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Updated precision measurement of the average lifetime of B hadrons

DELPHI Collaboration

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Abstract

The measurement of the average lifetime of B hadrons using inclusively reconstructed secondary vertices has been updated using both an improved processing of previous data and additional statistics from new data. This has reduced the statistical and systematic uncertainties and gives $\tau_B = 1.582 \pm 0.011$ (stat.) ± 0.027 (syst.) ps. Combining this result with the previous result based on charged particle impact parameter distributions yields $\tau_B = 1.575 \pm 0.010$ (stat.) ± 0.026 (syst.) ps.

[1] On leave of absence from IHEP Serpukhov.

1. Introduction

The precise measurement of the B hadron lifetime is important for the study of the weak decays of the b quark and of its couplings to the u and c quarks. Several direct measurements of the average lifetime of B hadrons, τ_B, have been performed at e^+e^- and $p\bar{p}$ colliders [1,2]. In this paper, an update to the previous result based on reconstructing secondary vertices is presented. In this method, the secondary vertices are used to reconstruct the B hadron decay length distribution. The mean B hadron lifetime is proportional to the mean decay length, the proportionality constant being determined by the momentum distribution (or fragmentation function) of the B hadrons. The result in this paper includes the data used for the secondary vertex method described in [1], therefore it supersedes the previous result based on this method.

2. The DELPHI detector

The DELPHI detector has been described in detail elsewhere [3], only those components which were relevant to these analyses are discussed here.

The tracking of charged particles was accomplished with a set of cylindrical tracking detectors whose axes were oriented along the 1.23 T magnetic field and the direction of the beam. The z axis was defined to be along the axis of the magnetic field, with positive z pointing in the direction of the outgoing electron beam. The Vertex Detector (VD) [4], located nearest the LEP interaction region, provided measurements in $R\phi$. The VD had an intrinsic precision of 5–6 μm and consisted of three concentric layers of silicon microstrip detectors at average radii of 6.3 cm, 8.8 cm, and 10.9 cm. Outside the VD between radii of 12 cm and 28 cm was the Inner Detector (ID), a jet chamber giving up to 24 spatial measurements. The VD and ID were surrounded by the main DELPHI tracking chamber, the Time Projection Chamber (TPC), which provided up to 16 space points between radii of 30 cm and 122 cm. The Outer Detector (OD) at a radius of 198 cm to 206 cm consisted of five layers of drift cells. The average momentum resolution of the tracking system was measured to be $\sigma(p)/p = 0.001\ p$ (where p is expressed in units of GeV/c), in the polar region between 30° and 150°.

After alignment corrections had been applied, the precision of the charged particle track extrapolation to the interaction region was measured using high momentum muons from $Z \rightarrow \mu^+\mu^-$ events. For charged particles with a polar angle, θ, between 45 and 135 degrees, having 2 or more associated VD hits, a value of $26 \pm 2\ \mu$m for this precision was obtained. In hadronic events, the extrapolation accuracy has been measured over the full momentum range to be $\sqrt{26^2 + 69^2/p_t^2}\ \mu$m, where p_t is the transverse momentum of the particle with respect to the z axis and is measured in units of GeV/c.

3. Data sets and event selection

The analysis used the data collected with the DELPHI detector during 1991 to 1993. After the following selection, the data contained over 1.5 million hadronic events.

Charged particles were required to have a measured momentum, p, greater than 100 MeV/c and less than 50 GeV/c, a polar angle, θ, greater than 20° and less than 160°, a reconstructed charged particle track length of more than 20 cm, and a distance of closest approach to the centre of the beam interaction region of less than 5 cm in radius and less than 10 cm in z. Neutral particles were required to have a measured energy of at least 100 MeV and less than 50 GeV.

Hadronic events were selected which contained at least 7 charged particles, where the sum of the squared transverse momenta of these particles was greater than 9 GeV^2/c^2. Furthermore, the sum of both the momentum of charged particles and energy of neutral particles in these events was required to be greater than 16 GeV or the invariant mass of the charged particles (neglecting the mass of each particle) had to be greater than 12 GeV/c^2.

A detailed Monte Carlo simulation was needed to help identify events containing B decays and extract the physics functions used to measure the lifetime. Thus, two Monte Carlo data sets of hadronic events were generated [5] and passed through a detailed simulation of the detector. In one sample, all the B hadron lifetimes were set to 1.200 ps, except the Λ_b lifetime which was set to 1.300 ps. This corresponded to an average lifetime for B hadrons of 1.208 ps. In the other sample, the lifetimes of all B hadrons were

1.600 ps, except for the Λ_b for which it was 1.300 ps. The average lifetime of B hadrons in this sample was 1.576 ps. Another simpler simulation was developed to model the charged particle track efficiency, position and momentum resolution of DELPHI detector. This was used to create large simulated data samples with different average lifetimes of B hadrons and fragmentation functions.

4. Lifetime analysis

The techniques for inclusively reconstructing secondary vertices, identifying B hadrons using these vertices and extracting an average B hadron lifetime using this information have been described in Section 5 of [1]. In this paper the analysis has not changed, the only difference being the increased statistics originating from the addition of the 1993 data set, and the use of a better understood 1991 and 1992 data set.

4.1. Secondary vertex identification

The procedure to find secondary vertices consisted of two parts. The first part was to define which charged particles belonged to candidate vertices. The second part was to refine these vertices by removing mis-associated charged particles and measuring the properties of the remaining candidate vertices [1].

Candidate vertices that contained four or more charged particles were considered to be secondary vertices. The simulations were used to check their reliability. The total energy, momentum and invariant mass of the charged particles at the vertex and the errors on the position of the vertex were then calculated. The radial precision of the reconstructed vertices was found to be 479 ± 11 μm.

4.2. B enrichment

The decay length, L, was calculated using the measured momentum, $\boldsymbol{P}_{\mathrm{vis}}$, defined to be the vector sum of the momenta of the individual charged particles associated with the vertex, and the transverse momentum, $P_{t\,\mathrm{vis}} = \sqrt{P^2_{x\,\mathrm{vis}} + P^2_{y\,\mathrm{vis}}}$, of the vertex. Then

$$L = R\,\frac{|\boldsymbol{P}_{\mathrm{vis}}|}{P_{t\,\mathrm{vis}}} = R/\sin\theta,$$

where θ is the angle between the momentum vector and the beam axis and R is the radial distance of the reconstructed vertex position from the beam centre. Vertices associated with random charged particle crossings were a source of vertex contamination. This background was reduced by requiring the number of charged particle tracks in a reconstructed vertex (v_{mult}) to be four or more. Vertices at low values of R were another source of background, since these vertices contained a large number of particles associated with the primary vertex. To reduce the number of such vertices, L was required to exceed 1.5 mm. Finally, in order to suppress light quark events, the largest invariant mass ($m_{v\,\mathrm{max}}$) associated with a vertex in the event passing the above requirements was required to exceed 1.7 GeV/c^2.

In the simulation, after requiring $m_{v\,\mathrm{max}} > 1.7$ GeV/c^2, $v_{\mathrm{mult}} \geq 4$ and $L > 1.5$ mm, the purity for events generated with $\tau_{\mathrm{B}} = 1.576$ ps was $93.5 \pm 0.3\%$ and the efficiency was $7.87 \pm 0.09\%$. In addition to increasing the purity, these selection criteria improved the reconstructed vertex precision from 479 ± 11 μm to 301 ± 24 μm.

This purity measured using the simulation was verified with the data in two ways. First, by fitting the momentum distributions of the leptons in these events and using the known branching ratios for $b \to$ lepton, $b \to c$ and $c \to$ lepton [6]. This method measured a purity of $91.9 \pm 2.0\%$. Second, by counting the number of events where two vertices were selected in the data, using the efficiency measured in the simulation for the background and using the known value of $\Gamma_{b\bar{b}}/\Gamma_{\mathrm{had}}$ [6], it was possible to measure the purity. After accounting for correlations induced due to the detector acceptance and beam centre correlations, the purity was measured in the data to be $93.1 \pm 0.3\%$.

4.3. Average B hadron lifetime

In a hemisphere, the B hadron vertex is expected to be the vertex closest to the beam centre. Therefore, in each hemisphere, only the closest vertex was used. In addition to the cuts needed for B enrichment, a cut of $L > 2.1$ mm has also been required in order to minimize systematic effects which were observed with the increased statistics (see Section 4.4). After applying this cut a total of 23167 vertices were selected in the 1991–1993 data.

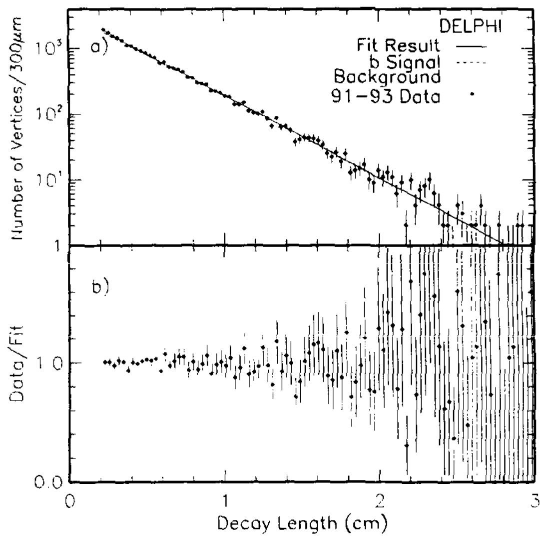

Fig. 1. a) Result of the fit to the decay length distribution of the 1991–1993 data, where $\tau_B = 1.582 \pm 0.011$ ps. The lower curve shows the background assumed in the fit using a parameterization for the background from the simulation and b) the ratio of the data to the fitted curve.

Separating the contributions coming from the $b\bar{b}$, $c\bar{c}$ and light quark events, decay length distributions were extracted from the simulation. The L distributions for the $c\bar{c}$ and light quark events were parameterized by the sum of two exponentials. The $b\bar{b}$ signal was parameterized by a single exponential, $\exp(-L/A)$. The simulations confirmed that the fitted value of the slope A could be parameterised as a linear function of the mean B hadron lifetime. The parameters of this linear dependence were determined from the simulation. Using the purity determined from the simulation, a likelihood fit was performed on the data to extract the slope of the exponential for the signal. The B hadron lifetime, in the data, was then calculated using this linear relationship. Fig. 1 shows the result of the fit to the data, yielding a value for the average B hadron lifetime of 1.582 ± 0.011 ps. Independent samples of Monte Carlo events were used to check the method. The lifetimes measured for these samples were 1.205 ± 0.016 ps and 1.590 ± 0.019 ps, to be compared with the generated values of 1.208 ps and 1.576 ps.

4.4. Systematic uncertainties

The B hadron lifetime was extracted from the distribution of the decay length. The distance L is equal to $\gamma\beta c t_B$ and thus depends on the momentum distribution of the B hadrons. The fragmentation of the Z into B hadrons in the simulation agreed with the mean B energy value measured by DELPHI [7].

To measure the effect of fragmentation uncertainties on the measured lifetime, the mean value of the fragmentation distribution was varied in the simulation. Shifts in the mean value were directly related to shifts in the measured value of the lifetime. Therefore, the estimate of the systematic uncertainty of ± 0.019 ps was due to the uncertainty of the mean value of X_E, measured to be $0.7020 \pm 0.0044 \pm 0.0021 \pm 0.0071$ [7], where $X_E = P_B/E_{BEAM}$.

Inherent to this analysis was an uncertainty in the knowledge of the B hadron lifetime coming from the linear parameterization of the exponential slope as a function of lifetime. The errors calculated for the linear parameterization contributed an uncertainty of 0.014 ps in the measurement of the lifetime.

The range in decay length fitted to determine the lifetime was varied, both by decreasing the maximum allowed distance and by increasing the minimum required distance. If there are differences in the lifetimes of the different B species a systematic variation in the measured average lifetime should be observed especially as the minimum decay length is varied. It is expected that the average lifetime should increase as the minimum decay length is raised. Also, as the minimum decay length is increased, higher momentum B hadrons are selected due to the shape of the fragmentation function. Therefore, differences in the shape of the fragmentation in the data and simulation can lead to systematic uncertainties in the measured average B hadron lifetime. Differences in lifetime between the different B hadrons and differences between the data and simulation in the shape of the B fragmentation function would both give a variation approximately proportional to the minimum decay length.

As shown in Fig. 2, the minimum decay length was varied from 1.5 mm to 7.2 mm. The measured average lifetime at 1.5 mm in Fig. 2 differs from the lifetime at 2.1 mm by 3.8 standard deviations after accounting for the strong correlation between these two measurements. The other lifetimes plotted in Fig. 2 are consis-

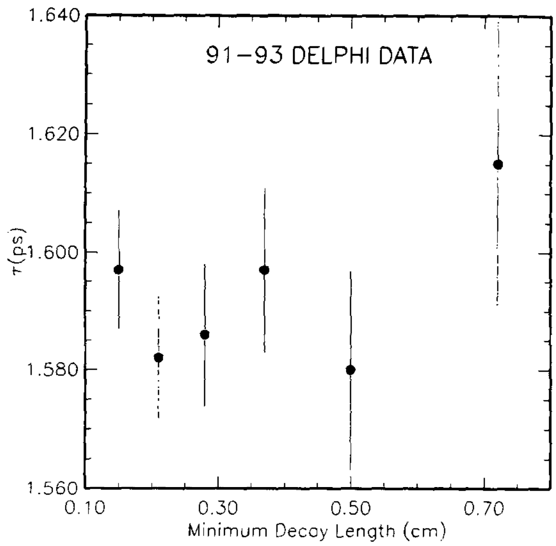

Fig. 2. The average B hadron lifetime as a function of the minimum decay length.

tent within the statistical errors. In the previous measurement, this effect was not seen due to the lack of statistics. Therefore, an additional cut of $L > 2.1$ mm has been made to reduce the uncertainty in the lifetime associated to this effect. When a linear fit to the resulting average lifetimes as a function of minimum decay length (for $L > 2.1$ mm) was extrapolated to zero minimum decay length, it yielded a value for the lifetime which differed by 0.008 ps from the quoted result. Therefore a systematic uncertainty of 0.008 ps was attributed for this effect.

The measurement of the lifetime depends on the determination of the angle θ. To check for any possible bias in θ due to detector effects, the data were separated into six ϕ bins in both positive and negative z, since the TPC, which measures θ, is divided in this way. The lifetimes were then computed separately in each region. The main systematic in the 1992 data set used in [1] was a detector effect which caused the lifetime to vary as a function of ϕ and z. In this measurement, a more recent processing of 1992 data has been used, where the alignment and other detector parameters are better understood. No systematic shifts in the lifetime were observed and therefore no systematic uncertainty due to detector dependent effects has been assigned. An uncertainty of 0.007 ps has been assigned based on the known measurement uncertainty in θ.

If the production rates of b and c hadrons, the subsequent branching ratios of b hadrons into c hadrons and the lifetimes of the c hadrons in the simulations were different from those in the data, this would also affect the measurement of the average B hadron lifetime. These production rates and branching ratios were varied within the uncertainties of their measured values [6]. The lifetimes of the c hadrons were varied independently for both the D^0 and $D^{\pm}$ by $\approx \pm 1.2\%$ [6] and the D_s by $\approx \pm 3.5\%$. The combined systematic uncertainty, due to these effects, on the average B hadron lifetime has been estimated to be 0.006 ps.

The measured distance, L, was distorted by the association of charged particles from cascade c decays as well as intrinsic detector resolution. The radial shifts of the vertex position were studied in the simulation. The difference between the measured radial distance R and the generated radial distance $R_{\rm phys}$ is given by $\rho = R_{\rm phys} - R$. The resolution for ρ was found to be 301 ± 24 μm and peaked near zero. A tail observed at negative values of ρ was attributed to charged particles from subsequent cascade decays moving the vertex position radially outwards, by an average of 95 ± 17 μm. The data were selected based on the error distribution of L, ΔL, in order to check if there were any systematic biases due to measurement uncertainty and resolution. The lifetime was recalculated and the maximum change of 0.005 ps was attributed as the systematic uncertainty due to the choice of ΔL.

The purity was correlated to the lifetime through the shape of the decay length distributions. Therefore, the purity was not allowed to vary in the fit to extract the lifetime. The purity was measured with an accuracy of 0.34%. Thus, the purity was changed by $\pm$ 0.34% in the fitting procedure to find the corresponding shift in the lifetime. The systematic uncertainty in the lifetime due to the purity was found to be 0.003 ps.

Other possible sources of systematic uncertainty were considered. They were found to give negligible contributions to the overall systematic uncertainty, but are described here for completeness.

The data were selected based on the χ^2 probability of the vertex fit as a systematic check of the lifetime. The resulting changes in the measured lifetime were consistent within the expectations coming from statistical fluctuations.

The efficiency for reconstructing a B vertex was measured as a function of decay length in the simulation. The measured lifetime was sensitive only to changes in the efficiency as a function of decay length, in particular to differences between the data and simulation. Reassociation of charged particles from the secondary vertex to the beam centre, in the process of refining candidate vertices, sometimes caused the true secondary charged particles to be reassociated with the beam centre, thus causing the vertex to be lost. These reassociated charged particles were by definition charged particles not associated to the secondary vertex but having a small impact parameter with respect to the secondary vertex position. The average number of these charged particles as a function of decay length is a measure of the efficiency for reconstructing a vertex as a function of decay length. The number of reassociated charged particles as a function of decay length was measured in both the simulation and data and found to agree well, within the statistics. Therefore, no systematic uncertainty on the lifetime was attributed to the variation of the efficiency with decay length.

The vertex resolution was measured in the data and simulation. This was done by removing from the vertex the charged particle with the largest transverse momentum with respect to the flight direction and recomputing the vertex position. The impact parameter of this charged particle was then calculated with respect to the recomputed vertex position. The resolution could then be measured in the data, relative to the simulation, by measuring the width of this impact parameter distribution. The widths found in the data and simulation, as a function of L, were in good agreement.

The parameters which control the shape of the background were changed by their uncertainties. No significant change in lifetime was found. Also no significant change in lifetime was observed for different selections of vertex multiplicity or vertex charge, defined to be the total charge of the particles associated to the vertex.

The total systematic uncertainty of $\pm$ 0.027 ps was calculated by adding in quadrature all the uncertainties summarized in Table 1. The major improvement with respect to the previous analysis [1] comes from the use of a better understood 1992 data set and improved knowledge of the fragmentation of B hadrons.

The average lifetime for B hadrons is determined by the production fractions and lifetimes of the various B hadrons. Therefore, any selection bias, in choosing events, which changes the relative fractions of the species may change the measurement of the average lifetime. Table 2 lists the fraction of the various B hadrons remaining in this analysis after applying all selection criteria, compared to the fraction of these hadrons originally produced in the simulation, assuming all the B hadrons have lifetimes of 1.60 ps. However, if the Λ_B lifetime was changed to be 1.20 ps, then based on the 2.1 mm decay length cut and the mean value of X_E used in this paper, the Λ_B fraction would reduce to 0.055 and the B^0, $B^{\pm}$, B_s and other B Baryons fractions would become 0.411, 0.401, 0.125, and 0.008 respectively.

Table 1
Systematic sources of uncertainty in the measurement of τ_B.

Source of Uncertainty	$\Delta\tau_B$ (ps)
B Fragmentation	$\pm$ 0.019
Monte Carlo Statistics	$\pm$ 0.014
Fit Range	$\pm$ 0.008
$\Delta\theta$	$\pm$ 0.007
Cascade c Decays	$\pm$ 0.006
ΔL	$\pm$ 0.005
B Purity	$\pm$ 0.003
Total	$\pm$ 0.027

Table 2
Fraction of B hadrons before and after event selection as obtained from the simulation. The lifetime for all B hadron species was 1.60 ps.

B hadron type	Generated	Selected
B^0	0.394	0.405 $\pm$0.005
$B^{\pm}$	0.396	0.395 $\pm$0.005
B_s	0.120	0.123 $\pm$0.003
Λ_B	0.080	0.069 $\pm$0.002
Other B baryons	0.010	0.008 $\pm$0.001

5. Conclusions

The average lifetime of B hadrons has been measured by the DELPHI experiment using the 1991–1993 data with a method based on the inclusive reconstruction of secondary vertices in hadronic events. The result of the analysis is

$\tau_B = 1.582 \pm 0.011 \pm 0.027$ ps.

Combining this result with the previous result [1] which used charged particle impact parameter distributions, first requires the previous result to be corrected for the change in the accepted mean value of X_E. Correcting this previous result of

$$\tau_B = 1.542 \pm 0.021 \pm 0.045 \text{ ps}$$

yields

$$\tau_B = 1.531 \pm 0.021 \pm 0.044 \text{ ps}.$$

Using the techniques developed by the LEP B Lifetimes Group [8], combining these two results gives

$$\tau_B = 1.575 \pm 0.010 \pm 0.026 \text{ ps}.$$

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References

[1] P. Abreu et al. (DELPHI Collaboration), Z. Phys. C 63 (1994) 3.
[2] D. Buskulic et al. (ALEPH Collaboration), CERN-PPE/95-121 (1995), subm. to Phys. Lett. B;
F. Abe et al. (CDF Collaboration), Phys. Rev. Lett., 71 (1993) 3421;
O. Adriani et al. (L3 Collaboration), Phys. Lett. B 317 (1993) 474;
R. Akers et al. (OPAL Collaboration), Z. Phys. C 60 (1993) 217;
K. Abe et al. (SLD Collaboration), Phys. Rev. Lett 75 (1995) 3624.
[3] P. Aarnio et al. (DELPHI Collaboration), Nucl. Instrum. Meth. A 303 (1991) 233.
[4] N. Bingefors et al., Nucl. Instrum. Meth. A 328 (1993) 447.
[5] LUND JETSET 7.3, T. Sjöstrand and M. Bengtsson, Comp. Phys. Comm. 43 (1987) 367.
[6] Particle Data Group, Phys. Rev. D 50 (1994) 1173.
[7] P. Abreu et al. (DELPHI Collaboration), Z. Phys. C 66 (1995) 323.
[8] LEP B Lifetimes Working Group DELPHI 94-164 PHYS 467, 18 January 1995.