EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Measurement of the Average Lifetime of b Hadrons in Z Decays

The L3 Collaboration

Abstract

We present a measurement of the average b hadron lifetime with the L3 detector at LEP. Two analyses have been performed. In the first one, the b decay position has been reconstructed as a secondary vertex of hadronic b decay particles. For this the data sample of the year 1994 consisting of 1.5 million hadronic events has been used. The second analysis is an updated measurement of τ_{b} using the impact parameter of leptons with high high-p and $\mathrm{p}_{\perp}$. It has been performed in a sample of 3 million hadronic events collected in 1991 to 1994. Both measurements exploit the precise tracking information of the L3 Silicon Microvertex Detector. The combined result is:

$$\tau_{\mathrm{b}} = 1549 \pm 9\,(\mathrm{stat})\ \pm 15\,(\mathrm{syst})\,\mathrm{fs}\,,$$

where the first error is statistical and the second is systematic. This result is preliminary.

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Introduction

Lifetimes of b hadrons are basic ingredients for the determination of the Cabibbo-Kobayashi-Maskawa matrix (CKM) element $|V_{cb}|$. The first measurement of the b hadron lifetime in 1983 at SLAC [1] provided the first evidence for a hierarchy of the CKM matrix elements. Today precision measurements of the b lifetime are made at LEP, SLC and at the Tevatron and recent results have been already published [2, 3].

All b flavoured hadrons are expected to have a similar lifetime due to the high value of the b quark mass. An inclusive analysis at the Z resonance, which result is a weighted average of individual lifetimes of $B^{\pm}$, B^0, B_s and Λ_b hadrons according their sample composition, can exploit the high statistical accuracy of the data samples collected at the Z resonance.

In this letter we present a measurement of $\tau_{\rm b}$ using two complementary and largely uncorrelated techniques. In the first analysis the full hadronic decay topology of $b\bar{b}$ events has been reconstructed. The track position measurements were used to determine the primary e^+e^- interaction point and the secondary decay positions of b hadrons. The b lifetime was derived from the position of secondary vertices with respect to the primary event vertex. This analysis has been performed in the data sample of the year 1994 consisting of 1.5 million hadronic events.

The second analysis followed our previous published measurement [3], based on the impact parameter distribution of high-p, $\mathrm{p}_{\perp}$ leptons. It has been applied in a sample of 3 million hadronic events collected in the years 1991 to 1994 and has improved the statistical and systematic accuracy compared to our previous measurement. Both measurements complement each other; they are almost statistically uncorrelated and have different systematic uncertainties. In both cases the lifetime measurement relied on data from the L3 Silicon Microvertex Detector (SMD) [4].

Hadronic Event Selection

The L3 detector has been described elsewhere [4, 5]. The selection of hadronic events was identical to the one used for the measurement of the total hadronic cross section [6]. In the time period from 1991 to 1994 2.9 million hadronic events have been selected, with an estimated selection efficiency of 99.4% and a background of 0.4%. Only events with more than four tracks measured in the Time Expansion Chamber (TEC) were kept to ensure a good tracking performance.

The response of the L3 detector was modelled with the GEANT [7] detector simulation program which included the effects of energy loss, multiple scattering and showering in the detector materials and in the beam pipe.

Secondary Vertex Method

The pair production of b quarks is characterized by two decay positions (secondary vertices) separated on average by ≈ 3 mm from the e^+e^- interaction point (primary vertex). The daughter particles of b hadrons arise at the secondary vertices and additional particles produced in the fragmentation process originate at the primary vertex. Therefore $b\bar{b}$ events among all hadronic events have been considered to consist of three distinct vertices, one primary and two secondary. In principle even five vertices would be expected because b quarks are members of the third quark family and two decay cascades take place with c hadrons as intermediate state. However the resolution did not allow to resolve the b from the c decay point. Therefore they were merged into one decay position. In this analysis we have assumed that three vertices exist and tried to find the best description under this hypothesis.

$b\bar{b}$ Event Reconstruction

At first hadronic jets were reconstructed from energy clusters in the calorimeter. The clusters were combined by the JADE algorithm [8] giving a measurement of the jet axis with a resolution of 40 mrad. The cut on the scaled invariant mass squared m^2/s was choosen at 0.04 in order to have mainly two jet events ($\sqrt{s} = 91.2$ GeV). The tracks in the event were associated to the closest jet. The two most energetic jets in the event have been considered to contain the original b quarks. Both of these jets must point into a fiducial region delimited by the barrel part of the detector $|cos\theta| < 0.74$. In case of three or more jet events tracks in the less energetic jets were not used for the lifetime measurement.

In the following the L3 coordinate system will be used. The direction of the e^- beam defined the z direction. The xy plane was the bending plane of the magnetic field, with the x direction pointing to the center of the LEP ring. The start position of a particle trajectory has been described by two parameters: $\delta^{r\phi}$, the minimum distance in the bending plane between the track and the electron beam, and δ^z, the z coordinate at the point of closest approach in xy. The reference point for $(\delta^{r\phi}, \delta^z)$ was the central beam position inside L3. It was reconstructed using tracks collected from hadronic events. The position was averaged over 200 events accumulated every 3 min, in order to closely follow drifts of the beam position. The result, called the 200-event-vertex, has been used as a constraint for the primary vertex in each event.

The three vertex hypothesis was tested with tracks that fulfil the following quality cuts:

- The transverse momentum with respect to the beam axis should be greater than 300 MeV in order to restrict the uncertainty due to multiple scattering.
- At least 25 hits should be included in the track fit and the difference between the outermost minus the innermost wire number should exceed 35. In addition at least two of the used hits have to belong to the inner TEC ring.
- The track should contain at least one SMD hit from the inner $r\phi$ ring to ensure a good extrapolation to the interaction point.
- Tracks from identified decays of K^0 and Λ hadrons were antiselected to reduce the number of downstream secondary vertices. The additional cut on the the impact parameter to be lower than 4 mm with respect to the 200-event-vertex was applied to remove remaining tracks from longlived hadrons and secondary tracks produced in interactions in the beam tube or the SMD.

Tracks that satisfy the above criteria were used for the calculation of the xy position of the track vertices. If in addition the track was well measured in the z projection it has been used in the calculation of the 3D vertex position. The track criteria for the z projection were:

- At least one SMD hit from the inner rz ring has to be included in the track fit.
- The z distance at closest approach to the interaction point should be smaller than 1.5 cm.

Before the vertex positions can be calculated a decision has to be made whether the tracks were fragmentation or b decay products. The better the 'history of the event' was recovered, the better the resolution on the b decay length would be. Our ansatz was to consider all associations of tracks to vertices as possible and to evaluate the most likely combination by well defined criteria. Obviously these criteria make use of the long lifetime of b particles but other information as the hard fragmentation can be added.

In the following we will describe our ansatz. For all track combinations χ^2 was defined as

$$\chi^2_{vertex} = \sum_{i=1}^{n} \left(\frac{\delta_i^{r\phi}(\vec{x}_j)}{\sigma_{\delta_i^{r\phi}}} \right)^2 + \left(\frac{\delta_i^{z}(\vec{x}_j)}{\sigma_{\delta_i^{z}}} \right)^2 + \sum_{k=1}^{3} \left(\frac{(\vec{x}_1 - \vec{x}_{BS})\vec{e}_k}{\sigma_{BS}^k} \right)^2$$

$$\mathrm{i} = 1, \cdots, \mathrm{n\ tracks}, \quad \mathrm{j} = 1,2,3\ \mathrm{vertices}, \quad \mathrm{k} = \mathrm{x,y,z\ projections}\,.$$

The sum of quadratic deviations of all track positions to the respective vertices has been minimized in $r\phi$ and z, respectively. It included the $r\phi$ impact parameters $\delta_i^{r\phi}(\vec{x_j})$ and z differences $\delta_i^z(\vec{x_j})$ with respect to the vertices $\vec{x}_j$ (j=1,2,3). The associated errors σ_{δ_i} were defined as the sum of uncertainties from the track fit and multiple scattering, added in quadrature. The impact parameter resolution can be measured by the distribution of the distance at which tracks of dilepton events miss each other at the beam center, it is shown id figure 1. From the width of this distribution a resolution of 32 μm was obtained. It was found that the additional multiple scattering error for tracks with an inner SMD hit was well described by $110/(p_\perp\sqrt{sin\theta})$ μm, with $p_\perp$measured in GeV, in agreement with the expected contributions from the beam tube and the SMD. If a track did not belong to the z selected sample the error $\sigma_{\delta_i^z}$ was set to ∞. The primary vertex $\vec{x}_1$ was constrained to be identical to the beam spot position, given by the 200-event-vertex $\vec{x}_{BS}$, within the horizontal beam spot size of $\sigma_{BS}^x = 135$ μm, the vertical size of $\sigma_{BS}^y = 25$ μm and the longitudinal size of $\sigma_{BS}^z = 1$ cm.

The minimum of χ^2 was found in two steps. At first the vertex coordinates were estimated for a given track combination to vertices. To simplify the problem χ^2 was assumed to be a linear function of the vertex coordinates $\vec{x}_j$. The advantage of an analytic and fast solution was caused by neglecting small nonlinear terms due to the track curvature and the dependence of the track error on the coordinates itself. However these deviations were small and were taken into account in an iterative solution of the linearized χ^2 problem. This procedure was repeated for all possible track combinations and that one with the minimal χ^2 was considered to be the optimal reconstruction of the $b\bar{b}$ event. In general the number of track combinations was 3^n where n was the number of selected tracks in the two most energetic jets. A resonable simplification was to assume that all tracks at the secondary vertex belong to the same jet which reduced the number of combinations to 2^n . Apart from that at least one track from each jet was required at the primary vertex and at least three tracks at the secondary vertex to reduce fake vertices of random track crossing. Therefore the minimal number of selected tracks per jet was four. The fit start efficiency has been determined to 43 %. Due to the higher multiplicity of $b\bar{b}$ events the b purity was slightly increased from 22 % to 27 %.

The result of the χ^2 fit were the three-dimensional positions $\vec{x}_j$ of the three vertices $j = 1,2,3$. In order to handle poorly measured tracks and remaining tracks from decays of longlived hadrons it was checked whether all $r\phi$ impact parameters $\delta^{r\phi}$ and z differences δ^z were below 1 mm and 3 mm, respectively. If a impact parameter was larger than 1 mm the track was taken out from the vertex calculation and if a z difference to the estimated vertex was larger than 3 mm, the track was removed from the z selected sample and only the $r\phi$ impact parameter was used in a new evaluation of the vertex positions.

Although the most inner points of the tracking system were most relevant for the lifetime measurement, the far placed calorimeters still contained an important information on the b flight direction, especially because of the big lever arm. The b flight direction was better defined with the calorimeters than the direction of the decay distance was measured by the tracking system. Therefore the flight direction, given by the line connecting primary and secondary vertex, was fixed to the jet axis, defined with the clusters in the calorimeter. The assumption of a fixed direction allowed a three-dimensional interpretation of χ^2 even if no track belonged to the z selected sample. In that limit χ^2 defined the two-dimensional projection of the decay length in the $r\phi$ plane scaled with $1/sin\theta_{jet}$ into a three-dimensional decay length.

Besides of the long lifetime the b quark is characterized by its heavy mass. The heavy mass causes a hard fragmentation of b quarks. This kinematical information can be used to distinguish b decay from fragmentation tracks. A variable that combines the high momentum and small angles of b decay tracks to the jet axis is the rapidity $\eta = 1/2 \; ln(E + p_{||})/(E - p_{||})$, where E stands for the particle energy (assuming pions) and $p_{||}$ for the momentum parallel to the jet axis [9]. The rapidity information was added in one analytic expression to χ^2 by:

$$\chi^2 = \chi^2_{vertex} - 2\sum_{i=1}^{n} lnP_j(\eta_i) \quad j = 1, 2\,,$$

where η_i was the rapidity of track i and $P_j(\eta_i)$ was the probability distribution for the rapidity of either b decay or fragmentation tracks. We have considered the minimum of χ^2 to be the most likely reconstruction of a $b\bar{b}$ event according to lifetime and kinematic properties, based on measurements in the SMD, the TEC, the z-chamber and the calorimeters.

The assumption of three vertices in a hadronic event was only valid for b and c events. In light flavour events the algorithm produced artificial secondary vertices that were compatible with the primary vertex within the resolution. No attempt was made to enrich the fraction of b events in the hadronic sample. Light flavour events have been considered as a background located at small distances in the decay length distribution.

An event selected in 1994 data with a high probability to be a $b\bar{b}$ event is shown in figure 2. The secondary vertices in both jets of the event are distinct from the primary vertex by more than five standard deviations.

Lifetime Fit

Lifetime measurements with hadronic b events at LEP already reach a statistical accuracy that is small compared to the systematic uncertainties in modeling heavy quark decays [2]. Our main purpose was thus to perform a fit where the values of uncertain parameters were determined from data itself. The relevant uncertainties were the b hadron momentum spectrum and the fraction of remaining background tracks from fragmentaion.

Two common used variables are sensitive to the b lifetime. One is the impact parameter, here defined as the impact parameter of those tracks attached to the secondary vertices in the minimum χ^2 configuration. The other is the decay length, which measures the distance between primary and secondary vertex for the minimum χ^2 configuration. The advantage of the impact parameter is that, if the mother particle is moving with a velocity close to the speed of light, its mean value is proportional to $c\tau$, whereas the decay length is proportional to $(p/m)c\tau$. The average impact parameter of tracks from b decays at LEP is therfore less sensitive to the b hadron momentum and to a precise knowledge of the b quark fragmentation parameters. We have performed two lifetime fits, one to the impact parameter distribution and the other to the decay length distribution. The comparison of both results has been used to cross check the assumption on the value of the average b hadron momentum.

The $\tau_{\rm b}$ value was obtained from a binned χ^2 fit to the respective distributions, with the lifetime dependent expected distribution predicted by a Monte Carlo simulation. The lifetime dependence was introduced by reweighting the events according to

$$\left(\frac{\tau_{MC}}{\tau_b}\right)^2 \frac{e^{-t_1/\tau_b}}{e^{-t_1/\tau_{MC}}} \frac{e^{-t_2/\tau_b}}{e^{-t_2/\tau_{MC}}} ,$$

where t_1 and t_2 are the proper times of the weakly decaying b hadrons in jet 1 and 2 and τ_{MC} is the lifetime value in the Monte Carlo, 1.55 ps. The one parameter lifetime fit is based on the assumption that all b hadrons have the same lifetime.

The reliability of the Monte Carlo has been checked by introducing a sign for the used variables. This sign was defined according to the position of the secondary vertex with respect to the primary one. It was positive if the secondary vertex crossed the jet axis in the positive direction and negative otherwise. By definition the sign of the impact parameters of all tracks at a secondary vertex was identical to that of the decay length. In order to allow small discrepancies in the resolution function between data and Monte Carlo additional resolution parameters were introduced. The distribution in data was described by the convolution of the Monte Carlo distribution with two Gaussian resolution functions with a standard deviation $\sigma_{1,2}$ applied to a small fraction $f_{1,2}$ of Monte Carlo events. The resolution correction parameters have been obtained from data by the shape of the respective distributions on the negative side.

An other important source of uncertainty regarded the fraction of background tracks. Due to finite resolution a fraction of fragmentation tracks has been attached to the secondary vertices. Monte Carlo studies showed that this background fraction was dependent from the b decay multiplicity. The less number of tracks originated from b decay the higher was the probability to merge fragmentation tracks to the secondary vertex. The distribution of the average secondary vertex multiplicity versus the decay length was sensitive to the b decay multiplicity. The b lifetime has been fitted simultaneously with the b decay multiplicity by adding the deviations in this multiplicity distribution between data and Monte Carlo into the definition of χ^2.

Monte Carlo studies showed that secondary vertices far placed from the primary event vertex tended to have one or two tracks from decays of longlived strange hadronds, mainly K^0_s and Λ decays. In order to make the measurement of the b lifetime independent from the uncertainty in the fraction $\langle n_K \rangle$ of K^0_s and Λ hadrons produced in Z decays, it was included as a free parameter into the fit.

The lifetime $\tau_{\rm b}$, the resolution correction parameters $f_{1,2}, \sigma_{1,2}$, the average b decay multiplicity $\langle n_b \rangle$ and the fraction of longlived hadrons $\langle n_K \rangle$ were fitted simultaneously by a binned χ^2 fit to the multiplicity distribution and respectively, the impact parameter or decay length distribution. The total number of secondary vertices used in the decay length fit was 583,972. The fit to the impact parameter distribution was performed with a total number of 2,007,415 tracks. The fit results were:

$$\begin{aligned} \tau_{\rm b} &= 1564 \pm 10\,\mathrm{fs}\,, \\ \langle n_b \rangle &= 4.90 \pm 0.04\,, \\ \langle n_K \rangle &= 1.29 \pm 0.02\,, \end{aligned}$$

for the impact parameter distribution and

$$\tau_{\rm b} = 1582 \pm 12\,\mathrm{fs}\,,$$

$$\langle n_b \rangle = 4.89 \pm 0.04\,,$$
$$\langle n_K \rangle = 1.33 \pm 0.05\,.$$

for the decay length distribution, where the errors are statistical only. The effect of the resolution correction parameters, for example on the decay length resolution, enhanced the half-width-at-half-maximum (HWHM) from 0.61 mm to 0.65 mm (in 3D).

The impact parameter and decay length distribution for the fitted parameters are shown in figure 3 and 4, respectively. A good agreement between data and MC was observed and the positive tail due to b decays was clearly visible.

Fig. 5 shows the average number of tracks at the secondary vertices as a function of the decay length. The peak at zero decay length was due to uds events where artifical secondary vertices were created consisting of primary tracks. The enhancement at positive decay lengths was due to b and c events and its magnitude depended from the number of charged particles from b decays. At very small and very big decay distances the secondary vertex multiplicity was dominated by the constraint of a minimum of three tracks.

The τ_{b} value is an average value according to the b hadron composition in Z decays. The world averages [10] determine $Z \rightarrow b\bar{b}$ decays to consist of 11.2 ± 1.9 % B_s mesons, 13.2 ± 4.1 % b baryons and respective 37.8 ± 2.2 % B^0 and $B^{\pm}$ mesons. It was checked in a Monte Carlo study that the composition of the accepted events was consistent with the original one within the statistical errors.

Systematic Uncertainties

The contributions to the systematic error in the b lifetime measurement are shown in table 1. In the following we discuss the uncertainties due to detector resolution and the incomplete knowledge of heavy flavour hadronization and decay processes.

Systematic Error from Detector Uncertainties

Systematic checks have been performed to evaluate possible differences in the reconstruction of quality tracks in the detector between data and Monte Carlo. A new calibration of the TEC chamber has been obtained with the use of the SMD. Systematic uncertainties affecting the TEC resolution have been reduced by taking into account local wire position dependent effects. The single-wire dependent resolution function has been determined with a calibration sample of $e^+e^-$and $\mu^+\mu^-$events. The SMD and TEC efficiencies were tuned on that values found in Bhabha and dimuon events. After taking into account all effects observed in $e^+e^-$and $\mu^+\mu^-$events the Monte Carlo was found to simulate hadronic events with sufficient accuracy.

The agreement in the overall normalization of quality tracks per event was better than 0.1 tracks. In the evaluation of the b decay multiplicity it has been corrected for this difference in the number of quality tracks per event. Small deviations of up to 5 % were found in the polar angle θ distribution of the accepted events. They produced a shift in τ_{b} of 5 fs, respectively 2 fs, for the (2D) impact parameter and (3D) decay length measurement.

In order to determine the error from the uncertainty in the resolution function the shift in τ_{b} resulting from the uncertainty in the resolution correction parameters has been estimated to 5 fs. The uncertainties arising from TEC calibration and SMD alignment have been studied and amount to 3 fs.

An uncertainty in the knowledge of the beam spot size and position was determined by varying the size of the beam spot within the accuracy of the 200-event-vertex (15 μm in x and

10 μm in y) and introducing a bias of 10 μm in x and 5 μm in y for the central beam position. The decay length distribution was reweighted according the new point and uncertainty, yielding a change in the lifetime of 6 fs.

The definition of the sign of the decay length depended on the jet direction. The resolution on the jet direction was estimated from comparisons between data and Monte Carlo on a two jet event sample. The maximum discrepancy found, 2 mrad, produced a shift in τ_b of 5 fs.

Systematic Error from Heavy Quark Physics Modeling

The precision of the lifetime measurement was further limited due to heavy-quark physics modeling. The dominant contributions arised from the uncertainty in the inclusive description of b decays.

Systematic errors due to b and c fragmentation were determined by varying ϵ_b and ϵ_c in the Peterson function [11] according to $\langle x_E \rangle_b = 0.702 \pm 0.008$ for b fragmentation and $\langle x_E \rangle_c$= 0.484 $\pm$ 0.008 for c fragmentation [12]. The uncertainty in τ_b from b fragmentation was estimated to be 9 fs and 30 fs for the impact parameter and decay length measurement, respectively. The b fragmentation error has also a contribution due to the uncertainty in the shape of the fragmentation function. Several models [13] were tuned on the mean value $\langle x_E \rangle_b = 0.702$ and the maximum shift in the lifetime found was 2 fs. The uncertainty of 30 fs for the decay length measurement dominated the total systematic error. The error from the uncertainty in c fragmentation has been estimated to less than 1 fs for the impact parameter and 2 fs for the decay length measurement.

An uncertainty in the shape of the b decay multiplicity distribution was taken into account by replacing the Monte Carlo distribution with a binomial distribution of the same mean and variance as in the Monte Carlo. The b decay multiplicity fit was repeated and shifted $\langle n_b \rangle$ by 0.06 and τ_b by 4 fs.

Sensitivity to the modeling of c quarks, occuring as primary $c\bar{c}$ events and as decay products of b hadrons was estimated by varying the lifetimes of c hadrons and the fraction of c hadrons in $c\bar{c}$ events and b decays. The production of D^+, D^0, D_s and Λ_c in $c\bar{c}$ events was varied according the LEP averages [12] and the branching fractions $B^0 \to D^+, D^0$ and $B_s \to D_s$ were taken according the world average values [10]. Also the lifetimes of D^+, D^0, D_s and Λ_c were varied by the uncertainty in their world averages [10].

The uncertainty from R_c, varied within the LEP average [14] was found to be 2 fs. The uncertainty on R_b was conservatively estimated from the difference between the LEP average [14] and the SM value. Its effect on τ_b was found to be small, 4 fs.

The modeling of b and c events amounted to a total error in τ_b of 16 fs for the impact parameter and 32 fs for the decay length mesurement.

Cross Checks

The detector performance has been studied by looking for variations in the measured lifetime between different detector parts. The total data sample of 1994 was divided into four azimuthal and two polar sections of the detector. No systematic dependence from the azimuthal angle and the forward/backward region could be inferred. In order to check possible influence of the TEC calibration the lifetime has been measured in subsamples of the local angle relative to the TEC wires. The variations did not exceed the statistical fluctuations. The dependence of the fit results on the b decay multiplicity distribution has been cross checked by changing the weight given to the entries in the fit according to the measured multiplicity at the secondary vertices. The impact parameter distribution has been reweighted by $1/n_{SV}$ and the decay length distribution by n_{SV}, where n_{SV} was the secondary vertex multiplicity. The change in $\tau_{\rm b}$ was 4 fs for the impact parameter measurement and 5 fs for the decay length. This change has been attributed to the different statistical composition of the samples and no additional error was assigned to $\tau_{\rm b}$.

Combination of Results

The impact parameter and decay length measurement were within their different sensitivity to the b momentum consistent with each other. In order to combine both results we have used the following ansatz. The uncertainty from b momentum has been separated from the total systematic error. The correlation between the impact parameter and decay length measurement in the remaining uncertainties has been estimated to ρ=0.87, where the statistical errors alone were found to be correlated with ρ=0.63 and the systematic errors were fully correlated. The main difference between the impact parameter and decay length measurement regarded the spread in the angular distribution of the track opening angles with respect to the jet. We assumed that the best estimate of a single measurement τ_i was a linear function of the average b energy, $\tau_i = \tau_i^0 + a_i(\langle x_E\rangle_b - \langle x_E\rangle_b^0)$, $i = 1, 2$. The values τ_i^0 were the results of the impact parameter and decay length measurements at the b energy $\langle x_E\rangle_b^0 = 0.702$ and a_i were the coefficients of the first order expansion term. The combined result of both measurements was:

$$
\begin{aligned}
\tau_{\rm b} &= 1556 \pm 10 \pm 17\, fs\,, \\
\langle x_E\rangle_b &= 0.709 \pm 0.004\,.
\end{aligned}
$$

The situation is illustrated in fig. 6. The error on $\langle x_E\rangle_b$ includes statistical and systematic uncertainties. These results are preliminary.

Lepton Impact Parameter Method

Event Selection

Electron candidates have been identified as charged electromagnetic clusters in the BGO calorimeter. The fiducial volume covered the barrel part, given by the polar angle range of $|\cos\theta| < 0.69$. An electromagnetic cluster was required to have more than 5 crystals with signal, more than 95% of the energy contained in a 3x3 matrix and a shower shape consistent with the deposit of an electromagnetic particle ($\chi^2_{\rm em\ shape} < 6$). The dominant background in the selection were hadronic particles. Those have been rejected by requiring an optimum energetic and angular matching between TEC track and BGO cluster in the bending plane ($\delta\phi < 5$ mrad, $\chi^2_{\rm energy} < 3$. In addition, the energy deposited in the hadron calorimeter inside a cone of half-angle 7° around the cluster direction had to be smaller than 3 GeV. The background from photon conversions, which increased due the presence of the SMD in 1993 and 1994, was still very low.

Muon candidates were identified as charged tracks in the muon spectrometer, satisfying $|\cos\theta| < 0.72$. Only muons with an associated TEC track and momentum and polar angle measurements were accepted for the analysis. Punch-through tracks from longlived hadrons were rejected by requiring a good consistency between the track extrapolation to the center of the beam collision point. Monte Carlo simulations showed that the contamination from K^0 or Λ decay products was small.

The fraction of $b\bar{b}$ events in the sample was enhanced by selecting leptons with high momentum and transverse momentum with respect to the closest jet. For this operation the jet parameters were redefined subtracting the lepton four-momentum. For electrons the cluster energy had to be larger than 3 GeV and the transverse momentum greater than 1 GeV. For muons the cuts were 4 GeV and 1.5 GeV, respectively.

The TEC track associated to the lepton candidate had to satisfy the following stringent criteria in order to provide accurate lifetime information:

- The track should contain at least 45 signals spanned over a distance of at least 58 wires.
- The azimuthal distance between the track at the origin and any cathod plane must be larger than 22 mrad.
- The azimuthal distance between the track at the origin and anode planes must be larger than 13 mrad for an inner anode planes and 11 mrad for outer anode planes.
- The TEC transverse momentum must be in the range [2 , 35] GeV/c.
- The impact parameter with respect to the average fill vertex can not exceed 5 mm. The mean value expected in semileptonic b-decays is below 0.5 mm.
- In the 1994 sample, the presence of a hit in the inner $r\phi$ layer of the SMD was required.

The quality cuts for leptons were choosen more stringent as in the hadron track selection because a single lepton track was sufficient to perform a lifetime fit, whereas several tracks were needed for the reconstruction of a secondary vertex. After all cuts have been applied, a sample of 17647 electron candidates and 23062 muon candidates was obtained. The expected sample composition is shown in Table 2 for the 1994 detector setup.

Lifetime fit

The inclusive b lifetime has been determined from a likelihood fit to the impact parameter $\delta^{r,\phi}$ distribution of the lepton candidates. In the following the variable δ will always denote the impact parameter $\delta^{r,\phi}$ in the bending plane. The impact parameter distribution for the lepton candidates has been expressed as a convolution of two functions: the true impact parameter distribution, which depended on the lifetime of b or c hadrons, and the resolution function, which described the smearing of δ due to finite resolution. The likelihood function $\mathcal{L}(\tau_\mathrm{b})$ is:

$$\mathcal{L}(\tau_\mathrm{b}) = \prod_{\mathrm{i}}^{\mathrm{tracks}} \left(\mathrm{f_b}\mathcal{P}_\mathrm{b}(\tau_\mathrm{b};\delta_\mathrm{i}) + \mathrm{f_{bc}}\mathcal{P}_\mathrm{bc}(\tau_\mathrm{b};\delta_\mathrm{i}) + \mathrm{f_c}\mathcal{P}_\mathrm{c}(\delta_\mathrm{i}) + \mathrm{f_{bkg}}\mathcal{B}(\delta_\mathrm{i})\right) \otimes \mathcal{R}(\delta_\mathrm{i},\phi_\mathrm{i},p_\perp,\sigma_{\mathrm{FIT,i}}) \qquad (1)$$

where $\mathcal{P}_\mathrm{b}$, $\mathcal{P}_\mathrm{bc}$, and $\mathcal{P}_\mathrm{c}$ were the impact parameter distributions for the prompt, cascade and charm components. They included the effects of lifetimes and the occasional mis-signing of δ, due to the approximation of the b hadron direction by the jet axis, but not the beam spot size nor the track measurement errors. The underlying distributions $\mathcal{P}_\mathrm{b}$, $\mathcal{P}_\mathrm{bc}$, and $\mathcal{P}_\mathrm{c}$ and the one for background tracks, $\mathcal{B}$, were extracted from Monte Carlo simulated events. $\mathcal{R}$, the track-by-track impact parameter resolution function, was parametrized as a superposition of three

Gaussian functions whose standard deviations depended on the track azimuthal angle ϕ_i, the momentum $p_\perp$ transverse to the beam, and the impact parameter error from the track fit $\sigma_{\mathrm{FIT},i}$:

$$\mathcal{R}(\delta_\mathrm{i}, \phi_\mathrm{i}, p_\perp, \sigma_{\mathrm{FIT,i}}) = \sum_{\mathrm{j=1}}^{3} \frac{\mathrm{f_j}}{\sqrt{2\pi}\sigma_{\mathrm{ij}}} \exp\left(-\frac{\delta_\mathrm{i}^2}{2\sigma_{\mathrm{ij}}^2}\right) \qquad \text{with} \quad \sum_{\mathrm{j=1}}^{3} \mathrm{f_j} = 1. \tag{2}$$

The j^{th} impact parameter resolution for the i^{th} track, σ_{ij}, was:

$$\sigma_{ij}^2 = a_j^2 \sigma_{\mathrm{FIT}}{}_{,i}^2 + (\sigma_\mathrm{h}^2 \sin^2\phi_i + \sigma_\mathrm{v}^2 \cos^2\phi_i) + \sigma_{\mathrm{ms}}^2(p_\perp) \tag{3}$$

where σ_h and σ_v were the beam spot transverse widths in the horizontal and vertical directions, respectively. The estimate of the uncertainty due to multiple scattering as a function of the momentum was $\sigma_{\mathrm{ms}}(p_\perp)$.

The factors a_j account for possible degradations of the resolution for a fraction $\mathrm{f_j}$ of tracks, due to the hadronic environment. The conditions $a_1 = 1$, $a_2 = a_3 = 0$ and $\mathrm{f_1} = 1$, $\mathrm{f_2} = \mathrm{f_3} = 0$ apply to the ideal case of high energy tracks in low multiplicity events (bhabha and dimuon events). The procedure to determine the parameters a_j, $\mathrm{f_j}$ of the resolution function followed the one developed in our previous publication [3]. A resolution sample has been selected by imposing the same track quality cuts on a sample of tracks that were unlikely to come from secondary decays. Typical results were: $a_1 \approx 1.2$, $a_2 \approx 2$, $a_3 \gg 4$, $\mathrm{f_1} \approx 0.8$, $\mathrm{f_2} \approx 0.2$, $\mathrm{f_3} \approx 0$.

In order to reduce systematic uncertainties which would otherwise limit the increase in statistical accuracy compared to our previous publication additional free parameters have been introduced in the likelihood fit. The relevant changes were:

- The parameters $\mathrm{f_j}$ have been left free. These fractions are not supposed to be similar for primary and secondary tracks, because they follow different distributions in phase space. Monte Carlo studies showed that $\mathrm{f_1} \approx 1$, $\mathrm{f_2} \approx 0$ for secondaries while $\mathrm{f_1} \approx 0.8$, $\mathrm{f_2} \approx 0.2$ for the sample enriched in primary tracks. In the previous analysis, a simple reweighting method on the expected relevant variables was applied.

- The background fraction, $\mathrm{f_{bkg}}$, was also treated as a free parameter. The background contribution $\mathcal{B}$ is almost invariant under the change $\delta \leftrightarrow -\delta$, which can be disentangled from the asymmetric shape of $\mathcal{P}_\mathrm{b}$. This approach decreased the statistical sensitivity of the fit, but reduced the systematics due to physics ($\mathrm{R_b}$, $\mathrm{Br(b \to \ell\nu X)}$, ...) by a sizeable amount.

The fit results are shown in Table 3 and in figure 7.

Systematic errors

The different sources of systematic errors can be found in Table 4. Theoretical uncertainties have been assigned following the recommendations of the LEP Heavy Flavour Electroweak Group in [12]. We observed small dependences with the Monte Carlo parameters that govern the heavy flavour production and decay fractions properties. The relevant uncertainties came from the theoretical description of the underlying distributions and from the performance of the central tracking detector.

Taking into account the correlation between muon and electron channel uncertainties, the final combined result was:

$$\tau_\mathrm{b} = (1544 \pm 16 \pm 21)\,\mathrm{fs}$$

where the first error is statistical and the second is systematic. This result is preliminary.

Results

The results from the secondary vertex and lepton analysis have been combined as an average from nine measurements. The mesurements with electrons and muons in the years 1991 to 1994 were added to the result from the secondary vertex analysis in 1994 taking into account the proper correlations between the measurements. The statistical correlation between the lepton and secondary vertex measurement was neglegible. The dominant systematic errors, the uncertainty in the underlying lepton distributions and the lepton track selection criteria on the one side and the charm hadron composition on the other side, were also independent in both measurements. The average from both methods is:

$$\tau_{\mathrm{b}} = (1549 \pm 9 \pm 15)\,\mathrm{fs}$$

where the first error is statistical and the second is systematic.

The result is in good agreement with our previous measurements of τ_{b}, with the World Average of the Particle Data Group 1550 ± 20 fs [10] and the recent update of the LEP B Lifetime Working Group 1566 ± 17 fs [15].

The secondary vertex analysis yielded in addition a measurement of the average b decay multiplicity and the normalized average b energy at LEP:

$$\begin{aligned} \langle n_b \rangle &= (4.90 \pm 0.04 \pm 0.11) \\ \langle x_E \rangle_b &= 0.709 \pm 0.004\,. \end{aligned}$$

These results are preliminary.

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Error source	$\Delta\tau_b^P$ (fs)	$\Delta\tau_b^{DL}$ (fs)	Δn_b
Detector Uncertainties	11	11	0.04
Quality track multiplicity	5	2	0.04
Resolution function	5	5	<0.01
TEC calibration and SMD alignment	3	3	<0.01
Beam spot size and position	6	7	<0.01
Jet direction resolution	5	5	<0.01
Heavy Quark Physics Modeling	16	32	0.10
b fragmentation	9	30	0.02
c fragmentation	<1	2	<0.01
b decay multiplicity distribution	4	4	0.06
D fraction in $c\bar{c}$ events	3	2	<0.01
D content in b decays	11	10	0.04
D lifetimes	3	2	<0.01
R_b	4	4	0.07
R_c	2	2	0.01

Table 1: Systematic errors in the measurement of τ_{b} with secondary vertices. The first column shows the errors for the impact parameter method, the second for the decay length method. The corresponding errors in the b decay multiplicity $\langle n_b \rangle$ are given in the third column.

Composition (94)	Electrons	Muons
$b \to lX$ (Prompt)	83.1%	76.2%
$b \to c \to lX$ (Cascade)	9.6%	9.1%
$c \to lX$ (Charm)	4.6%	7.8%
Background	2.7%	6.9%

Table 2: Composition of the 1994 sample of selected lepton candidates, as estimated from the Monte Carlo simulation.

Electrons	91 data	92 data	93 data	94 data
τ_b (ps)	1.537 ± 0.066	1.496 ± 0.046	1.506 ± 0.046	1.555 ± 0.036
f_1	1.030 ± 0.046	0.995 ± 0.033	1.014 ± 0.029	0.947 ± 0.016
f_2	-0.033 ± 0.046	-0.003 ± 0.033	-0.033 ± 0.030	0.052 ± 0.016
f_{bkg} (%)	4.7 ± 6.0	11.6 ± 3.5	13.1 ± 3.5	11.6 ± 1.9
Muons	91 data	92 data	93 data	94 data
τ_b (ps)	1.688 ± 0.101	1.504 ± 0.042	1.478 ± 0.043	1.627 ± 0.034
f_1	0.963 ± 0.029	0.828 ± 0.030	0.917 ± 0.064	0.967 ± 0.016
f_2	0.037 ± 0.029	0.158 ± 0.030	0.062 ± 0.063	0.030 ± 0.016
f_{bkg} (%)	10.9 ± 6.0	1.1 ± 3.9	5.1 ± 4.4	9.6 ± 1.9

Table 3: Final results of the likelihoods fit for the lepton impact parameter distributions. The fitted parameters f_1, f_2 and f_{bkg} are reasonably consistent with the Monte Carlo expectations. Errors are only statistical.

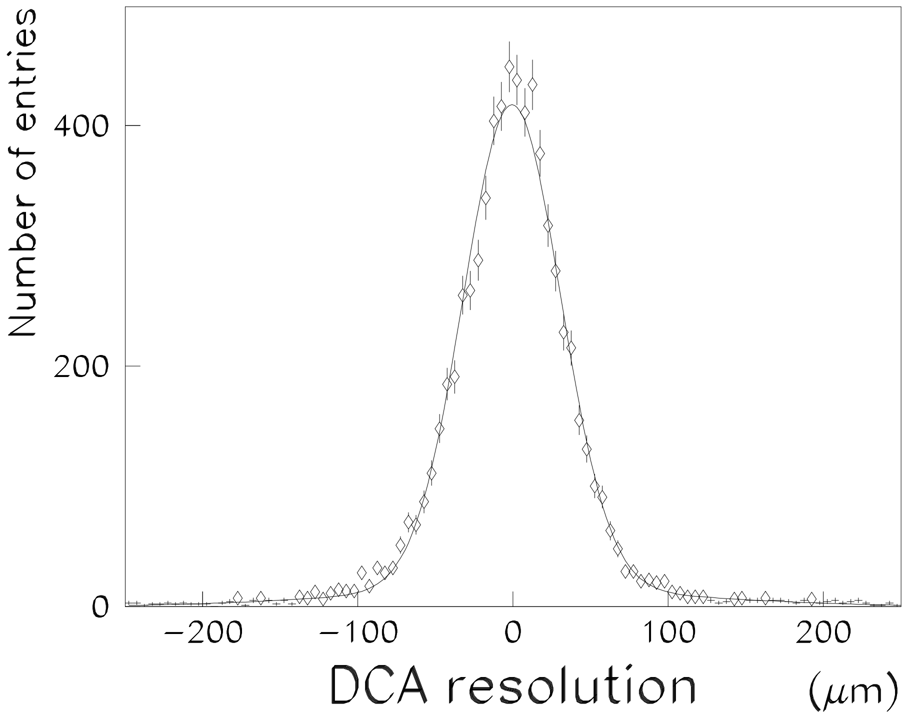

Figure 1: The resolution on the impact parameter. It was derived from the distribution of the distance at which electrons from Bhabha events miss each other at the beam center by scaling the distribution's width by $1/\sqrt{2}$. The superimposed gaussian fit has a width of 32 μm.

Source	$\Delta\tau_{\mathrm{b}}^{\mathrm{e}}$ (ps)	$\Delta\tau_{\mathrm{b}}^{\mu}$ (ps)	Correlated ?
Monte Carlo Parameters			
• $\mathrm{R_b}$	±0.0	±0.5	Yes
• $\mathrm{R_c}$	±1.5	±1.0	Yes
• $< x_E >_b$	±4.5	±2.5	Yes
• $< x_E >_c$	±1.0	±1.0	Yes
• Semileptonic Branching Fractions	±0.5	±0.5	Yes
• Inclusive lepton Spectra:			
$\mathrm{b} \to \ell$	${}^{+4.5}_{-0.5}$	${}^{+6.5}_{-1.5}$	Yes
$\mathrm{c} \to \ell$	${}^{+0.5}_{-3.0}$	${}^{+1.0}_{-4.0}$	Yes
• τ_c Lifetime:			
$\mathrm{c} \to \ell$	±0.0	±0.5	Yes
$\mathrm{b} \to \mathrm{c} \to \ell$	±4.0	±4.0	Yes
Angular Jet Resolution	±4.0	±5.0	Yes
Underlying Distributions:			
• $\mathcal{P}_{\mathrm{b}}$	±14.0	±11.0	No
• $\mathcal{P}_{\mathrm{bc}}$	±7.0	±6.0	No
• $\mathcal{P}_{\mathrm{c}}$	±1.5	±1.0	No
Experimental Resolution:			
• Resolution Function	±3.0	±1.5	No
• Monte Carlo Statistics	±0.0	±0.0	No
• Bias from MC τ_{b} input	±0.0	±0.0	Yes
TEC Calibration Corrections	±14.5	±9.0	Yes
Primary Vertex Uncertainty	±5.5	±6.0	Yes
Beam Spot Uncertainty	±0.5	±0.0	Yes
Background Parametrization	±2.0	±7.0	Yes
Track Selection Criteria:			
• Distance to Closest Track	±5.0	±5.0	Yes
• p_t cut	±10.0	±10.0	Yes
• Number of wires with Signal	±10.0	±10.0	Yes

Table 4: Systematic errors in the measurement of τ_{b} with leptons. The errors for the electron measurement are given in the first column, that for the muons in the second column. The third column flags the cases in which the errors for the muon and the electron channel are considered as fully correlated. The systematics due to uncertainties in the Monte Carlo input parameters and on the resolution function were small. Several uncertainties, as for instance the TEC calibration, depended from the running period and were not fully correlated between the years. The values in the table represent the average values from 1991 to 1994. In the calculation of the final result, the year specific systematic errors were used. From that calculation the overall systematic error has been estimated to 21 fs.

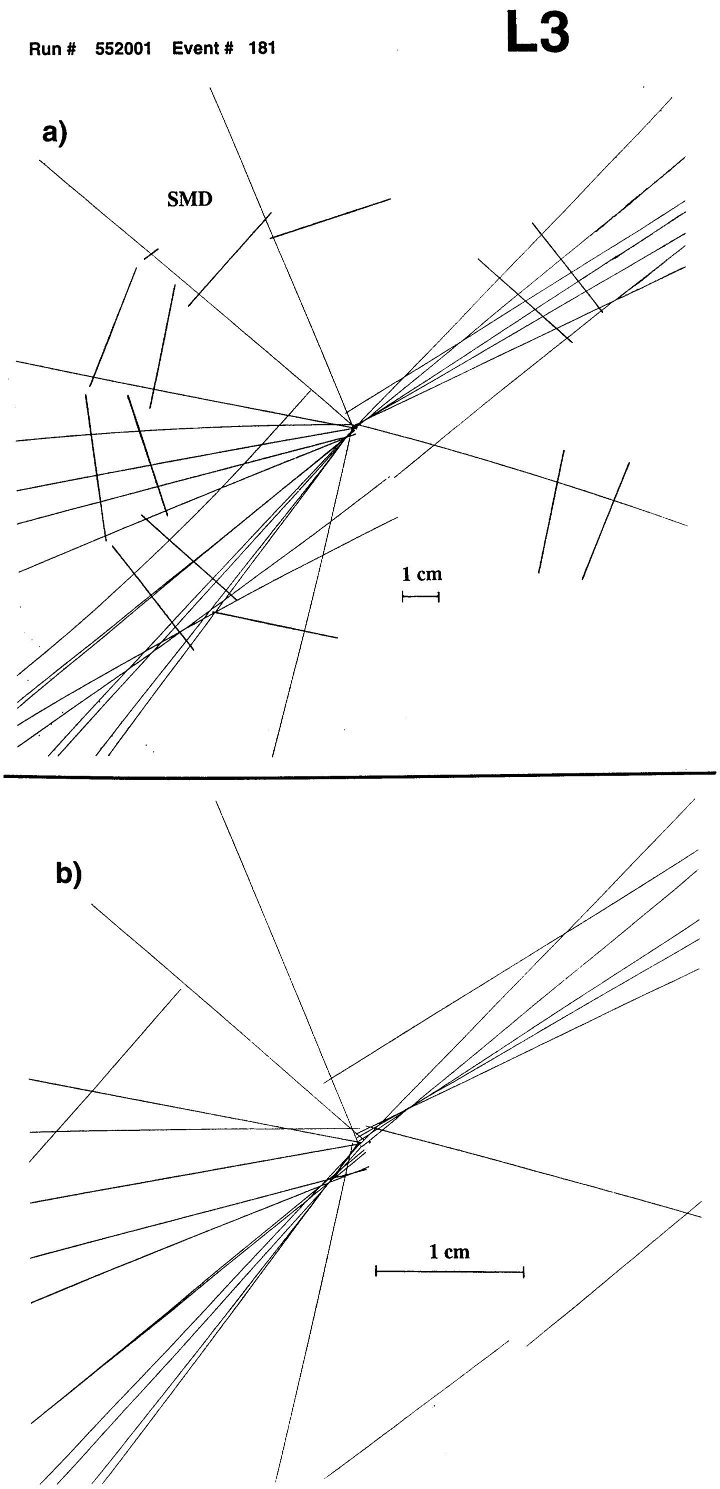

Figure 2: A $b\bar{b}$ candidate event in 1994 data shown in the $r\phi$ plane of the L3 detector: a) at the level of the Silicon Microvertex Detector and b) in a zoom of the vertex region.

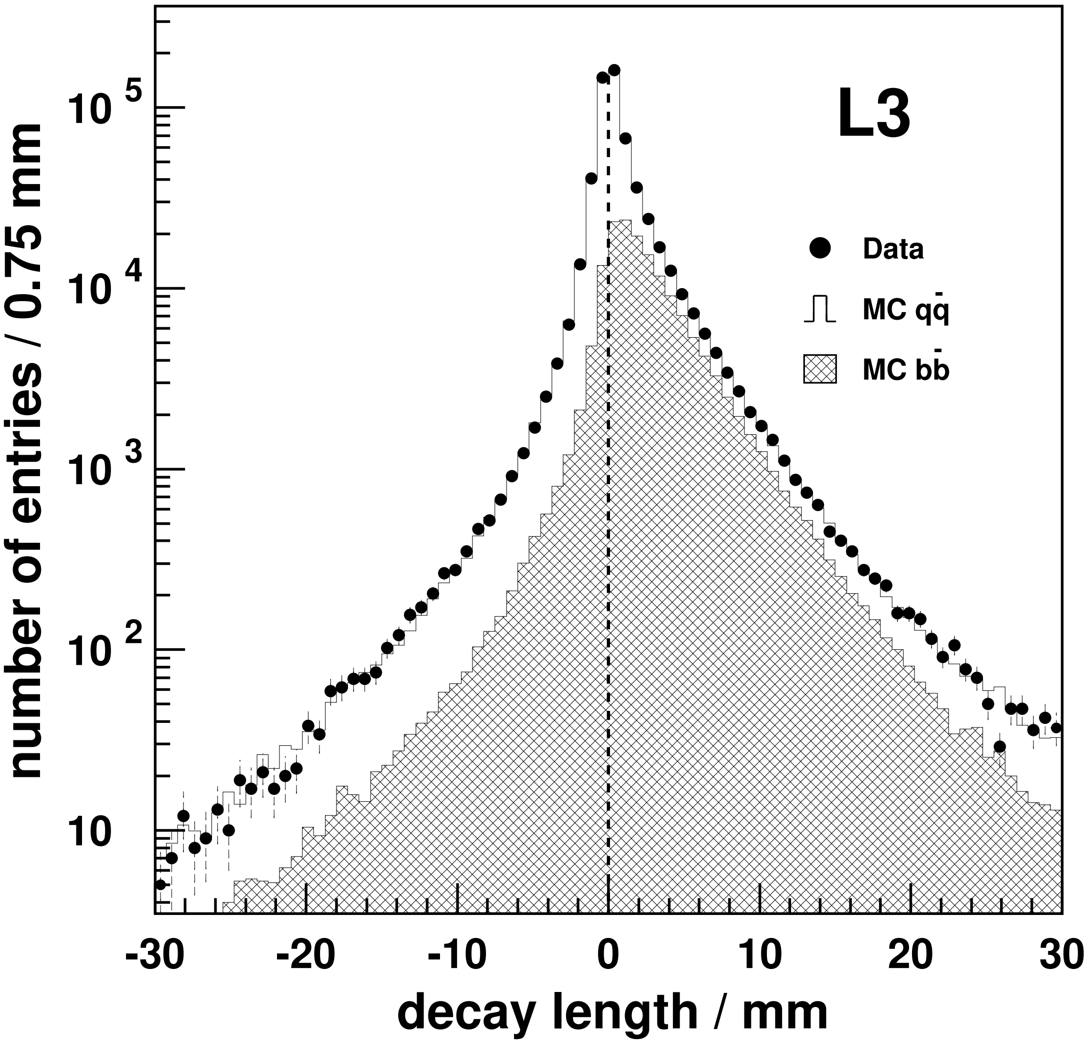

Figure 3: Decay length distribution of reconstructed secondary vertices. The points represent the 1994 data and the histogram shows the MC distribution for the fitted lifetime $\tau_{\mathrm{b}} = 1.582$ ps. The b component in the MC sample is indicated by the shaded histogram.

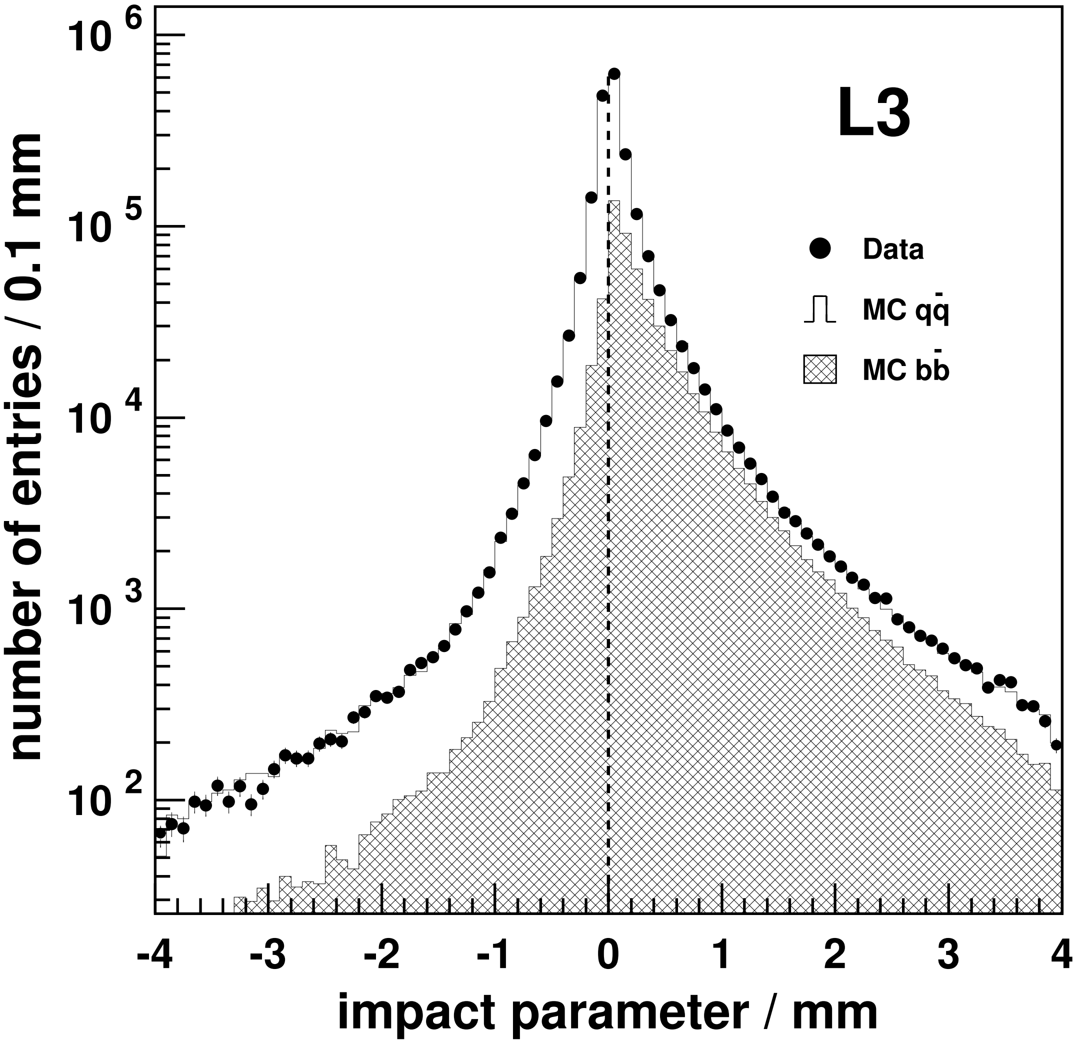

Figure 4: Impact parameter distribution of tracks from secondary vertices. The points represent the 1994 data and the histogram shows the MC distribution for the fitted lifetime $\tau_{\mathrm{b}} = 1.564$ ps. The b component in the MC sample is indicated by the shaded histogram.

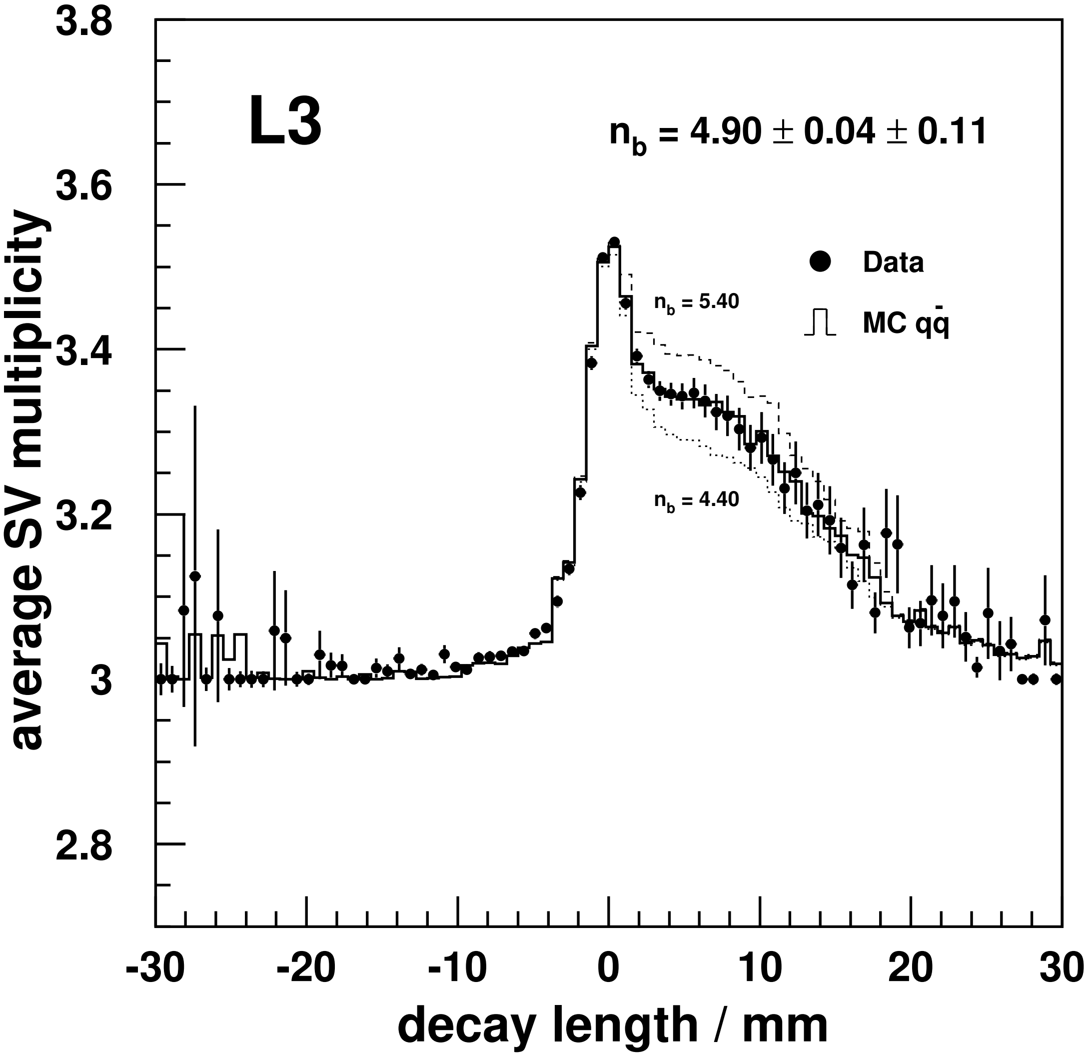

Figure 5: Average multiplicity of tracks at the secondary vertices as a function of the decay length. The points represent the 1994 data and the histogram shows the MC distribution for the fitted average b decay multiplicity $n_b = 4.90$.

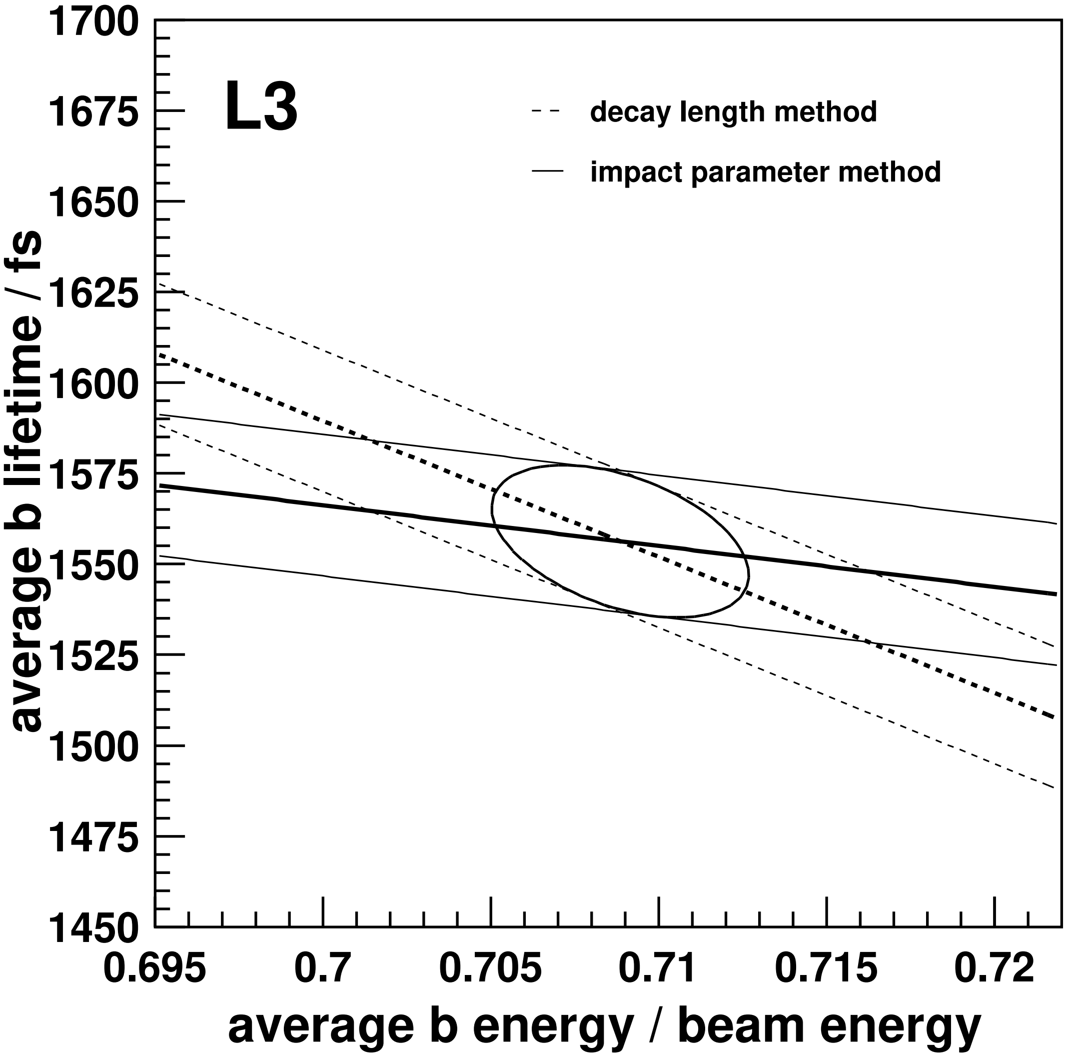

Figure 6: Combination of impact parameter and decay length measurement. Both measurements are compatible with each other at an average b energy of $\langle x_E \rangle_b = 0.709 \pm 0.004$ (scaled to the beam energy) and a b lifetime of $\tau_\mathrm{b} = 1.556 \pm 20$ fs.

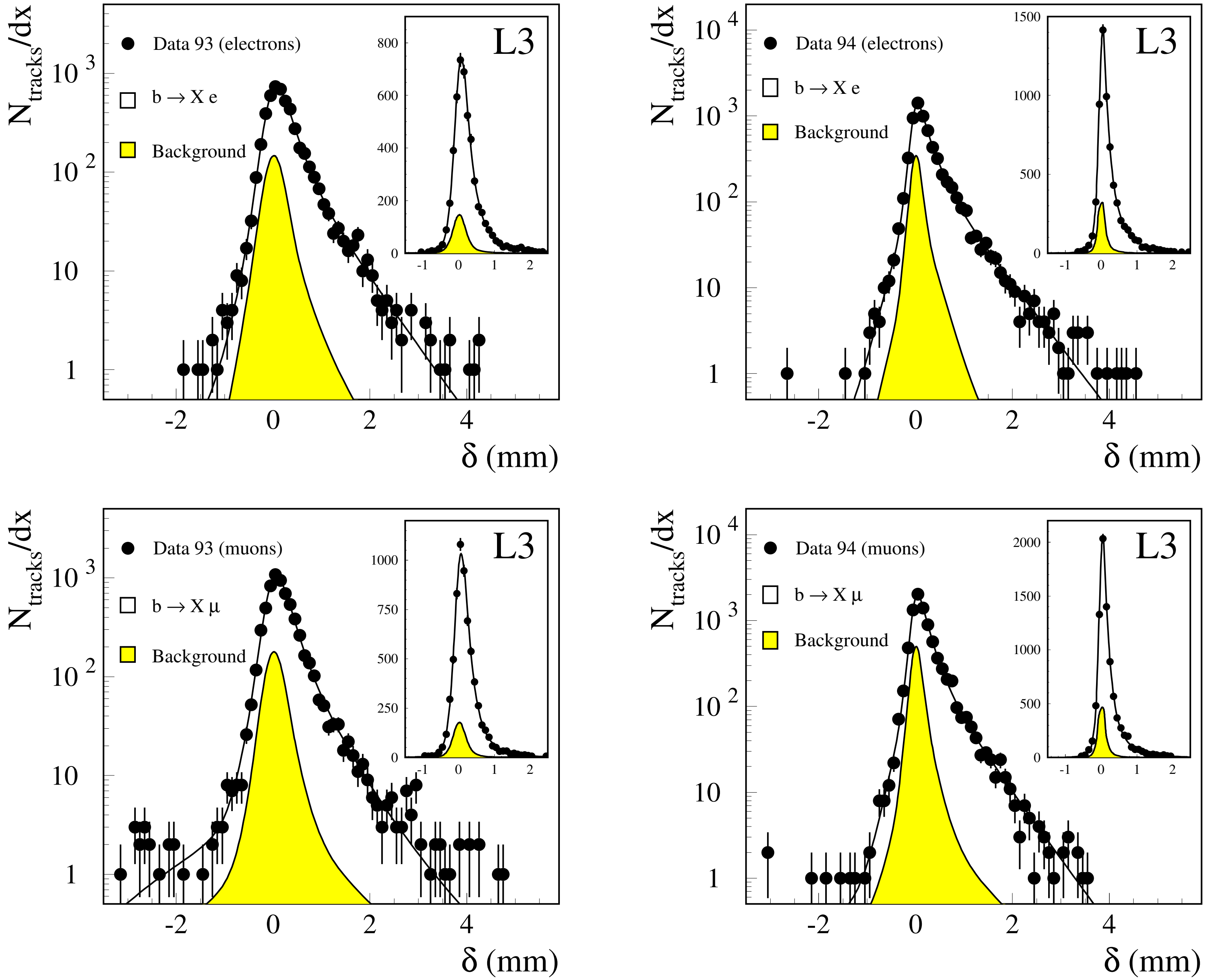

Figure 7: Results of the likelihood fits for the lepton impact parameter distribution in 1993 and 1994. Both logarithmic and linear scales are shown.