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A precise measurement of the average b hadron lifetime

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The ALEPH Collaboration

Abstract

An improved measurement of the average b hadron lifetime is performed using a sample of 1.5 million hadronic Z decays, collected during the 1991-1993 runs of ALEPH, with the silicon vertex detector fully operational. This uses the three-dimensional impact parameter distribution of lepton tracks coming from semileptonic b decays and yields an average b hadron lifetime of $1.533 \pm 0.013 \pm 0.022$ ps.

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1 Introduction

Precise measurements of the lifetimes of the various species of b hadrons are of interest for studying the weak decay of the b quark. The individual B meson and b baryon lifetimes are expected to differ by at most 10% [1] and as the present measurements have not reached this accuracy, there remains an interest in a precision measurement of the average lifetime in order to constrain the exclusive measurements. The measurement described in this letter yields an average over the lifetimes of all the hadrons containing a b quark, weighted by their production rates in Z decay and their semileptonic branching ratios.

Several measurements of the average b lifetime have been performed in the past at e^+e^- and $p\bar{p}$ colliders [2], and a remarkable improvement in the experimental uncertainty has been achieved by the LEP experiments using the large number of boosted b hadrons produced at the Z resonance. This measurement is an update of the previous ALEPH published value [3]. A high purity sample of semileptonic b decays is selected by means of the characteristically high transverse momentum of the leptons with respect to the jet axis. Then the impact parameter distribution of the lepton tracks, relative to the reconstructed primary vertex, is used to measure the b hadron lifetime via a maximum likelihood fit. This new measurement profits from an increase in statistics of almost a factor of 5. In addition, an improved fitting procedure, based on the calculation of the impact parameter in three dimensions, allows a reduction of the systematic errors.

2 The detector and the event selection

The ALEPH detector is described in detail in reference [4]. Only a brief description is given here.

A high resolution vertex detector, consisting of two layers of double-sided silicon microstrip detectors, is positioned at the core of the tracking system [5]. Each layer provides measurements in both the $r\phi$ and rz views at average radii of 6.3 and 10.8 cm, with a spatial resolution of 12 μm for the $r\phi$ coordinate and, depending on the track polar angle, between 12 and 22 μm for the z coordinate. The inner and the outer layers cover 85% and 69% of the solid angle. The vertex detector is surrounded by the Inner Tracking Chamber (ITC) and the Time Projection Chamber (TPC). The ITC is a cylindrical drift chamber which provides up to 8 points per track in the $r\phi$ view at radii from 16 to 26 cm. The TPC reconstructs up to 21 space points per track at radii between 40 and 171 cm. The tracking detectors are immersed in an axial magnetic field of 1.5 T, providing a measurement of the momentum of charged particles with a resolution $\delta p_t/p_t = 0.0006\, p_t \oplus 0.005$ (p_t in GeV/c). The TPC also provides up to 338 measurements of the specific ionization (dE/dx) of each charged track. For electrons in hadronic events, the dE/dx resolution is 4.5% for 338 ionization samples. The electromagnetic calorimeter (ECAL), which surrounds the TPC and is completely contained within the superconducting coil of the magnet, is a lead proportional tube calorimeter, segmented into $0.9^\circ \times 0.9^\circ$ projective towers and read out in three separate longitudinal stacks. The calorimeter is used to measure the electromagnetic energy with a resolution of $\delta E/E \sim 18\%/\sqrt{E}$ and, together with the TPC, to identify electrons. The hadron calorimeter (HCAL) is composed of the iron of the magnet return yoke interleaved with 23 layers of streamer tubes, and is surrounded by two layers of streamer tubes to enhance the identification of muons.

From the data recorded in the 1991, 1992 and 1993 runs, 1.5 million hadronic events are selected as described in reference [6]. Semileptonic b decays are selected by requiring the presence of a lepton candidate with momentum p greater than 3 GeV/c and transverse momentum p_t, relative to the associated jet axis, greater than 1 GeV/c. Jets are reconstructed in each event with the JADE scaled invariant mass algorithm [7] ($y_{\mathrm{cut}} = 0.0045$) using charged tracks and the energy deposition of neutral particles. The lepton is included in the determination of the jet axis. Electrons are identified using the shower shape in the ECAL and the dE/dx information

Muons	%	Electrons	%
$b \to \mu$	80.8%	$b \to e$	88.0%
$b \to (c/\tau) \to \mu$	8.0%	$b \to (c/\tau) \to e$	8.2%
$c \to \mu$	3.3%	$c \to e$	3.0%
Misidentified hadrons	4.1%	Misidentified hadrons	0.5%
π and K decays	3.8%	γ conversions	0.3%

Table 1: Monte Carlo lepton sample composition.

of the TPC. The candidates identified as coming from photon conversion are rejected using the method described in [8]. Electron candidates are required, as in [3], not to have radiated a bremsstrahlung photon which can be detected by searching for additional energy deposition in the region of the electromagnetic calorimeter close to the electron cluster. Muons are selected using the pattern of digital hits in the hadron calorimeter and requiring one associated hit in the muon chamber. Full details of lepton identification in ALEPH are described elsewhere [9].

The candidate lepton track is required to have at least 10 hits in the TPC, 4 hits in the ITC and 2 hits in each projection of the VDET, a χ^2/DOF of the track helix fit less than 3 and an impact parameter less than 5 mm. Tracks compatible with K^0 and Λ decays are rejected. The strong requirement on the VDET hits reduces the number of tracks which are badly reconstructed due to a wrong assignment of hits in the vertex detector.

The final data sample contains 19844 lepton candidates of which 12197 are identified as muons and 7647 as electrons. The efficiency for the electron sample is lower, due to the dE/dx requirement.

A Monte Carlo sample of about 3 million simulated hadronic events, generated using the Lund parton shower model (JETSET 7.3) [10], is also analysed. After having applied the cuts described above for the data, lepton candidates are selected and the composition of the sample is derived, as shown in table 1.

3 The impact parameter

The three-dimensional impact parameter is defined as the distance of closest approach in space between the lepton track and the estimated b production point. The impact parameter is signed positive (negative) if the point of closest approach between the lepton track and the b direction, estimated by the jet axis, is in the same (opposite) hemisphere as the track. The hemisphere is defined by the plane perpendicular to the b direction and containing the estimated b production point. However, in contrast to the previous analysis [3], the absolute value of the impact parameter is used as input to the lifetime fit, avoiding the uncertainty in the jet axis direction. Nevertheless, the negative sign of the impact parameter is used to select tracks without lifetime contribution for resolution studies.

The error on the impact parameter for each candidate, σ_δ, is obtained by combining the tracking error, which includes the contribution from multiple scattering, with the error in the estimation of the b production point. The two errors are combined using the covariance matrices of the track and vertex fits.

The b production point or primary vertex, is reconstructed for each event with a technique designed to give an accurate estimate of the position and error even for $Z \to b\bar{b}$ events. The method combines the beam spot position, found by averaging a group of 75 consecutive Z decays, with the track information of the particular event. The tracks are associated to their nearest jet, defined in terms of angular separation, and they are projected into the plane perpendicular to this jet. This projection removes the bias due to tracks coming from secondary vertices, in the approximation that the jet axis reproduces the direction of the decaying particle. The projected tracks are then combined with the beam spot position to find the primary vertex. The beam spot size is around 150 μm horizontally and smaller than 10 μm vertically and the position is determined with a precision of 20 μm and 10 μm respectively. This method yields a typical primary vertex resolution of about 50 μm for the horizontal coordinate, 10 μm for the vertical, and 60 μm along the beam direction. The resulting impact parameter resolution for the selected lepton tracks is about 70 μm, as obtained from Monte Carlo events.

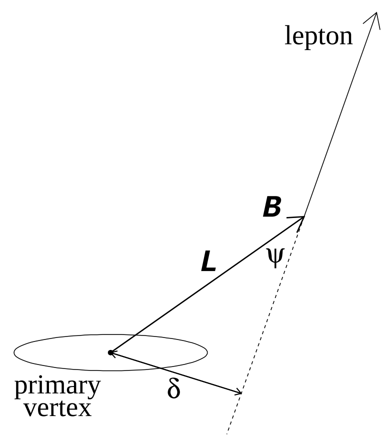

Figure 1: Definition of the impact parameter.

4 Lifetime extraction

The impact parameter of a lepton track coming from a b hadron decay is directly related to the proper decay time of the b hadron. As shown in fig. 1, the impact parameter δ, is determined by the relation $\delta = L \sin\psi$, where L is the decay length of the b hadron and ψ is the angle in space between the b direction and the lepton track in the laboratory frame. By expressing L as a function of the proper decay time t_b, and ψ as a function of the decay angle in the b center of mass, θ^*, the impact parameter becomes

$$\delta = ct_b \frac{\beta \sin\theta^*}{1 + \beta\cos\theta^*}, \tag{1}$$

where β is the b hadron velocity. At LEP the b hadrons are produced with high momentum, $\beta \approx 1$, and therefore the impact parameter is to a good approximation independent of the b momentum. The above relation shows also that the impact parameter is proportional to the proper decay time. This can be expressed by introducing a factor k, which depends on quantities related to the lepton kinematics:

$$\delta = \frac{ct_b}{k}; \qquad k = \frac{1 + \beta\cos\theta^*}{\beta\sin\theta^*}. \tag{2}$$

Based on this relation, the observed impact parameter distribution of the lepton tracks from b decays can be expressed as a convolution of three functions: an exponential decay distribution for the b proper time, a k factor distribution $K(k)$ for the kinematics of the semileptonic decay, and a resolution function G which describes the smearing due to detector effects on the impact parameter measurement

$$P\left(\delta_{\mathrm{rec}}\right) = \exp\left(-t/\tau_b\right) \otimes K\left(k\right) \otimes G\left(\left(\delta_{\mathrm{rec}} - \delta_{\mathrm{true}}\right)/\sigma_\delta\right), \tag{3}$$

where δ_{rec} and δ_{true} are the reconstructed and true impact parameters. The average b lifetime is then extracted by an unbinned maximum likelihood fit to the impact parameter distribution. In the same way as in the previous analysis, the observed distribution of all the selected muon and electron candidates can be described as the sum of five different components (shown in table 1) which contribute to the lepton candidate samples.

The expected impact parameter distribution for each component x is described by a probability density function P_x weighted by the fraction of candidate leptons f_x arising from that particular source. Different probability functions are used for six different ranges of the momentum of the lepton candidates, as there is a correlation between the decay angle and the lepton momentum enhanced by the p_{t} selection cut. The lepton source fractions are estimated from the Monte Carlo for the six ranges of lepton momentum. The average values are shown in table 1.

The likelihood function is then built up as the product of the total probability density functions for the N selected lepton candidates:

$$\begin{aligned}\mathcal{L} \;=\; & \prod_{j=1}^{N}[f_b P_b(\tau_b, \delta_j, \sigma_{\delta_j}) + f_{bc} P_{bc}(\tau_b, \delta_j, \sigma_{\delta_j}) + f_c P_c(\delta_j, \sigma_{\delta_j}) + \\ & f_{\mathrm{mis}} P_{\mathrm{mis}}(\delta_j) + f_{\mathrm{dec}} P_{\mathrm{dec}}(\delta_j)],\end{aligned} \tag{4}$$

where δ_j and σ_{δ_j} are the impact parameter and the relative error for the j^{th} candidate. The average b hadron lifetime τ_b is then determined as the only free parameter of the fit.

The probability density functions for the prompt lepton sources ($b \to \ell$, $b \to c \to \ell$ and $c \to \ell$) are obtained by performing the convolution with the k factor distribution (equation 3). For each source of prompt leptons, six different $K(k)$ distributions are used depending upon the lepton momentum. The K distributions are determined from Monte Carlo events, as the ratio between the true lepton impact parameter and the parent hadron proper time. Fig. 2 shows the six K distributions for $b \to \ell$ leptons. The convolution with the decay exponential and the resolution function is then performed numerically by binning the K distribution. In the case of cascade leptons, the additional decay path of the c hadrons is taken into account. An exponential distribution with an average c hadron lifetime of $\tau_c = 0.72$ ps is used to obtain the probability functions for the third ($c \to \ell$) component.

Different resolution functions have been also used in the lifetime fit for different bins in the lepton momentum to take into account a momentum dependence of the resolution. Each resolution function is estimated in Monte Carlo events from the distribution of the difference between the true and the measured impact parameter divided by the measured error, as shown in fig. 3. In addition, a correction factor is applied to take into account a possible difference in the tracking resolution between data and Monte Carlo. This correction factor is obtained from the negatively signed part of the impact parameter distribution of hadron tracks in a mainly light quark sample of data and Monte Carlo events selected with an anti-b-tag algorithm in the opposite hemisphere [11] (fig. 4).

The expected impact parameter distribution for the misidentified hadrons is obtained for each range of momentum from the impact parameter distribution of hadron tracks selected in the data with the same kinematic cuts as the candidate leptons. A parametrisation with a central positive gaussian and two exponential tails is used. The exponential tails are due to tracks which come from b decays. The impact parameter distribution for the non-prompt leptons, like muons from π and K decays, is determined from $Z \to q\bar{q}$ Monte Carlo events.

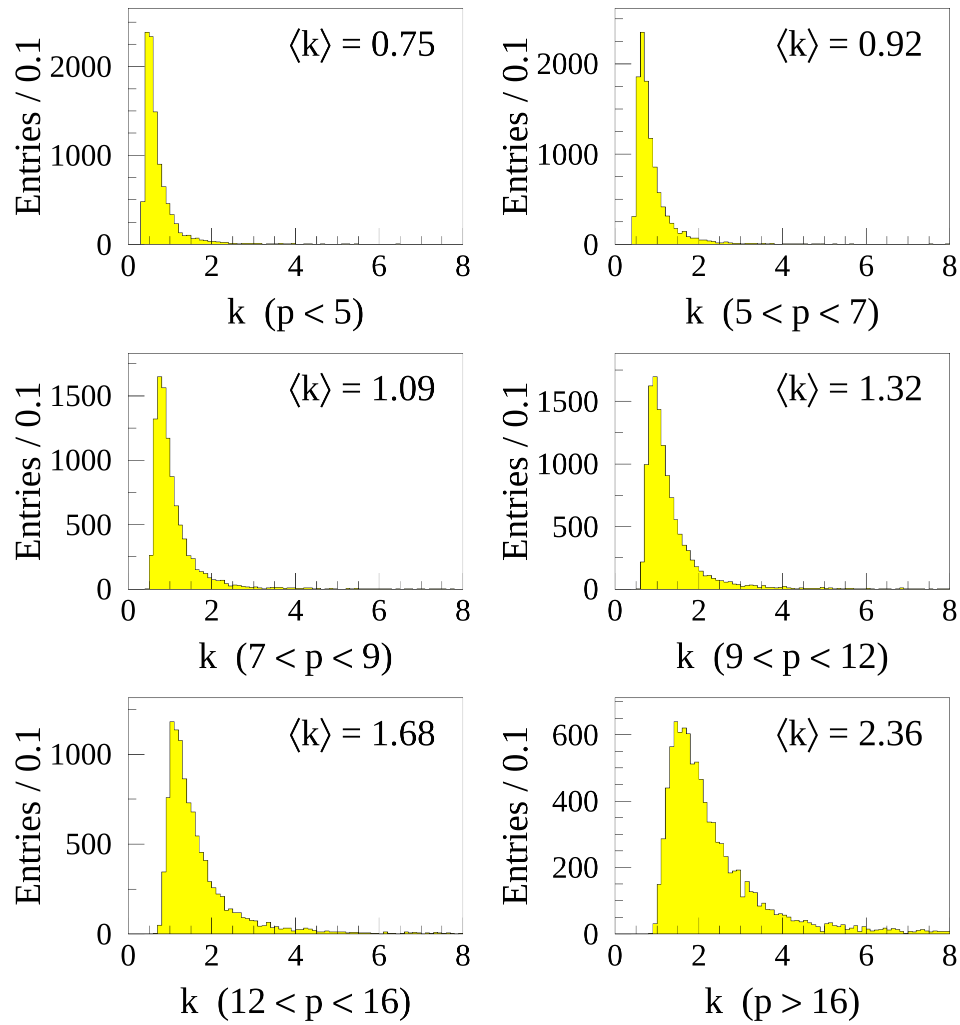

Figure 2: k distributions for $b \to \ell$ leptons. Each distribution is obtained for a specific range of lepton momentum (given in GeV/c)

An unbinned maximum likelihood fit is performed to the data samples collected in the years 1991, 1992, and 1993. Different resolution functions and different weights for the lepton components are used for each year to take into account small differences in the tracking performances and in the lepton identification efficiencies from year to year. The likelihood fit yields an average b hadron lifetime of $\tau_b = 1.511 \pm 0.034$ ps in the 1991 data, $\tau_b = 1.543 \pm 0.020$ ps in the 1992 and $\tau_b = 1.531 \pm 0.020$ ps in the 1993. A combined fit to all three years yields a result of $\tau_b = 1.533 \pm 0.013$ ps. Fig. 5 shows the observed impact parameter distribution together with the fit function and the different predictions for the various components.

5 Consistency checks

The analysis procedure is checked for possible systematic effects. To check that the lifetime extraction procedure is unbiased, the full analysis is applied to samples of Monte Carlo events and to test the various components of the probability density function, the lifetime fit is

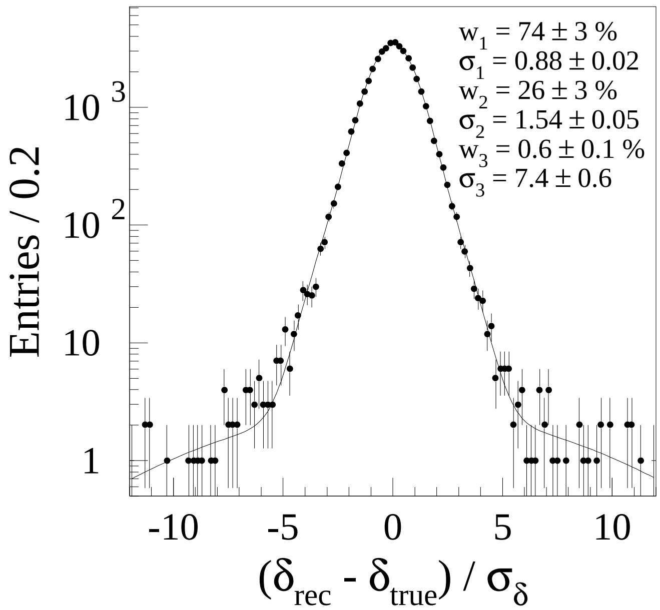

Figure 3: Resolution function from Monte Carlo lepton tracks. $\delta_{\rm rec}$ and $\delta_{\rm true}$ are the reconstructed and true impact parameters. The curve is the result of a three-gaussian fit to the points. The w_j and σ_j are the area fractions and widths of each gaussian.

performed on the simulated data classified on the basis of the true information of the lepton sources. In particular, the full fit applied to two samples of $Z \to q\bar{q}$ Monte Carlo events, with a size comparable to the real data, generated with b lifetimes of 1.3 and 1.5 ps, yields $\tau_b^{\rm fit} - \tau_b^{\rm MC} = -0.003 \pm 0.007$ ps and $\tau_b^{\rm fit} - \tau_b^{\rm MC} = 0.002 \pm 0.007$ ps respectively, where the quoted error is only statistical.

Other checks are employed by fitting the b lifetime in two different and uncorrelated subsamples of data with similar statistics. The data are divided using particular cuts which could isolate particular systematic effects. The following divisions are employed:

- electron-muon separation, in order to isolate effects due to bremsstrahlung or muon background;
- horizontal-vertical separation, which can show biases due to the size and position of the beam or to correlations between the impact parameter and the azimuthal angle ϕ;
- separation between a central region and a forward-backward region to check the dependence of the impact parameter resolution on the polar angle θ;
- forward-backward separation, which could show differences due to the two halves of the TPC;
- charge separation.

The fit results of the two subsamples are compared; if the relative difference is bigger than the combined statistical error, a systematic distortion could be present. The fitted results, shown in fig. 6, are in good agreement and all the observed deviations can be explained as statistical fluctuations.

A further check is performed by fitting the lifetime in data samples isolated by varying the kinematic selection cuts of total and transverse momentum. This checks the stability of the

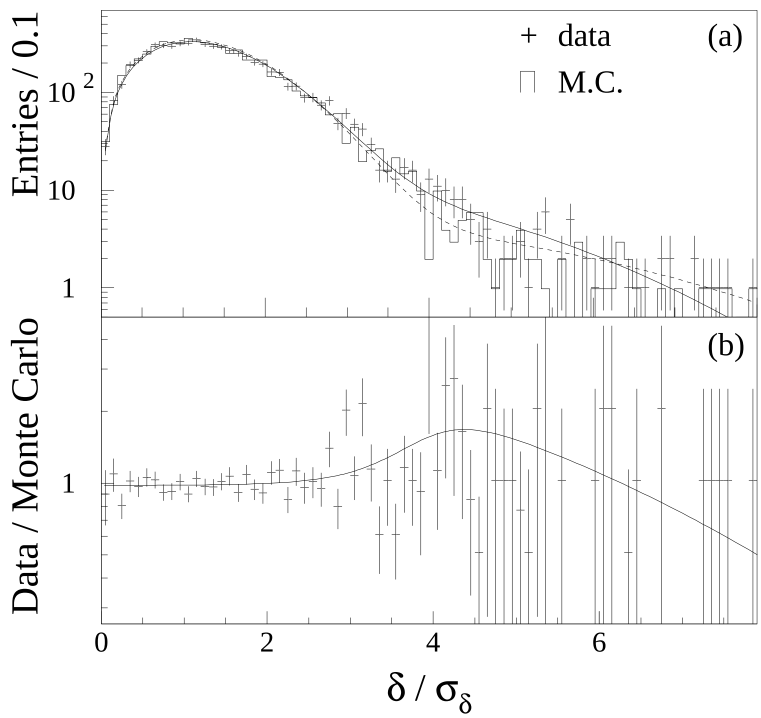

Figure 4: (a) Impact parameter distribution of hadron tracks in *uds* events in data and Monte Carlo. The tracks have a negative impact parameter but the absolute value is plotted. The solid curve is the result of the fit to the data points, while the dashed curve is the Monte Carlo fit result. In (b) the ratio of the two distributions and the ratio of the two curves are plotted.

measurement as a function of the cuts. The momentum cut modifies the impact parameter distribution, in particular the K distribution and the sample composition. The $p_{\rm t}$ cut changes mainly the sample composition, rejecting leptons coming from c hadron decays. Any trend in the fitted values as a function of the cut would indicate the presence of a bias.

The stability plots of the lifetime as a function of the p and $p_{\rm t}$ cuts are shown in fig. 7. The observed deviations can be accounted as statistical fluctuations with a total probability of 23% for the p plot and 45% for the $p_{\rm t}$.

6 Systematic errors

The dominant systematic uncertainty is due to an incomplete knowledge of the hadronization and decay processes of the heavy flavours. Both the K distributions and the source lepton fractions are obtained from simulated events and therefore they are influenced by these physical uncertainties. In order to be consistent with other heavy flavour analyses that are based on the lepton tag and are performed at LEP, a common treatment of b and c quark physics has been employed, following the prescriptions given by the LEP electroweak heavy flavour group [12]. A consistent set of input values is used in the determination of the central value of the measurement, while the corresponding systematic error is estimated varying each parameter inside the defined range. The values of the parameters are implemented in the Monte Carlo by assigning appropriate weights to the events. The main sources of uncertainties, which are common in all analyses based on the lepton tag, are

- semileptonic decay model of b and c hadrons;

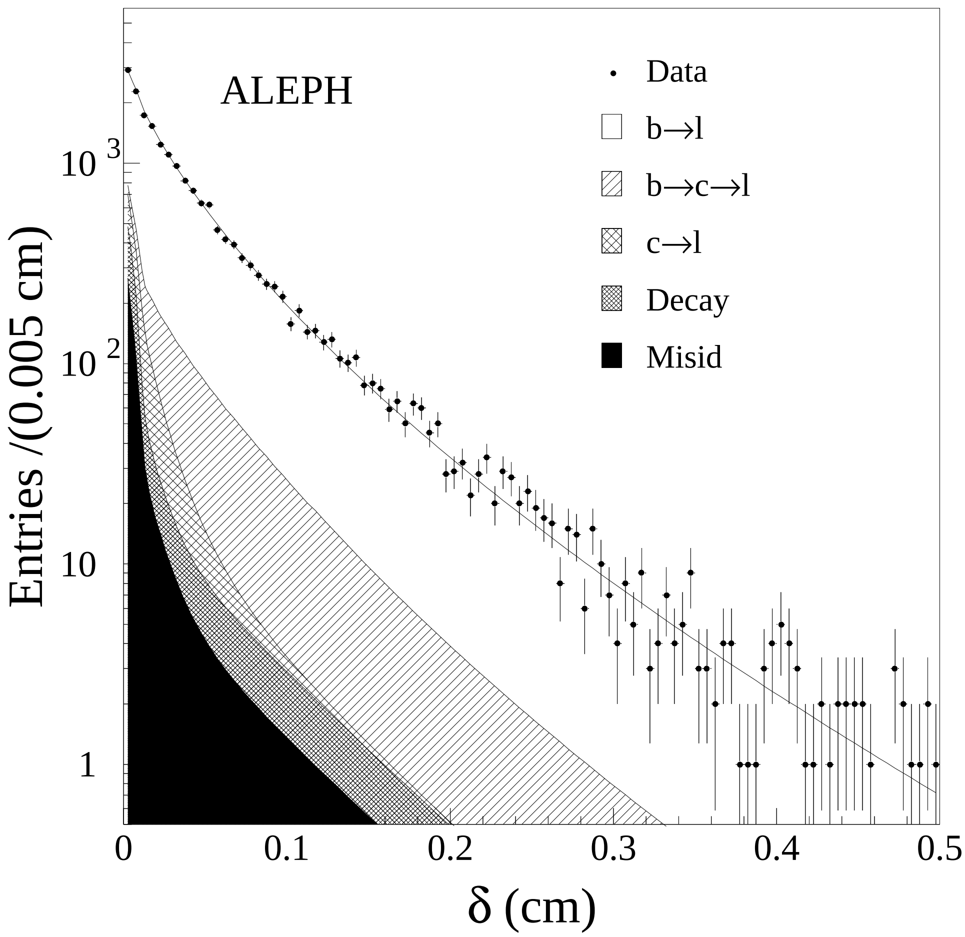

Figure 5: Impact parameter distribution of the selected lepton candidates. The solid curve is the probability function at the fitted value of the lifetime. The hatched distributions represent the contributions of the different components to the lifetime fit.

- b and c quark fragmentation;
- semileptonic branching ratios of b and c hadrons;
- heavy quark production rates ($\Gamma_{b\bar{b}}/\Gamma_{\rm had}$ and $\Gamma_{c\bar{c}}/\Gamma_{\rm had}$).

A choice of a semileptonic decay model is needed to adjust the b and c decay spectra to the low energy data measured by CLEO [13]. In the case of $b \to \ell$ decay, the ACCMM model [14] is used to determine the central value of the measurement. The maximum deviation from the central value obtained using alternatively the standard ISGW model [15] with an 11% D^{**} contribution or the modified ISGW with 32% D^{**} contribution, is taken as systematic error due to the $b \to \ell$ model. The $b \to c \to \ell$ decay has been treated as a combination of a model for the $b \to c$ decay and one for the $c \to \ell$ decay spectrum. The $b \to D$ decay spectrum has been measured by CLEO [16] with a small uncertainty. The ACCMM model is used also for the $c \to \ell$ decay with parameters obtained from a fit to the DELCO data [17]. The K_{bc} and K_c distributions are both changed when the $c \to \ell$ model is varied and the observed difference in the lifetime is assigned as a systematic uncertainty.

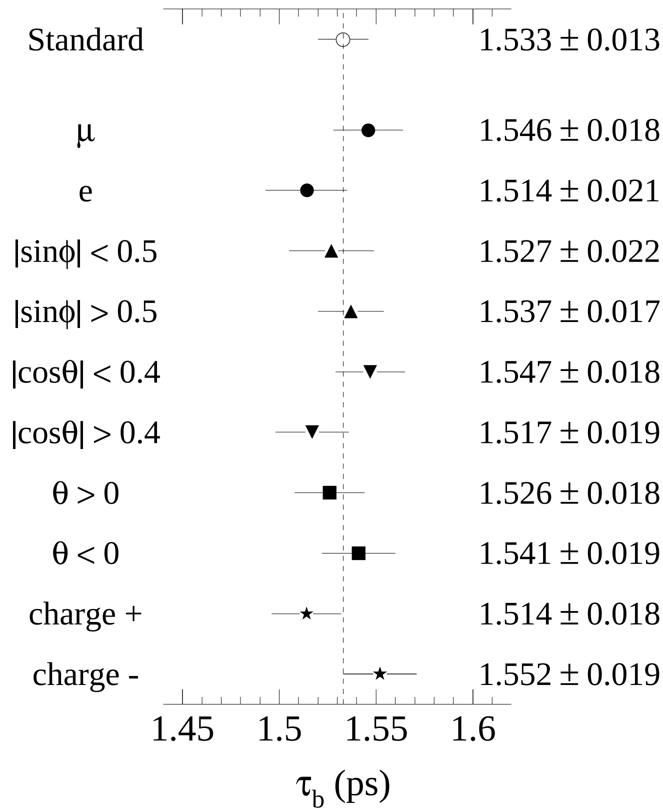

Figure 6: Lifetime values for the various selected subsamples of data.

The fragmentation of both b and c quarks is modelled in the Monte Carlo with the Peterson fragmentation function [18], with values of the parameters ϵ_b and ϵ_c resulting from the measurements of the average energy of b and c hadrons observed by ALEPH in inclusive semileptonic decays [19]. The systematic error is estimated by varying ϵ to reproduce the allowed range in the average hadron energy.

The uncertainties in the semileptonic branching ratios are less relevant because they influence only the lepton source fractions. The latest ALEPH measurements [19] have been used to determine the central value. The systematic error is estimated from an uncertainty in the $b \to \ell$ branching ratio of 5%, in the $b \to c \to \ell$ of 15% and in the $c \to \ell$ of 5%. The systematic error contribution due to $\Gamma_{b\bar{b}}/\Gamma_{\rm had}$ turns out to be almost negligible.

A further contribution to the systematic error is due to the average c hadron lifetime which is input to the probability density function for the $c \to l$ leptons. This parameter is an average of the lifetimes of c hadrons weighted with their production rates and semileptonic branching fractions. The error in τ_c takes into account both the uncertainties in the lifetime and in the relative production rates of different c hadrons.

A possible polarisation of the b baryon is also considered as a source of systematic error. The polarisation influences the lepton angular decay distribution and therefore the impact parameter. A systematic error is estimated for an uncertainty in the b baryon polarisation between 0 and 94%, with the assumption of a b baryon production rate with respect to all b hadrons of 10%.

Table 2 reports the estimated systematic contributions due to uncertainties of the Monte Carlo in the simulation of the b and c quark physics. A total error of 0.018 ps is attributed to this source.

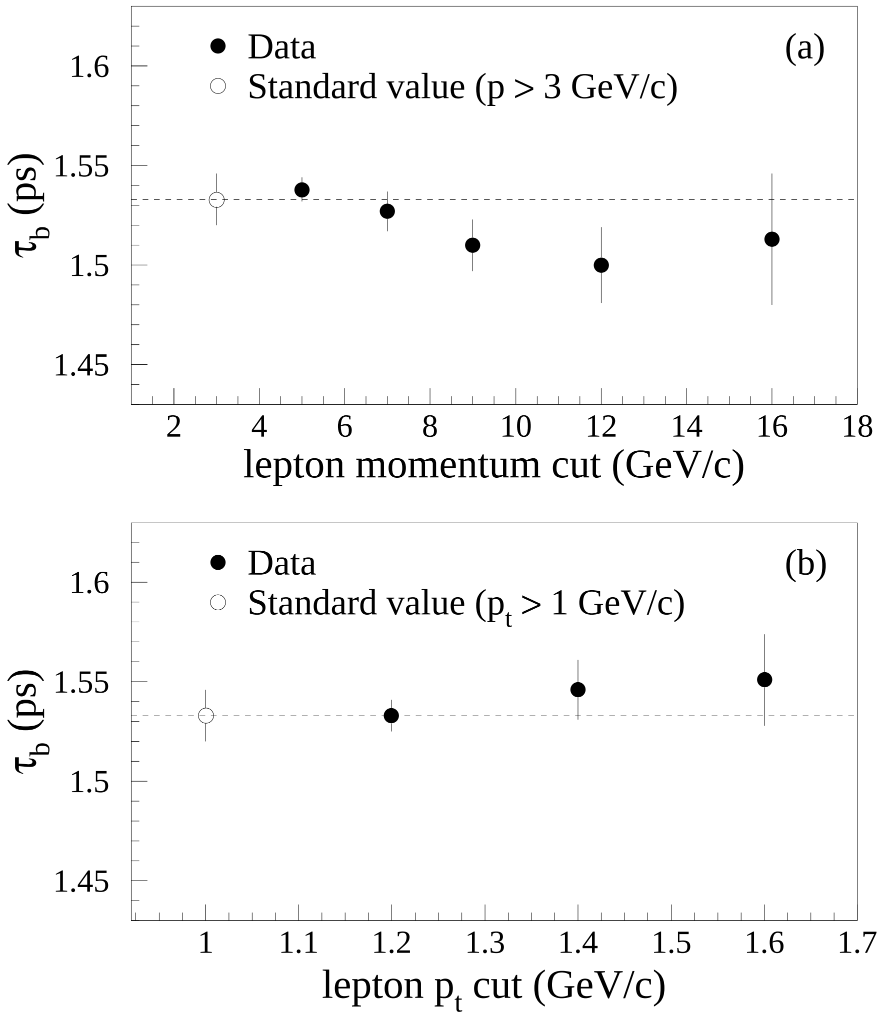

Figure 7: Lifetime values as function of the cut on the lepton momentum cut (a) and on the transverse momentum. (b). The error at the open dot is statistical while uncorrelated statistical errors with respect to this open dot are shown on other solid points.

The determination of the K distribution is influenced by the statistical fluctuations of the Monte Carlo. The corresponding systematic contribution has been evaluated by studying the variation of the lifetime using different K distributions which are obtained from statistically independent samples of Monte Carlo data. Effects due to the lepton momentum dependence have been studied using K distributions obtained for smaller ranges of lepton momentum. The observed deviations in the value of τ_b are included in the estimated systematic uncertainty.

The statistical uncertainty on the lepton source fractions in the Monte Carlo samples yields a small contribution to the systematic error. A larger uncertainty in the fractions is due to the amount of lepton background. An uncertainty of 20% is attributed to the simulation of the misidentification processes, such as muon punch-through, and 10% to the decays in flight of K's and π's. Studies based on the combination of the lepton tag with an event flavour tag in the opposite hemisphere, have shown that the global number of candidate leptons with high p_t in light flavour (uds) events is underestimated in the Monte Carlo. A correction factor of $16 \pm 40\%$ in the number of candidate leptons in uds events has been considered in the determination of

Source of systematic error	Value and variation	$\sigma_\tau^{\rm sys}$ (ps)
$b \to \ell$ decay model	ACCMM-ISGW	0.014
$b \to c \to \ell$ and $c \to \ell$ decay models	DELCO errors	0.002
b fragmentation	$\langle x_b \rangle = 0.714 \pm 0.012$ [19]	0.010
c fragmentation	$\langle x_b \rangle = 0.487 \pm 0.012$ [19]	0.002
BR($b \to \ell$)	0.114 ± 0.005 [19]	0.003
BR($b \to c \to \ell$)	0.082 ± 0.012 [19]	0.002
$R_c \cdot$ BR($c \to \ell$)	0.017 ± 0.001 [20]	0.002
$R_b = \Gamma_{b\bar{b}}/\Gamma_{\rm had}$	0.219 ± 0.004 [11]	0.001
τ_c	0.72 ± 0.07 ps [20]	0.002
Λ_b polarisation	$\mathcal{P}_{\Lambda_b} = -47 \pm 47\%$	0.002
Total b and c physics contribution		0.018

Table 2: Systematic error due to the simulation of heavy quark physics.

the central value of τ_b and in the evaluation of the systematic uncertainty due to the background level.

A further systematic uncertainty is due to the parametrisation of the expected impact parameter distribution for the background lepton candidates. The probability function for the misidentified leptons is determined using hadron tracks in real data with a negligible uncertainty. In contrast, the impact parameter distribution of the non-prompt leptons is obtained from K and π decays selected in $Z \to q\bar{q}$ Monte Carlo events. The systematic error on τ_b from the background parametrisation includes a statistical term due to the limited number of usable tracks and an uncertainty in the Monte Carlo due to the K/π ratio.

The uncertainty in the resolution function is due to residual differences between Monte Carlo and data. The correction factors taken from the hadron impact parameter resolution produce a shift in the lifetime value of only 0.003 ps, confirming that the Monte Carlo agrees with the data in the simulation of resolution effects. This agreement is reached by requiring good track quality reconstruction of the candidate lepton tracks, such as demanding two associated hits in the VDET. Nevertheless a conservative estimate of the systematic error due to the resolution is given in view of the presence of additional tails outside the double gaussian function.

Other possible sources of systematic errors such as the electron bremsstrahlung or the beam size and position determination are estimated to give negligible contributions. All the contributions are shown in table 3. A total value of 0.022 ps is obtained by summing the contributions in quadrature.

7 Conclusions

From a total of about 1.5 million hadronic Z decays collected with the ALEPH detector during the period from 1991 to 1993, a sample of 19844 lepton candidates has been isolated and the average lifetime of b hadrons extracted from a maximum likelihood fit to the three-dimensional impact parameter distribution of the lepton tracks. The result is

$$\tau_b = 1.533 \pm 0.013 \pm 0.022 \text{ ps}$$

with a total uncertainty of 1.7%, summing in quadrature the statistical and systematic errors. This value is a weighted average over the production fractions and semileptonic branching ratios of the various b hadrons produced in hadronic Z decays. This result supersedes the previous

Source of systematic error	σ_{τ}^{sys} (ps)
b and c physics simulation (table 2)	0.018
K determination	0.005
lepton source fractions (MC statistics)	0.002
lepton background level	0.008
background parametrisation	0.006
resolution function	0.005
Total systematic error	0.022

Table 3: Contributions to the systematic error

ALEPH measurement based only on the 1991 data [3]. The result agrees with the previous measurements [2] and improves significantly the precision of the world average [20].

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