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A measurement of the average lifetime of B-hadrons produced by e^+e^--collision at $\langle\sqrt{s}\rangle = 36.3$ GeV

JADE-Collaboration

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Abstract. Data taken with an improved tracking system have been used to determine the average lifetime of B-hadrons, τ_B. A study of the pseudo decay length gave

$$\tau_B = (1.46 \pm 0.22(\text{stat.}) \pm 0.34(\text{syst.}))\ \text{ps}.$$

From the impact parameter distribution of high $p\perp$ electrons and muons, values of

$$\tau_B = \left(1.27\,{}^{+0.35}_{-0.29} \pm 0.17\right)\ \text{ps}$$

and

$$\tau_B = \left(1.36 \pm {}^{0.32}_{0.27} \pm 0.14\right)\ \text{ps}$$

were obtained. Combining these results, allowing for correlations and adding statistical and systematic errors in quadrature, we obtain

$$\tau_B = \left(1.36\,{}^{+0.25}_{-0.23}\right)\ \text{ps}.$$

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I Introduction

The average lifetime, τ_B, of hadrons containing a b quark provides important information on the $b \to c$ and $b \to u$ transition amplitudes which are fundamental parameters of the standard model. The lifetime differences of the various hadrons containing a heavy quark, Q, are expected to decrease with increasing mass, m_Q, such that τ_B to a good approximation [1] represents the inverse of the b-quark decay width Γ_b.

Finite values of τ_B, close to the upper limit previously obtained by the JADE experiment [2], were first measured by the MAC [3] and MARKII [4] experiments at PEP and were later confirmed by the JADE [5] and TASSO [6] experiments at PETRA and by the DELCO [7] and HRS [8] experiments at PEP. A summary of the most recent results is given in Sect. V.

In this article a new measurement of τ_B by the JADE collaboration is described. The data used were taken with an improved track measuring system during 1985–86. Two different methods were used to determine τ_B. In the first method two pseudo decay vertices were determined and the distance between the two used as a measure of τ_B. The product of the boosted sphericities [6], which parametrizes the global event topology, was used to discriminate between b-quark and light quark production. The second method used the impact parameter of high momentum muons and electrons to determine τ_B. Both the transverse momentum of these leptons relative to the event axis and the boosted sphericity were used to select B-decays. The two methods have different systematic uncertainties. The advantage of the first is that no a priori knowledge of the production vertex is needed, whereas the second is less dependent on the details of the fragmentation process.

The organisation of the paper is as follows. The pseudo decay length technique and the results obtained using it are described in Sect. III, the impact parameter method and the results so determined are presented in Sect. IV, and the results are summarized in Sect. V. A short description of the apparatus and the data taking is given in Sect. II.

II Apparatus and data taking

The JADE detector is described in [9]. In 1984 it was equipped with a vertex chamber which was essentially an extension of the central jet chamber to smaller radii and replaced the former beam pipe counters. A more detailed description of the vertex chamber and the Flash-ADC read out system is given in [10]. These modifications of the tracking system improved the accuracy of the track extrapolation to the origin by more than a factor of 2, resulting in extrapolation uncertainties for high momentum traacks of about 160 μm and of about 500 μm for a track with a momentum of 1 GeV. These uncertainties are well reproduced by the Monte Carlo detector simulation program as shown in detail in [10].

The data used in the analysis presented here were taken with an active vertex chamber in 1985–86 at the c.m. energies listed in Table 1, where the number of events accumulated in this period and the number which passed the standard JADE multihadron selection criteria [11] are also given. Since a good reconstruction of the event axis was important for this analysis only events with $|\cos\theta|<0.75$ were accepted, where θ is the angle between the beam line and the sphericity axis. This cut minimizes uncertainties caused by particles escaping detection through the beam pipe. Furthermore we require at least 3 good charged particle tracks in each event hemisphere. The number of events satisfying these criteria is listed in Table 1. The further event selection differs

Table 1. Parameters of the data and number of events passing the various selection cuts

Data	1985	1986
$\langle\sqrt{s}\rangle$ [GeV]	41.5	35
Int. luminosity [pb^{-1}]	21.2	85
# of multihadronic events	5295	26985
With $\|\cos\theta\|<0.75$	3839	19996
$\geqq 3$ tracks per hemisphere	2768	14557
2 good jet vertices	2456	12930

for the two analyses and is discussed in the appropriate sections.

The impact parameter method requires the position and extension of the luminous region to be known. The mean position of the interaction vertex was determined for each fill from a sample of collinear Bhabba events. It was assumed that the shape of the luminous region was constant for a given energy. The measured extension of the luminous region in the $r-\phi$ plane, to which the beam direction is normal, is about 350 μm in the horizontal and about 50 μm in the vertical direction. For more details we refer to [10].

III Measurement of τ_B by the pseudo decay length

III.a *The method*

The expected vertex structure from B-hadrons pair-produced by e^+e^--annihilation is sketched in Fig. 1. The B-hadrons are produced, together with light fragmentation particles, at the primary vertex; they then decay forming two secondary vertices. The B-hadrons decay dominantly into charmed particles, the decays of which lead to tertiary vertices. Since the resolution of the vertex detector was not good enough to identify and separate these vertices, more global techniques were used.

Each event was separated into two hemispheres by a plane which included the interaction point and to

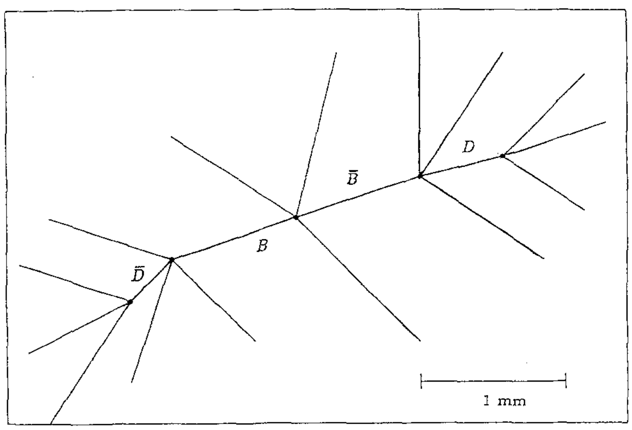

Fig. 1. Typical vertex structure expected for B-hadrons pair-produced in e^+e^--annihilation at PETRA energies

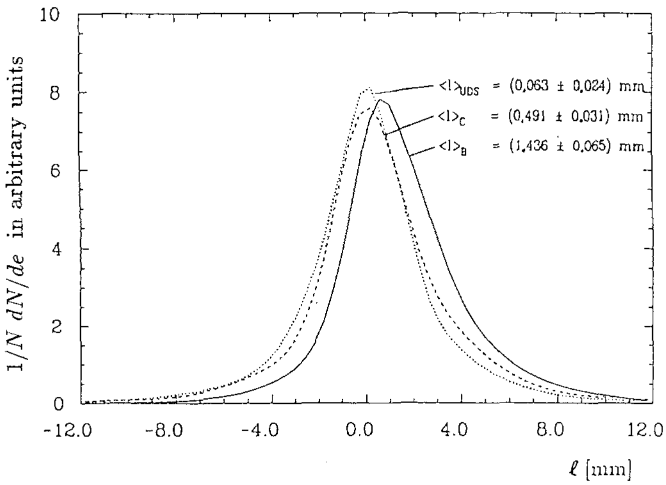

Fig. 2. Distribution of pseudo decay lengths l for u-, d-, s-quarks, c-quarks and b-quarks obtained from a Monte Carlo simulation assuming $\tau_B = 1.5$ ps

which the sphericity axis was normal. The tracks of each hemisphere were then used to determine two pseudo vertices. Only the projections of the tracks onto the $r-\phi$ plane were used to fit the vertices, since in this plane the tracks are most accurately measured. Tracks were only accepted for the fit if they had hits in the vertex chamber, more than 12 hits in the central jet-chamber and if their distance in the $r-\phi$ plane to the nominal interaction point was less than 8 mm. The two vertices were constrained to lie on the sphericity axis and the distance between them, the "pseudo decay length", l, was determined. It was given a negative sign if the vertex of one hemisphere was "behind" the vertex of the other hemisphere.

Since the fragmentation of b-quarks is rather hard, only a limited number of particles are produced at the primary vertex in $b\bar{b}$-events, and the length l is quite sensitive to τ_B. This is demonstrated in Fig. 2 where the expected distributions of l are shown separately for uds, c and b quark production. These curves were obtained by Monte Carlo techniques assuming $\tau_B = 1.5$ ps and using the Lund 5.2 event generator. The charmed particle lifetimes [21] were incorporated into the event generator.

On average the b-events are clearly shifted towards larger l, but it is also evident that this shift is smaller than the experimental resolution. A good understanding of the resolution function is therefore important for a correct evaluation of τ_B.

III.b Separation of b-production

The sensitivity of the measurement of τ_B can be enhanced if the b-quark contribution to l can be separated from the contribution of the light quarks. The global event shape, which is sensitive to the quark mass, was used to discriminate between the heavy b and the light u-, d-, s- and c-quarks. For a quantitative measure of the event shape we follow [6] and use the product of boosted sphericities $S_1 \times S_2$. It was calculated as follows. The momenta of the particles in each hemisphere were boosted into a coordinate system moving approximately with the velocity expected for the center of mass of a b jet. The boost direction was along the event sphericity axis. The boost parameter γ was chosen to optimize the separation, its value was, however, not critical. At 35 GeV we used $\gamma = 1.35$, at 41.7 GeV $\gamma = 1.5$.

Figure 3a shows the expected distributions of $S_1 \times S_2$ for b-quark and u, d, s, c-quark production. The b-events have in general a larger value of $S_1 \times S_2$ and values of $S_1 \times S_2 > 0.25$ are predominantly due to b events. The distributions in Fig. 3, obtained using the Lund model Monte Carlo simulation, were used for the discrimination procedure discussed below. Figure 4a demonstrates that the sum of the two distributions in Fig. 3a describes well the experimentally observed distribution. A further check of the model calculation is shown in Fig. 4b, where for a b enriched sample of semileptonic events, obtained as described in Sect. IV, the distribution of the boosted sphericity S of the hemisphere not containing the energetic lepton is plotted. The agreement between the data and the model calculation is again good.

The Monte Carlo data were also used to study the correlation between l and $S_1 \times S_2$, which could mimic the effect of a finite τ_B. Figure 5 indicates that this correlation is small and similar for the b-quark and the light quarks.

As evident from Fig. 3, it is not possible to separate b-quark production from light quark production on an

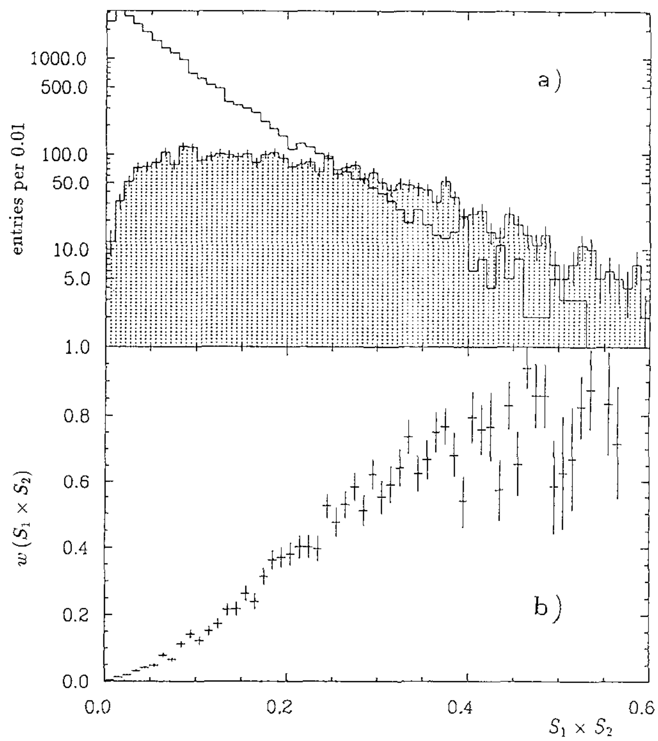

Fig. 3. a Distribution of events versus $S_1 \times S_2$ for b-quark production (shaded area) and u, d, s, c-quark production. The areas underneath the curves are scaled to the corresponding production cross sections. **b** The weight function $w(S_1 \times S_2)$. Both plots are obtained from the Monte Carlo simulation

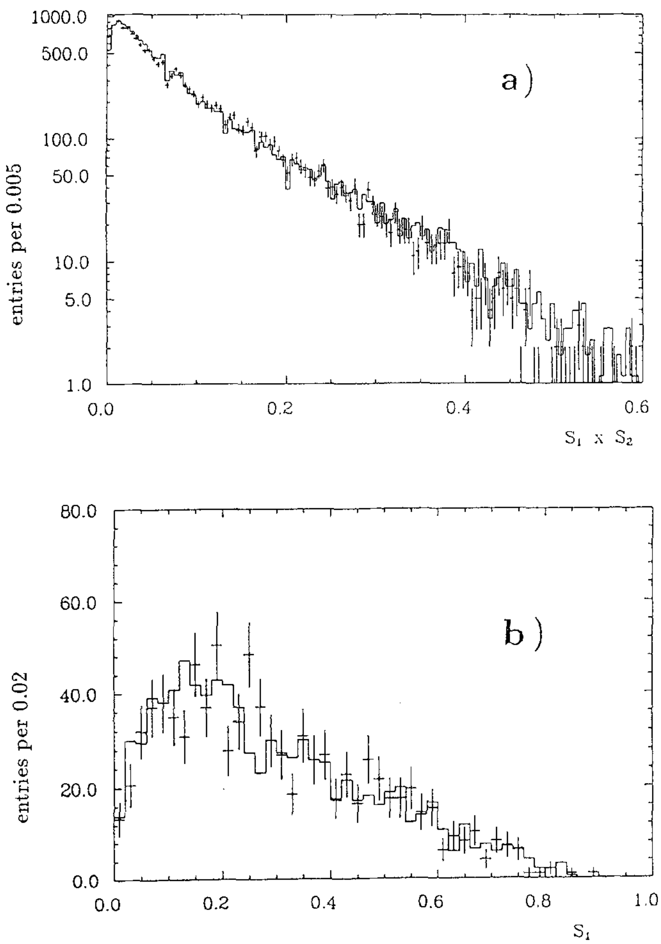

Fig. 4a, b. Comparison of data and Monte Carlo predictions. The data are indicated by crosses, the Monte Carlo results by histograms. **a** $S_1 \times S_2$ distribution, **b** the distribution of S for events containing a muon of high momentum in the hemisphere opposite to the jet. About 32% of the events in (**b**) are expected to be from $b\bar{b}$-production

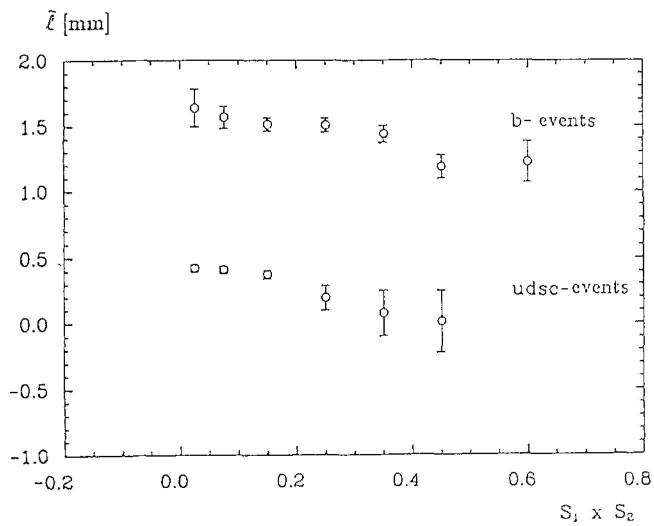

Fig. 5. Average pseudo decay length $\bar{l}$ versus $S_1 \times S_2$ for b-quark and u, d, s, c-quark production as obtained from the Monte Carlo simulation

event by event basis. Statistical methods must be used. Here the weighting technique described in [12] was chosen. If a sample of N events contains N_S signal and N_B background events

$$N = N_S + N_B \tag{1}$$

and $w_j = w(x_j)$ is a weight function of a discriminating variable x, one defines a weighted sample

$$N_w = \sum_j w_j = \bar{w}_S N_S + \bar{w}_B N_B \tag{2}$$

where $\bar{w}_S$ and $\bar{w}_B$ are the mean values of the weight of the signal and background samples. Solving these equations for N_S one obtains

$$N_S = \frac{N_w - \bar{w}_B N}{\bar{w}_S - \bar{w}_B} = \frac{\sum_j (w_j - \bar{w}_B)}{\bar{w}_S - \bar{w}_B} \tag{3}$$

and a corresponding expression for N_B. The statistical error of N_S determined in this way is $\sqrt{N_S} \cdot F$, where the dilution factor F is given by

$$F = \left\{ 1 + \frac{\overline{w_S^2} - \bar{w}_S^2 + N_B/N_S(\overline{w_B^2} - \bar{w}_B^2)}{(\bar{w}_S - \bar{w}_B)^2} \right\}^{1/2}. \tag{4}$$

In this analysis $x = S_1 \times S_2$ and the weight function

$$w(x) = \frac{N_S S(x)}{N_S S(x) + N_B B(x)} \tag{5}$$

was constructed from the histograms shown in Fig. 3a, where N_S and $S(x)$ are the number of b-events and their normalised x-distribution, and N_B and $B(x)$ the analogous quantities for the sum of the u, d, s and c-events. The weight function $w(x)$ is plotted in Fig. 3b. The dilution factor F is approximately 1.8.

III.c Results

Figure 6 shows the distribution of the measured pseudo decay lengths l for all multihadron events together with the distribution obtained from a Monte Carlo simulation assuming $\tau_B \equiv 1.5$ ps. The distribution of the uncertainties Δl of the l measurements for data and the simulation are shown in Fig. 7. Both l and Δl are quite well reproduced by the simulation program.

The data shown in Fig. 6 were weighted as defined in (5) and signal and background histograms were formed using (3). The normalised distributions so obtained are shown in Fig. 8. The distribution of l is shifted towards larger l for the b sample as compared to the u, d, s, c sample, evidence for a finite value of τ_B.

For a quantitative analysis we use the trimmed mean technique. A fraction ε of the events was removed symmetrically from the tails of the l distribution. It was verified that the mean value of l was not sensitive to ε. In Fig. 9 the relationship between the trimmed mean of l and τ_B is plotted for two values of ε. This relation was

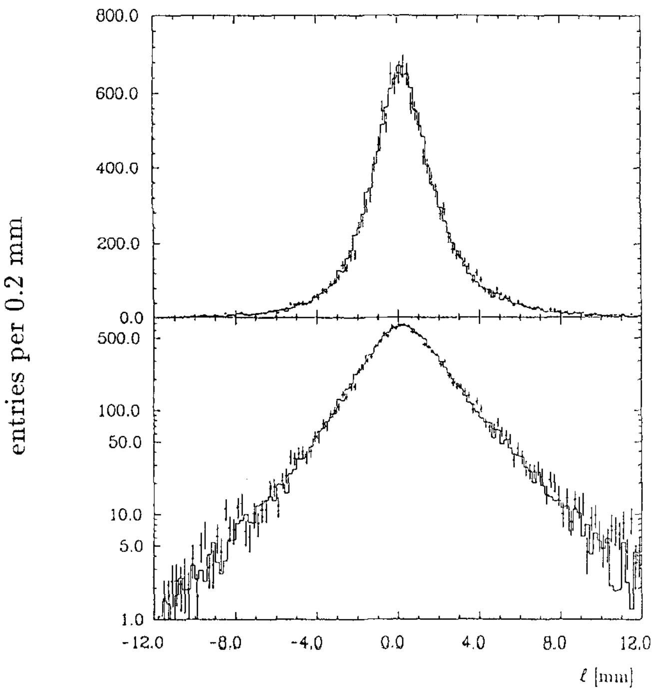

Fig. 6a, b. Pseudo decay length distribution of the multihadron data, shown as crosses, and of the Monte Carlo simulation, shown as histogram, a linear scale, b log scale

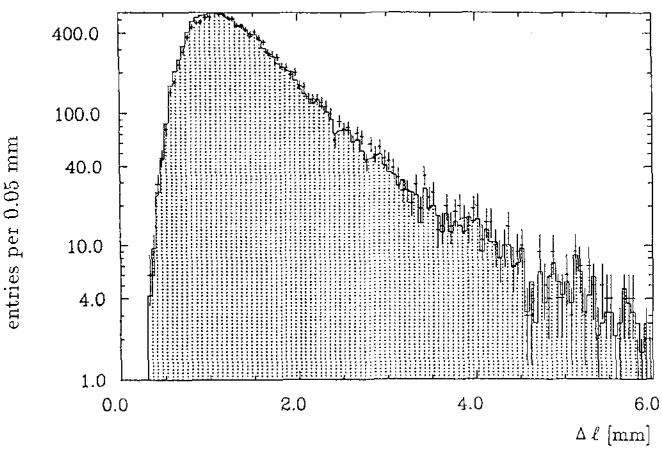

Fig. 7. The distribution of errors of the pseudo decay length Δl for the data, shown as crosses, and for the Monte Carlo simulation, shown as histograms

determined using a Monte Carlo simulation, the statistical uncertainties of which are indicated. From the measured $\bar{l}$ we deduce, as indicated in Fig. 9, $\tau_B = (1.46 \pm 0.22)$ ps, where the error accounts for the statistical uncertainties only.

Extensive use of Monte Carlo studies was made to estimate the systematic error, the various contributions to which are listed in Table 2. The main uncertainties are those in the jet vertex determination and in the number of tracks from the primary vertex relative to the secondary vertex. The latter is influenced by the b-fragmentation function, which was varied within reason-

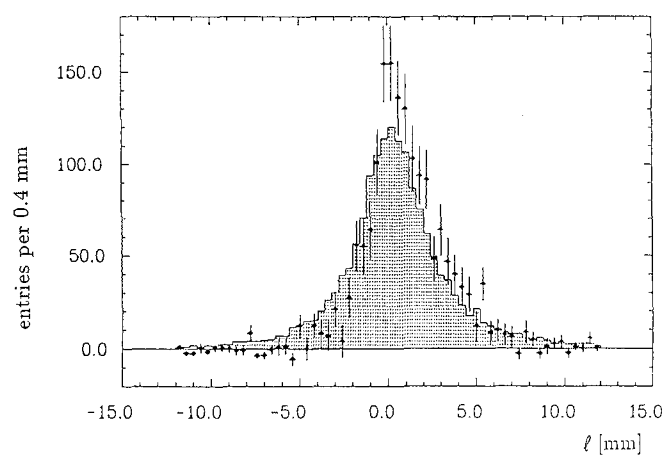

Fig. 8. Pseudo decay length distribution of the signal sample shown as data points and of background sample shown as shaded histogram

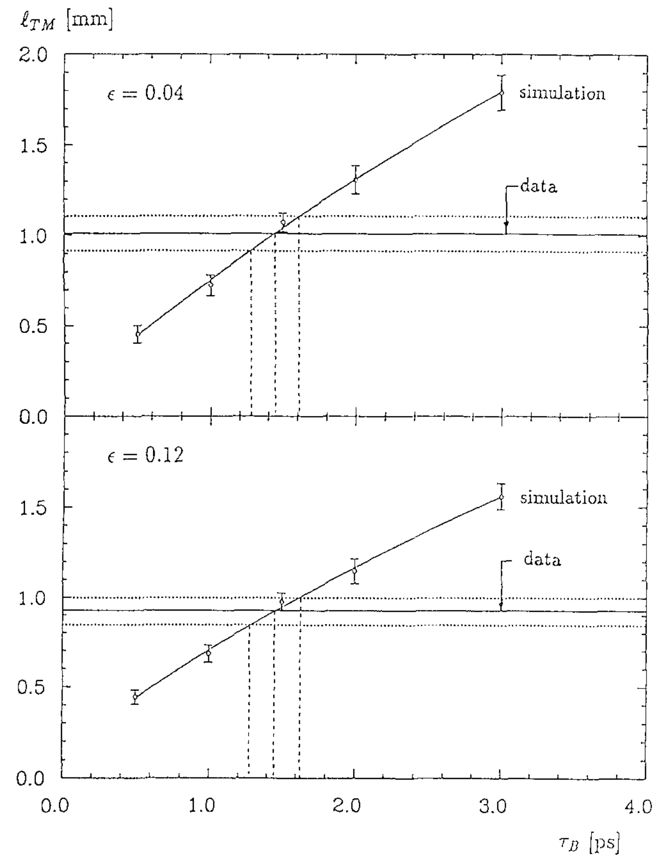

Fig. 9. Relation between the trimmed mean l_{TM} of the pseudo decay length l and τ_B as determined by the Monte Carlo simulation for 2 different trim parameters ε. The experimental results are indicated with their error bands

able limits [13], corresponding to an average fragmentation parameter $\bar{z}$ varying between 0.77 and 0.88, and by the B-hadron decay multiplicities, which were varied such that the ratio of the number of tracks from the primary vertex to the number of all tracks varied be-

Table 2. Contributions to the systematic error of τ_B for the pseudo decay length method

b-Fragmentation and decay multiplicity	0.21 [ps]
c-Fragmentation and decay multiplicity	0.10 [ps]
c-Lifetime	0.06 [ps]
B-Fraction	0.14 [ps]
Vertex determination	0.17 [ps]
Sum	0.34 [ps]

Table 3. Leptonic event samples after various cuts

Selection	# of events
Events with $\|\cos\theta\| \leqq 0.75$	18549
With electron	467
and $p_\perp^e > 1$ GeV/c	144
With muon	1245
and $S_1 \times S_2 > 0.1$	288
and $p_\perp^\mu > 1$ GeV/c	135

tween 0.2 and 0.4. The corresponding quantities for the c-quark are somewhat less critical.

Taking the systematic error into account we find using the pseudo decay length technique a lifetime of

$$\tau_B = 1.46 \pm 0.22(\text{stat.}) \pm 0.34(\text{syst.})\ \text{ps}.$$

IV Measurement of τ_B by the impact parameter

IV.a Method

The impact parameter method is a well established technique, which in some respects is complementary to the method discussed above. As used here it was based on a selected sample of relatively clean b-events using the track of a lepton which, with high probability, was due to a B-decay.

The impact parameter δ was defined to be the distance of closest approach of the decay lepton trajectory to the primary vertex projected onto the r-ϕ plane, i.e. $\delta = t^* \cdot \beta \cdot \gamma \cdot c \cdot \sin\theta \cdot \sin\alpha \equiv t^* \cdot \rho$, where θ is the angle between the B trajectory and the beam direction, α the angle in the r-ϕ plane between the B direction and the direction of the decay lepton, and t^* is the decay time in the B rest system. Two simplifications were made in determining δ: the primary vertex was approximated by the center of the luminous region, and the B-direction by the event thrust axis. The sign of δ was defined to be negative if, due to measurement errors, the lepton trajectory intersects the thrust axis "behind" the primary vertex. For a more detailed description see [5].

IV.b Lepton identification

This analysisa was performed using electrons and muons of momenta $p > 1.8$ GeV. The electron selection was made using the energy loss in the jet chamber, dE/dx, a comparison of the energy deposited in the lead glass E with the measured momentum p and an analysis of the lead glass cluster shape. Only the barrel part of the lead glass was used, limiting the angular acceptance to $|\cos\theta| \leqq 0.75$. The energy loss was required to be within $+2$ and -1 standard deviations of that expected for electrons and the ratio $E/p > 0.8$. Finally the electron track was required to have at least three hits in the vertex chamber. The background remaining after these cuts was about 13% of the sample and was primarily misidentified pions. For details see [14].

Muon identification was done using the muon filter, a system of absorber interleaved with drift chambers. Tracks identified as muons were required to have passed through at least 4.8 hadronic interaction lengths of material leaving hits in the muon chambers compatible with a track extrapolated from the jet chamber and to have at least three hits in the vertex chamber. Only 56% of these tracks were from prompt decays, the remainder being due to π and K decays or to punch through. For consistency checks a smaller sample of muons was also defined which were required to have passed through at least 5.8 interaction length of absorber material.

The numbers of electrons and muons passing these cuts are listed in Table 3. Only the 1986 data were considered in this analysis. It was carefully checked that the relative amount of leptons and their various distributions were reproduced by the Monte Carlo simulation.

IV.c B-enrichment

The aim was to apply the impact parameter method to a relatively clean sample of b-events. To achieve this we further demanded that the leptons have $p_\perp > 1.0$ GeV/c, where $p_\perp$ is the momentum component perpendicular to the thrust direction. After these cuts about 63% of the electron sample was due to B-decays and the detection efficiency for semielectronic B-decays amounted to 59% as deduced from the Monte Carlo simulation. However, only 46% of the muon event sample were due to B-decays. We therefore, for the muon sample, made the additional requirement that $S_1 \times S_2$, calculated as in Sect. III, be greater than 0.1. This cut increased the fraction of B-decays in the muon sample to about 75% and reduced the detection efficiency for B-decays from 53% to about 36%.

Figure 10 shows the $p_\perp$ distribution for electrons and for muons with the additional cut $S_1 \times S_2 > 0.1$ for both the data and the Monte Carlo simulation. The numbers of events passing the various cuts are given in Table 3. For the final analysis the angle α between the lepton flight direction and the thrust axis was limited to $0.6 \leqq |\cos\alpha| \leqq 0.99$. The upper limit reduces the number of events with a negative impact parameter δ significantly, whereas the lower limit rejects some background events caused by hard gluon radiation.

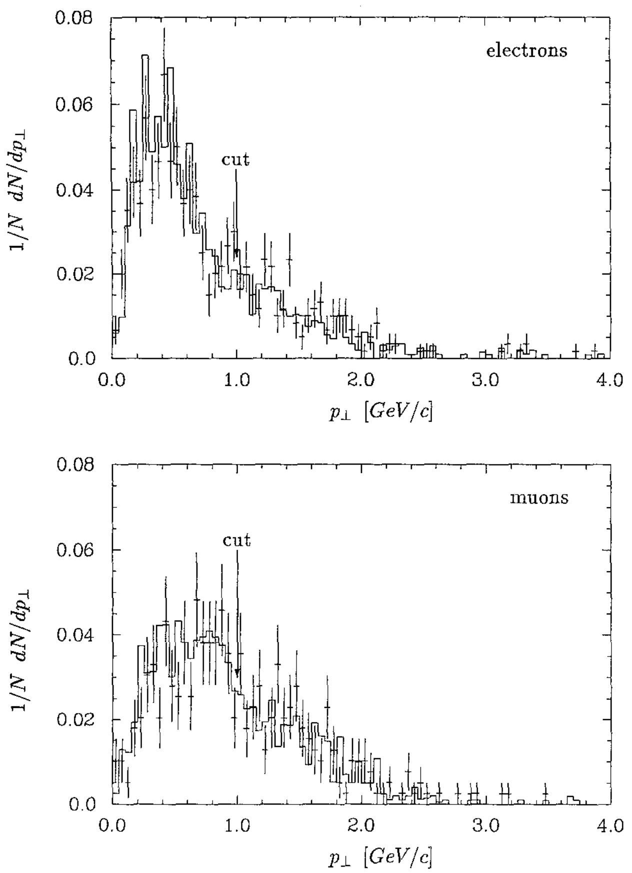

Fig. 10. Transverse momentum distribution of electron and muon candidates. The data are shown as crosses, the Monte Carlo simulation as histograms

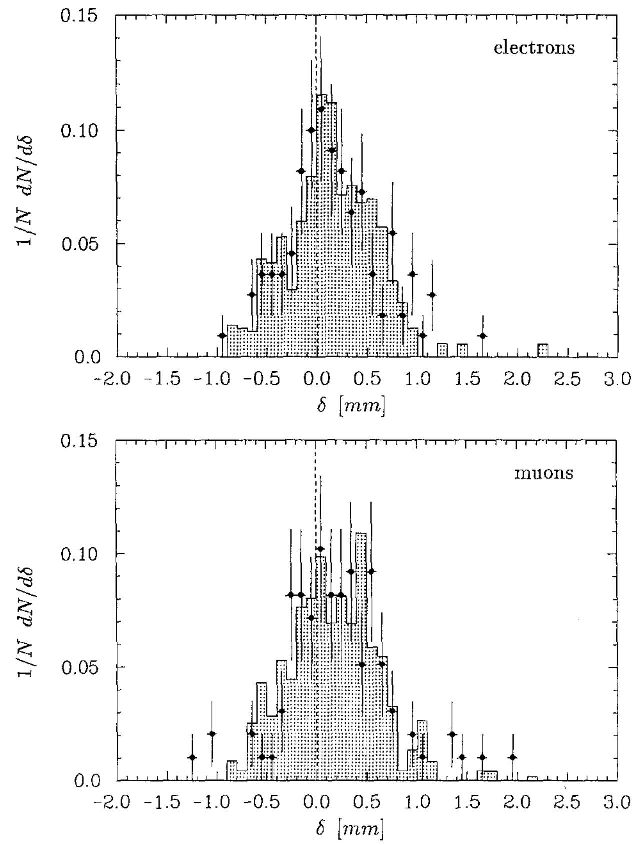

Fig. 11. Impact parameter distribution of electrons and muons. The Monte Carlo prediction for $\tau_B = 1$ ps are shown as shaded histograms

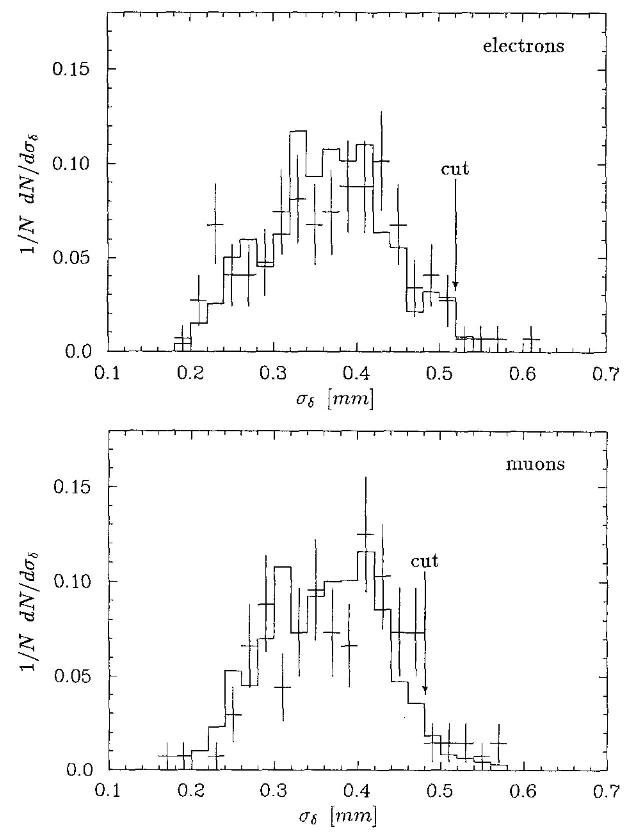

Fig. 12. The distribution of errors σ_δ of the measured impact parameters (crosses) and of the Monte Carlo simulation (histograms) for electrons and muons. The cuts applied are also indicated

IV.d The impact parameter distribution and maximum likelihood fit

For each lepton track passing these cuts the impact parameter, δ, was calculated relative to the center of the luminous region. The results are shown in Fig. 11 together with the corresponding Monte Carlo prediction for $\tau_B \equiv 1$ ps. The error σ_δ of δ was calculated from the track extrapolation uncertainty and the extension of the luminous region. The σ_δ distribution, shown in Fig. 12, was well reproduced by the Monte Carlo simulation. The few lepton tracks with $\sigma_\delta > 520$ μm for electrons and with $\sigma_\delta > 480$ μm for muons were rejected from the further analysis and are not included in Fig. 11. This cut is somewhat tighter for the muon than the electron candidates since Monte Carlo studies indicated that some muons from strange particle decays could so be rejected.

The relation between the decay time t^* in the B rest system and the impact parameter $\delta = \rho \cdot t^*$ is given in Sect. IV a. The distribution $g(\rho)$ of the ρ-parameter was determined using the Monte Carlo simulation. A likelihood function was constructed by folding an exponential decay time distribution and a gaussian resolution function with $g(\rho)$. The maximum likelihood method was then used to determine τ_B. In constructing the likelihood

Table 4. The various fractions of the event classes contributing to the likelihood function. The corresponding average ρ-values are also given

Source	Fraction [%]	$\langle\rho\rangle$ [mm/ps]
Electron candidates		
$B \to e + X$	61.6 ± 3.7	0.18 ± 0.01
$B \to c \to e + X$	4.1 ± 1.5	0.28 ± 0.09
$C \to e + X$	26.2 ± 3.4	0.08 ± 0.02
$B \to \tau + X$	0.6 ± 0.6	0.28
Prompt prod.	6.4 ± 1.9	–
γ Conversion	1.1 ± 0.8	–
Muon candidates		
$B \to \mu + X$	72.3 ± 3.0	0.19 ± 0.01
$B \to C \to \mu + X$	8.4 ± 1.8	0.27 ± 0.04
$C \to \mu + X$	11.4 ± 2.1	0.11 ± 0.03
$B \to \tau + X$	0.9 ± 0.6	0.21
$K_s \to \pi^+ \pi^-$	0.4 ± 0.4	–
$K \to \mu \nu$	0.4 ± 0.4	–
$\Sigma \to p + X$	0.4 ± 0.4	–
Prompt prod.	5.7 ± 1.5	–

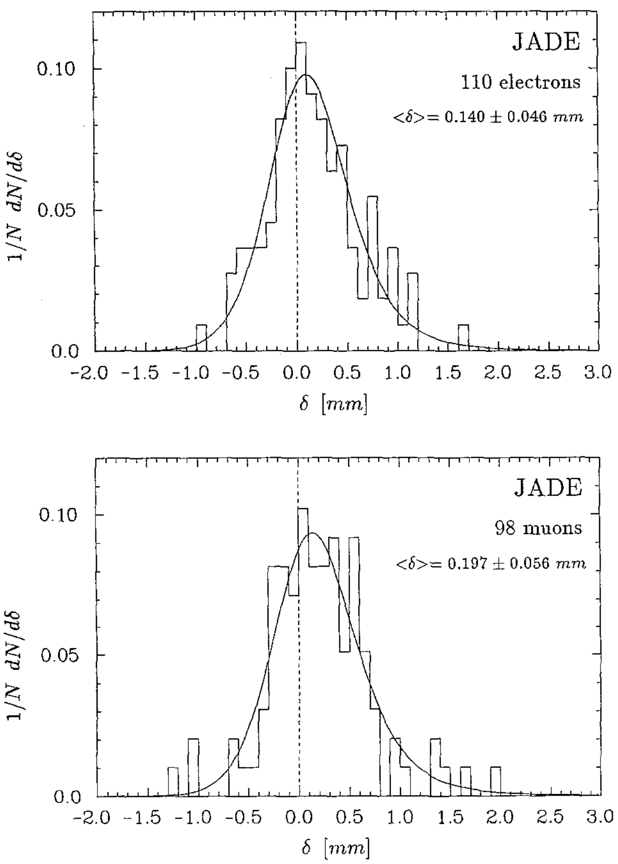

Fig. 13. Maximum likelihood fit to be experimental impact parameter distribution for electrons and muons

function not only the decays $B \to l + X$ but also the cascade decays $B \to C \to l + X$, the charm decays $C \to l + X$ and the background from tracks originating from the production vertex were considered. Furthermore, decays into a τ-lepton, which in turn decayed into an electron or muon were included. The relative amounts of the various contributions to the likelihood function are listed in Table 4 together with the corresponding average ρ values. The resulting maximum likelihood fits to the δ distributions are shown in Fig. 13.

IV.e Results

The maximum likelihood fit to the impact parameter distribution δ gives $\tau_B = \left(1.27\,^{+0.35}_{-0.29}\right)$ ps for the electron distribution and $\tau_B = \left(1.36\,^{+0.32}_{-0.27}\right)$ ps for the muon distribution. The errors quoted are the statistical uncertainties.

The main contributions to the systematic error are listed in Table 5. The error estimates were obtained from Monte Carlo studies. Adding the various contributions to the systematic error in quadrature we obtain for the impact parameter method the results

$$\tau_B = \left(1.27\,^{+0.35}_{-0.29} \pm 0.17\right) \text{ ps for electrons, and}$$

$$\tau_B = \left(1.36\,^{+0.32}_{-0.27} \pm 0.14\right) \text{ ps for muons.}$$

The two results are in good agreement and we combine both numbers, adding statistical and systematic error in quadrature. The procedure described in [15] was used to take the strong correlation of the two systematic errors, the correlation coefficient is 88%, into account. The combined result for the impact parameter method is

$$\tau_B = 1.32\,^{+0.28}_{-0.25} \text{ ps.}$$

V Summary

The two essentially independent methods used to determine τ_B yield compatible results and one is tempted to combine the two numbers. Both methods, however, use different B-hadron selection schemes and have different

Table 5. Contributions to the systematic error of the impact parameter method for electron and muon tracks

	e	μ
b-Fragmentation	0.09 ps	0.09 ps
B and $B \to C$ fractions	0.12 ps	0.08 ps
C-Lifetime	0.03 ps	0.02 ps
Impact parameter	0.04 ps	0.03 ps
Interaction point	0.06 ps	0.04 ps
Background	0.03 ps	0.03 ps
ρ-Distribution	0.03 ps	0.03 ps
	0.17 ps	0.14 ps

Table 6. Compilation of recent measurements of τ_B. The statistical and systematic errors are added in quadrature

τ_B [ps]	Experiment	
$1.17^{+0.32}_{-0.27}$	DELCO	Ref. 16
$1.02^{+0.41}_{-0.37}$	HRS	Ref. 8
1.29 ± 0.29	MAC	Ref. 17
0.98 ± 0.18	MARK II	Ref. 18
1.35 ± 0.26	TASSO	Ref. 19
$1.36^{+0.25}_{-0.23}$	This experiment	

acceptances for the various B-hadron decays. The same results are therefore only expected for the two methods if the differences in the decay times of different B-hadrons are negligible.

Making this assumption we combine the two results and obtain, taking the small correlation between the statistical errors and the correlation of the systematic errors into account.

$$\tau_B = 1.36^{+0.25}_{-0.23} \text{ ps.}$$

This result is in good agreement with our previous measurement [5] of $\tau_B = \left(1.80^{+0.50}_{-0.40} \pm 0.40\right)$ ps, which was obtained from different data samples taken without the vertex chamber. Our result is also in good agreement with the other recent measurements of τ_B which are compiled in Table 6.

The decay time τ_B is related to the elements V_{ub} and V_{cb} of the Kobayashi Maskawa matrix

$$|V_{ub}|^2 + 0.48 \cdot |V_{cb}|^2 = \frac{192\,\pi^3\, B_{s.l.}}{G_F^2\, M_b^5\, \tau_B},$$

where $B_{s.l.}$ is the branching ratio for semileptonic B decays, G_F the Fermi coupling and M_b the mass of the b-quark. With $B_{s.l.} = (11.4 \pm 0.5)\%$, $\tau_B = 1.36^{+0.25}_{-0.23}$ ps and $M_b = (5.0 \pm 0.25)$ GeV and with the upper limit $|V_{ub}| < 0.16\,|V_{cb}|$ [20] we obtain the result

$$|V_{cb}| = 0.039 \pm 0.007$$

where the error is mainly determined by the uncertainty of the b-quark mass. The weak coupling between the third and second generation of quarks is obviously quite a lot smaller than that between the second and first generation ($|V_{us}| = 0.22$).

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