zitoun, Z.Phys. C42 (1989) 469

[13] DELPHI collaboration, Nucl.Phys. B444 (1995) 3, recalculated in [4]

[14] OPAL collaboration, CERN – PPE/96 – 166 (1996) submitted to Z.Phys.

[15] ALEPH collaboration, NIM A346 (1994) 461

[16] ALEPH collaboration, Z.Phys C62 (1994)179

[17] ALEPH collaboration CERN – PPE/96 – 072

[18] ALEPH collaboration, pa01 – 072 contributed paper ICHEP 96, Warsaw, Poland

[19] OPAL collaboration, Z.Phys. C63 (1994) 181

[20] ALEPH collaboration, Phys.Lett. B359 (1995) 236

[21] DELPHI collaboration, Z.Phys C68 (1995) 375