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Measurements of Mean Lifetime and Branching Fractions of b Hadrons Decaying to J/ψ

The ALEPH Collaboration [1]

Abstract

From a data sample of 450,000 hadronic events recorded with the ALEPH detector at LEP, 92 ± 10 events are observed containing a J/ψ meson decaying to $\mu^+\mu^-$ or e^+e^-. From these data the measured inclusive branching fraction for a b flavoured hadron to decay to a J/ψ is $BR(b \rightarrow J/\psi X) = 1.21 \pm 0.13(stat) \pm 0.08(syst)$ %, and the average b hadron lifetime in the events tagged with a J/ψ is $\tau_b = 1.35^{+0.19}_{-0.17} \pm 0.05\ ps$. Five events are observed consistent with the exclusive decay $B^\pm \rightarrow J/\psi K^\pm$ and from these events the exclusive branching fraction is measured to be $BR(B^\pm \rightarrow J/\psi K^\pm) = 0.22 \pm 0.10 \pm 0.02$ %. Upper limits for other exclusive branching ratios are given.

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1 Introduction

The observation of a J/ψ meson in a hadronic Z° decay provides a clear signature for the presence of a b flavoured hadron [1] in the event. Theoretical calculations [1], [2] predict the backgrounds of J/ψ's from other sources to be small. Experimentally, the di-lepton decay modes of the J/ψ provide a clean method for recognising the events and the J/ψ decay vertex can be used to locate the B decay point with high precision for lifetime measurements.

This letter presents an analysis of data taken by the ALEPH collaboration at LEP during 1990 and 1991. The data sample consists of approximately 450,000 hadronic events taken at centre-of-mass energies near the Z° peak. Events containing a J/ψ decay to e^+e^- or $\mu^+\mu^-$ are selected and used to measure the inclusive branching fraction $BR(b \to J/\psi X)$ and the average B lifetime. In the J/ψ events, a study has been made of exclusively reconstructed B decays, yielding a measurement of the branching fraction for $B^- \to J/\psi K^-$ [2] and limits on five other exclusive decay modes.

2 The ALEPH detector

The ALEPH detector is described in detail in reference [4]. For the 1991 data a double-sided silicon microstrip vertex detector [5] was added. Only a brief description of the apparatus will be given here.

Charged particles are tracked with three devices inside a superconducting solenoid providing an axial field of 1.5 T. Closest to the beampipe is the vertex detector (VDET), which consists of silicon wafers with strip readout in two dimensions, arranged in two roughly cylindrical layers at average radii of 6.4 and 11.5 cm. This detector covers a solid angle of $|\cos\theta| < 0.85$ for the inner layer only and $|\cos\theta| < 0.65$ with both layers. The point resolution is 12 μm at normal incidence in the $r\phi$ and z dimensions. Surrounding the VDET is the inner tracking chamber (ITC), which is a drift chamber giving up to 8 measurements in the $r\phi$ dimension, each with a point resolution of 150 μm. The angular acceptance of this chamber extends to $|\cos\theta| < 0.96$. Outside the ITC, the time projection chamber (TPC) provides up to 21 space points for $|\cos\theta| < 0.79$, and a decreasing number for smaller angles, with 4 points at $|\cos\theta| = 0.96$. In the TPC the point resolution is 170 μm in $r\phi$ and 740 μm in z. The charged tracks from J/ψ decays used in this analysis have an average momentum of 10 GeV/c. A track of this momentum has a spatial resolution at the interaction point of approximately 25 (140) μm in the $r\phi$ dimension, 35 (800) μm in z dimension and a momentum resolution of $\Delta p/p = 0.0006(0.0008)\ p\ (GeV/c)^{-1}$, with (without) VDET hits.

[1] In this paper the term B is used to refer to a b flavoured hadron.

[2] The charge conjugate reaction is implicit throughout the letter.

Hadronic events are selected by requiring at least five 'good' charged tracks and a sum of charged particle energies greater than 10% of the centre-of-mass energy. A 'good' track must have: momentum greater than 0.2 GeV/c; $|cos\theta| <$ 0.95; at least 4 TPC points; and must pass within a cylinder of radius 2 cm and length 20 cm, centred at the beam interaction point.

Lepton identification in ALEPH is described in detail elsewhere [6]. Electrons are identified using the electromagnetic calorimeter (ECAL) and the ionization in the TPC. The ECAL is a lead/proportional-tube calorimeter with cathode-pad readout in finely segmented projective towers. The towers subtend a transverse angle typically $0.8° \times 0.8°$ and have a readout in three separate longitudinal stacks. The electron identification uses one ECAL estimator which compares the track momentum with the calorimeter energy in the four towers closest to the track, and another which tests that the average depth of the shower is consistent with that expected from an electron. The TPC measures the ionisation of an electron track with a resolution of 4.6% and a candidate track is rejected when this ionisation is more than 2.5 σ below the expectation for an electron of that momentum. Electron candidates which come from photon conversions are rejected using the algorithm described in reference [6]. Muons are identified using the hadron calorimeter (HCAL) and the muon chambers. The HCAL is composed of the iron of the magnet return yoke interleaved with 23 layers of streamer tubes. The readout of the HCAL consists of strips with a pitch of 1 cm which are used for the muon tracking, and projective towers with subtended angles of approximately $3° \times 3°$, which are used for the hadronic energy measurement. The muon chambers surround the HCAL after a total of 7.5 interaction lengths of material and have 3D readout. These chambers consisted of two layers of streamer tubes for the 1990 data, while for the 1991 data this system had four layers. For this analysis, muon candidates are accepted if they have a muon-like pattern of fired planes in the HCAL or if they have at least one associated 3D hit in the muon chambers. The average identification efficiency, after kinematic cuts, for electrons in this analysis is 80%, and is derived from measurements in the data using electron pairs from photon conversions. The average detection efficiency for muons is 88%, estimated from Monte Carlo calculations.

3 Selection of J/ψ events

To select the events with $J/\psi \to e^+e^-$ and $\mu^+\mu^-$ decays, two 'good' tracks, both identified as the same kind of lepton, are required with $|cos\theta| < 0.93$ and momentum greater than 2.5 GeV/c. The opening angle between the tracks is required to be less than 90° and for the branching fraction and lifetime measurements the momentum of the J/ψ candidate must be greater than 10 GeV/c. No minimum number of hits in the VDET or ITC is demanded and in the 1990 data, which is 34% of the total, no VDET hits are used. In the total event sample, 60% of the events have a VDET hit on at least one of the lepton tracks.

For events selected with the requirements described so far, the major background to the J/ψ signal consists of events with a cascade semileptonic decay $b \to cl\bar{\nu}$, $c \to s\bar{l}\nu$. To reject these events which have two undetected neutrinos the ALEPH energy flow algorithm [7] is used to sum the total neutral and charged energy in the event hemisphere, defined by the thrust axis, containing the J/ψ candidate. This algorithm measures the total energy in hadronic events with a typical resolution of 9% and events are rejected if the hemisphere energy is less than 0.85 times the beam energy. The use of this cut reduces the background to the J/ψ signal by approximately a factor 2.

Figure 1(a) shows the di-muon invariant mass spectrum for the selected events. A fit to the $\mu^+\mu^-$ spectrum with a Gaussian signal plus an exponential background function gives a mass of 3094 ± 3 MeV/c^2 and a r.m.s. width of 28 ± 4 MeV/c^2, consistent with the Monte Carlo simulation.

For the decay $J/\psi \to e^+e^-$, the di-electron invariant mass distribution has a significant low mass tail due to final-state radiation and bremsstrahlung emitted as the electrons pass through material in the detector before the momentum measurement. This radiation also significantly softens the electron momentum spectrum, relative to the muons, and reduces the electron acceptance after the minimum lepton momentum cut. In the Monte Carlo simulation, final-state radiation for leptonic J/ψ decays is simulated using a first-order calculation [10]. The effect of this radiation is to move 10% (4%) of $J/\psi \to e^+e^-(\mu^+\mu^-)$ events to di-lepton invariant masses below 2.95 GeV/c^2. The bremsstrahlung in the detector moves another 30% (1%) of events to this tail. To reduce the magnitude of this low-mass tail in the e^+e^- decays, a correction is made if a photon is observed which is consistent with having been radiated from either electron. Since both final-state and bremsstrahlung photons are emitted approximately collinear with the electron flight path, and since the majority of radiation occurs before the track enters the TPC, it is sufficient to search for these photons in only a small, well defined, region of the ECAL. When a photon is found, the photon momentum is added vectorially to that of the electron. The di-electron invariant mass distributions with and without this correction are shown in figures 1(b) and 1(c). For the branching fraction measurement, the di-lepton invariant mass is required to lie in the signal mass range between 2.95 and 3.20 GeV/c^2. Having applied the above correction, the Monte Carlo simulation predicts that 75% of the selected $J/\psi \to e^+e^-$ events lie inside this mass region, while without the correction this proportion would be only 60%. For $\mu^+\mu^-$ events no correction is applied and this fraction is 95%.

4 Inclusive branching fractions

For the measurement of the inclusive branching fraction, the acceptance for the J/ψ's from B decay is calculated from a Monte Carlo simulation based on the JETSET 7.3 [8] model. This Monte Carlo generates events with the b quark hadronising to mesons and baryons in the ratio $B_d : B_u : B_s : b_{baryons} = 40 : 40 : 11 : 9$, and uses experimentally measured 2-body B decay branching fractions [9], with the higher multiplicity decay modes being generated according to the JETSET hadronisation model. Theoretical calculations[1] predict a background of J/ψ production from hard gluons with a rate approximately 3.5% of that from B decays, with other background sources contributing less than 1%. The acceptance of the gluon source of J/ψ's has been calculated using a Monte Carlo program provided by the authors of reference [1].

Figure 2 compares data and Monte Carlo distributions of the J/ψ scaled energy (x_E) and the angle of the J/ψ to the thrust axis ($\theta_{\psi-thr}$). The data distributions are corrected for acceptance and contain a background subtraction using the $e^{\pm}\mu^{\mp}$ events, as described later. To show the region with $x_E < 0.2$, no cut on J/ψ momentum is used in making these distributions. The data in this region have a large background with no significant observed signal and are rejected for all other results presented. Due to the different kinematics, J/ψ's which originate from gluons have on average lower x_E and higher $\theta_{\psi-thr}$ than those from B's. Within statistics, the data and Monte Carlo distributions agree, showing that the simulation and the theoretical expectations for the background are consistent with the data.

The Monte Carlo predicts that double semileptonic cascade decays constitute approximately 85% of the background in the e^+e^- invariant mass spectrum and 40% of the background in the $\mu^+\mu^-$ spectrum. For the $\mu^+\mu^-$ spectrum, another 30% of the background consists of events where one muon comes from semileptonic b decay and the other track is a misidentified hadron or a muon from pion or kaon decay. In the data, the background under the J/ψ peak is estimated using the spectrum of $e^{\pm}\mu^{\mp}$ events shown in figure 1(d). The Monte Carlo predicts that 75% of the events in this spectrum come from cascade decays. The $e^{\pm}\mu^{\mp}$ spectrum is fitted with an exponential function of the form: $a_1 \exp(-a_2 \times M_{l^+l^-})$, in the invariant mass range between 2 and 4 GeV/c^2. The same exponential form with the slope parameter a_2 fixed from this last fit, is fitted to the e^+e^- and $\mu^+\mu^-$ spectra in the mass range between 2.0 and 2.8 GeV/c^2 to obtain the normalization parameter a_1. The background is then the integral of this function in the J/ψ signal mass range. Using the like-sign $\mu^{\pm}\mu^{\pm}$ invariant mass spectrum (which approximates the misidentified muon background) to obtain the background slope parameter gives results within statistical errors. The numbers of signal events observed are 32.0 ± 5.8 for e^+e^- and 59.7 ± 7.9 for $\mu^+\mu^-$, with backgrounds of 4.0 ± 1.0 and 10.3 ± 1.8 events respectively.

The branching fractions are calculated using:

$$BR(Z^0 \to J/\psi X) = \frac{N_{J/\psi}}{N_{had}\ BR(J/\psi \to l^+l^-)} \times \frac{\epsilon_{had}}{\epsilon_{J/\psi}} \times \frac{\Gamma_{had}}{\Gamma_Z},$$

with the efficiencies for reconstructing a J/ψ in the defined signal mass range ($\epsilon_{J/\psi}$) of $22.1 \pm 0.8\%$ for e^+e^- and $41.0 \pm 0.8\%$ for $\mu^+\mu^-$; the efficiency for recognising a hadronic event (ϵ_{had}) of 97.4 ± 0.2 %[11]; $\Gamma_{had}/\Gamma_Z = 0.702 \pm$

Source of uncertainty	Estimate of error (%)	
	$J/\psi \rightarrow e^+e^-$	$J/\psi \rightarrow \mu^+\mu^-$
Simulation of photon radiation	4	1
Simulation of J/ψ acceptance	5	4
Lepton identification efficiency	3	4
Search for radiated photons	3	—
Background subtraction procedure	2	2
Total systematic error	8	6

Table 1: Systematic error estimates on inclusive branching fraction.

0.008 [11]; $BR(J/\psi \rightarrow l^+l^-) = 5.91 \pm 0.23$ % [12]; the number of hadronic events (N_{had}) of 441,000 and the number of signal events ($N_{J/\psi}$) as given above. The resulting branching fractions are:

$$\begin{aligned} BR(Z^0 \rightarrow J/\psi X) &= (3.79 \pm 0.67 \pm 0.31 \pm 0.15) \times 10^{-3} \quad (J/\psi \rightarrow e^+e^-) \\ &= (3.82 \pm 0.49 \pm 0.23 \pm 0.15) \times 10^{-3} \quad (J/\psi \rightarrow \mu^+\mu^-), \end{aligned}$$

where the first error is statistical, the second an estimate of the systematic error, and the third comes from the uncertainty on the $BR(J/\psi \rightarrow l^+l^-)$. The systematic error contributions are listed in table 1. The systematic error for the simulation of J/ψ acceptance takes into account the uncertainties in the hadronisation process and B decay modes in the Monte Carlo simulation. A weighted average of the two decay modes gives:

$$BR(Z^0 \rightarrow J/\psi X) = (3.81 \pm 0.41 \pm 0.26) \times 10^{-3},$$

where the two systematic errors have now been combined. This result is consistent within errors, with the value reported by OPAL [13], equivalent to $(5.3 \pm 0.9 \pm 0.5) \times 10^{-3}$ after adjustment for the latest result on $BR(J/\psi \rightarrow l^+l^-)$[12].

The standard model value of $\Gamma_{b\bar{b}}/\Gamma_{had} = 21.7\%$ [6] is used to obtain the fraction of events with a b quark. The non-B fraction of J/ψ's is taken from theoretical calculations with acceptance correction and is $f_{pr} = 2^{+2}_{-1}\%$. Then, the branching ratio for a b flavoured hadron to yield a J/ψ is:

$$BR(b \rightarrow J/\psi X) = 1.21 \pm 0.13 \pm 0.08 \ \%.$$

At LEP, the b quark is expected to hadronise to B_s or $b_{baryons}$ in 20% of the cases, so this branching fraction has a different b hadron content compared with that measured at the $\Upsilon(4S)$. However, the ALEPH result agrees with the average value measured by ARGUS and CLEO [14], equivalent to 1.3 ± 0.2 % after adjustment for the BR($J/\psi \rightarrow l^+l^-$). The result agrees with the theoretical predictions [15].

5 Exclusive B decays

Candidates for the decay $B^- \to J/\psi K^-$ are selected from among the J/ψ events by forming combinations of the two leptons from the J/ψ and a charged track with momentum greater than 4 GeV/c within a cone of half-angle 45° around the J/ψ direction. The mean ionisation for this charged track is required to be within 2σ of that expected for a kaon of the measured momentum. In the momentum range of interest, approximately 50% of pions are rejected by this cut. The three track system is required to have momentum greater than 20 GeV/c and to form a common vertex with probability greater than 1%. The invariant mass spectrum observed with these cuts and with the J/ψ mass constrained, is shown in figure 3. Five events are observed in the signal region between 5200 and 5360 MeV/c^2. The data are fitted with a Gaussian function parameterizing the signal and an exponential function whose slope parameter is fixed from a fit to the background observed in a Monte Carlo simulation. The Gaussian peak is at 5282 ± 9 MeV/c^2 with r.m.s. width 19 ± 5 MeV/c^2, consistent with the accepted $B^\pm$ mass and the Monte Carlo expectation for the resolution. From the fit, the background in the signal region is estimated to be 0.2 ± 0.1 events. A check on the background has been made by forming an invariant mass distribution with the tracks which fail the kaon ionisation requirement. In this distribution, no events are observed with an invariant mass greater than 4.8 GeV/c^2. The backgrounds in these distributions are consistent with the predictions of the Monte Carlo simulation, where almost all the entries are from real B decays to a different mode with a J/ψ. The exclusive branching fraction is calculated in a similar fashion to the inclusive branching fraction. The efficiency for reconstructing a $J/\psi K^-$ event is 2.8 ± 0.2 %, averaged between the $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ modes. Assuming the fraction of b quarks giving a $B^\pm$ meson as 0.4, the result is

$$BR(B^- \to J/\psi K^-) = 0.22 \pm 0.10 \pm 0.02 \ \%.$$

The systematic error includes the same contributions as the inclusive branching fraction with additional contributions for the dE/dx and vertexing requirements. This exclusive branching fraction is consistent with the value measured at the $\Upsilon(4S)$ 0.09 ± 0.03 [16] (again adjusted for BR($J/\psi \to l^+l^-$)) and with recent theoretical models [17].

In addition to the five $J/\psi K^-$ events, two other B decays have been fully reconstructed. One of these events is consistent with $B^0 \to J/\psi K^0_S$, $K^0_S \to \pi^+\pi^-$, the other with $B^0 \to J/\psi K^{*0}$, $K^{*0} \to K^+\pi^-$. Two other exclusive B meson channels have been studied with no signal events being observed: $B^\pm \to J/\psi K^{*\pm}$, $K^{*\pm} \to K^0_S\pi^\pm$, $K^0_S \to \pi^+\pi^-$ and $B^0_s \to J/\psi\phi$, $\phi \to K^+K^-$. A search has been made for the decay $\Lambda_b \to J/\psi\Lambda, \Lambda \to p\pi$, which has recently been reported by the UA1 experiment with the $BR(\Lambda_b \to J/\psi\Lambda) = 1.8 \pm 1.1\%$[3]. For the B^0_s and Λ_b decay modes, no event is observed with an invariant mass greater than 5 GeV/c^2. Table 2 summarizes the expectations and observations for all the exclusive modes studied.

Decay mode	Efficiency (%)	Events obs.	Events exp.	Est. back.	BR (%) or 90% CL limit
$B^+ \to J/\psi K^+$	2.8	5	2.0	0.2	0.22 ± 0.10
$B^0 \to J/\psi K^0$	0.6	1	0.3	0.1	< 0.9
$B^0 \to J/\psi K^{*0}$	0.6	1	0.6	0.2	< 0.8
$B^+ \to J/\psi K^{*+}$	0.2	0	0.2	0.05	< 1.4
$B_s^0 \to J/\psi \phi$	1.0	0	0.2	0.03	< 1.0
$\Lambda_b \to J/\psi \Lambda$	1.2	0	3.8	0.05	< 1.1

Table 2: Results of searches for exclusive B decay modes with a J/ψ . The reconstruction efficiencies include the branching ratios to the detected final states described in the text. The expected numbers of events and background estimates are calculated from the Monte Carlo with the UA1 measurement for the $BR(\Lambda_b \to J/\psi\Lambda)$ and the assumption $BR(B_s^0 \to J/\psi\phi) = 0.1\%$. The limits on the branching fractions assume $BR(b \to B_u) = BR(b \to B_d) = 0.40$, $BR(b \to \Lambda_b) = 0.09$ and $BR(b \to B_s) = 0.11$.

6 Inclusive lifetime

In order to measure the B lifetime, the proper-time (t) is reconstructed for each event from the decay length (l) and the boost $(\gamma\beta)$ of the B. The decay length, which is on average approximately 2 mm in this experiment, is measured in three dimensions from an event-by-event primary vertex and a B decay point tagged by the vertex of the $J/\psi \to l^+l^-$ decay. The boost of the B is measured by approximately reconstructing the B momentum from a jet including the J/ψ and nearby charged and neutral particles. The decay length is calculated by projecting the vector joining the primary and secondary vertices onto the reconstructed B direction.

The algorithm to reconstruct the B momentum nucleates a jet with the J/ψ. Charged and neutral particles, with energy greater than 0.5 GeV, are added to the jet, taking first the particle which adds the least to the jet invariant mass according to the relation: $M_i^2 = 2E_{jet}E_i(1 - cos\theta_{jet,i})$, where E_{jet} is the energy of the existing jet, E_i is the energy of particle i, $\theta_{jet,i}$ is the angle between the jet and the particle. After adding a particle, the jet parameters are recalculated by adding four-momenta, and the next closest particle is searched for. The addition is stopped when no particle can be added without increasing the invariant mass of the jet to a value greater than 6 GeV/c^2. Figure 4 shows the distribution of the Monte Carlo quantity: $\kappa = (\gamma\beta)_{jet}/(\gamma\beta)_B^{true}$, where $(\gamma\beta)_{jet}$ is the reconstructed boost from the jet, calculated as the ratio of the jet momentum and the jet mass, and $(\gamma\beta)_B^{true}$ is the true B boost in the simulation. A correction factor $C_{\gamma\beta}$ is defined as the mean of this κ distribution, and the proper-time is calculated as: $t = l\ C_{\gamma\beta}\ /\ (\gamma\beta)_{jet}\ c$, with $C_{\gamma\beta} = 1.015$. The resolution obtained on the B boost with this method is improved by approximately a factor two compared to that which would be obtained by using only the J/ψ momentum in the estimation.

The secondary vertex is formed from the two lepton tracks. To ensure well measured secondary vertices, the probability of the vertex is required to be greater than 1%. For the $J/\psi \rightarrow e^+e^-$ mode, events are removed if a radiated photon is observed with energy greater than 20% of the corresponding electron energy. These two cuts remove 13% of the total signal events.

The determination of the primary vertex combines track information with a beam position[18] found from averaging many events. This method is designed to be insensitive to the presence of secondary vertices in the event. The algorithm begins by grouping the tracks into jets, which are constructed with the standard JADE clustering algorithm [19]. Tracks within a particular jet are projected onto the plane perpendicular to the jet direction, and so the lifetime information is removed in the approximation that the jet axis measures the direction of the B. The primary vertex is calculated as the point which is most consistent with the projected tracks and the beam envelope, which is taken as the average beam position with the dimensions of the LEP beamspot.

The error on the proper-time (σ_t), is taken as the quadratic sum of the decay length error calculated for each event and a constant error for the boost ($\sigma_{\gamma\beta}$). The value of $\sigma_{\gamma\beta}$ is taken as 0.105 from a fit to the κ distribution of figure 4 which is reasonably approximated by a Gaussian function. For the events without VDET hits, the error on the J/ψ vertex position dominates the resolution in proper time, while for the events with VDET hits this error and the error on the boost have similar contributions. The Monte Carlo simulation leads to the following estimates of the average experimental resolutions, with (without) VDET hits: 60 (270) μm on the primary vertex position; 180 (1200) μm on the secondary vertex position; 210 (1200) μm on the calculated decay length; and 0.2 (0.7) ps on the proper-time.

The proper-time distribution for the combined e^+e^- and $\mu^+\mu^-$ events in a signal mass range between 3.0 and 3.2 GeV/c^2, after the extra vertexing cuts, are shown in figure 5(a). There are two distinct backgrounds to the B events in this distribution: true J/ψ's from gluons; and 'fake' J/ψ's from the continuum of the di-lepton spectrum. The J/ψ's from gluons are produced in the fragmentation processes at the primary vertex and hence have zero lifetime. The majority of the fake J/ψ background is associated with B events. The lifetime of this background is measured in the data using a sample of events consisting of e^+e^- and $\mu^+\mu^-$ events with invariant masses between 2.4 and 2.9 GeV/c^2 plus $e^\pm\mu^\mp$ events with invariant masses between 2.4 and 4.0 GeV/c^2. The effective proper-time distribution for these background events is shown in figure 5(b).

Signal and background distributions are fitted simultaneously using an unbinned maximum likelihood method. The fitted signal distribution has three components:

1. A signal component which is an exponential function, having lifetime τ_b,

Source	Uncertainty (ps)
B boost central value ($C_{\gamma\beta}$)	±0.02
B boost resolution ($\sigma_{\gamma\beta}$)	±0.01
Decay length resolution	±0.01
Beam spot size and position	±0.01
Fake J/ψ background	±0.03
Prompt J/ψ background	$+0.03\ -0.02$
MC statistics on check of method	±0.02
Total systematic error	±0.05

Table 3: Systematic error estimates on B lifetime measurement.

convoluted with a Gaussian resolution function having width equal to the error on each measured proper-time σ_t.

2. A fraction f_{bk} of fake J/ψ background component, which is an exponential having lifetime τ_{bk}, convoluted with the same Gaussian function.

3. A fraction f_{pr} of prompt background component of J/ψ's from non-B sources, which is just the Gaussian resolution function.

The background distribution is fitted with 100% of component (2). The background fraction is measured from the data using the $e^{\pm}\mu^{\mp}$ sample with the same technique as for the branching fractions, giving $f_{bk} = 11 \pm 2$ %. The result of the fit is: $\tau_b = 1.35^{+0.19}_{-0.17}$ ps from 87 signal events, with $\tau_{bk} = 1.69^{+0.20}_{-0.18}$ ps from the 94 background events.

The measured lifetime of the background is consistent with Monte Carlo predictions in which the cascade B decay events dominate. These cascade decays have an effective lifetime somewhat longer than a B lifetime because the second lepton comes from the D decay after an extra flight length. The systematic error on the background lifetime τ_{bk} is estimated in the data by comparing the lifetime of separate background subsets. The lifetimes for all subsets agree within statistical errors and a systematic error of 0.3 ps on τ_{bk} is assigned from the statistics on the comparison.

The complete list of systematic error sources considered is given in table 3. The systematic errors due to uncertainties in $C_{\gamma\beta}$ and $\sigma_{\gamma\beta}$ have been studied by varying the branching fractions for different B$\rightarrow$ $J/\psi X$ exclusive modes and the b quark fragmentation parameters in the Monte Carlo within the experimental knowledge of these quantities. The resulting changes are $\pm2\%$ in $C_{\gamma\beta}$ and $\pm20\%$ in $\sigma_{\gamma\beta}$. The uncertainty on the decay length resolution, which is dominated by the secondary vertex position, has been obtained from a general sample of hadronic data events. Pairs of tracks are selected with similar kinematics to the J/ψ decay tracks, but without a lepton identification requirement, and if two such pairs are found in an event, the pairs of tracks are separately vertexed. The distribution of the separation of two such vertices in the same event is fitted with the sum of two Gaussians, one for vertices formed at the same point in space and one for vertices formed at different points. The width of the first Gaussian then measures the resolution on the secondary vertex position and the second Gaussian parameterizes events with displaced vertices. From this study, a 20% systematic error is assigned to the decay length resolution. The systematic error for the fake J/ψ background contains a contribution for the error on the fake J/ψ background fraction f_{bk} as well as the systematic error on the background lifetime τ_{bk}. The uncertainty on the prompt J/ψ background is taken from theory. The final systematic error entry in the table comes from a Monte Carlo simulation of the full lifetime measurement method. This simulation tests for possible biases in the J/ψ event selection, in the decay length algorithm and for correlations between the measurements of boost and decay length. The lifetime measured in the simulation agrees within statistics with the value generated and the statistical error on the comparison is taken as an extreme estimate of the systematic error on the lifetime.

The result from this analysis is:

$$\tau_b = 1.35^{+0.19}_{-0.17} \pm 0.05 \ ps.$$

The average B lifetime from this J/ψ tag analysis is directly comparable with the average B lifetime measured using the lepton impact parameter method only if the semileptonic and J/ψ branching fractions of the different b flavoured hadrons are in the same ratio. The value measured in this analysis is consistent with the value of $1.49 \pm 0.03 \pm 0.06$ ps[18] measured by ALEPH in the impact parameter analysis.

7 Conclusions

From a total of 450,000 hadronic events, ALEPH has observed 92 ± 10 events containing a J/ψ. With these events, the measured inclusive branching fraction is:

$$BR(b \to J/\psi X) = 1.21 \pm 0.13 \pm 0.08 \ \%.$$

Five events are exclusively reconstructed as $B^- \to J/\psi K^-$, yielding the branching fraction:

$$BR(B^- \to J/\psi K^-) = 0.22 \pm 0.10 \pm 0.02 \ \%.$$

One event has been reconstructed in the decay mode $B^0 \to J/\psi K^0_S$ and one in the mode $B^0 \to J/\psi K^{*0}$. No events have been observed in the modes: $B^\pm \to J/\psi K^{*\pm}$, $B^0_S \to J/\psi \phi$ and $\Lambda_b \to J/\psi \Lambda$.

The average lifetime of the b flavoured hadrons in the sample is measured to be:

$$\tau_b = 1.35^{+0.19}_{-0.17} \pm 0.05 \ ps.$$

8 Acknowledgements

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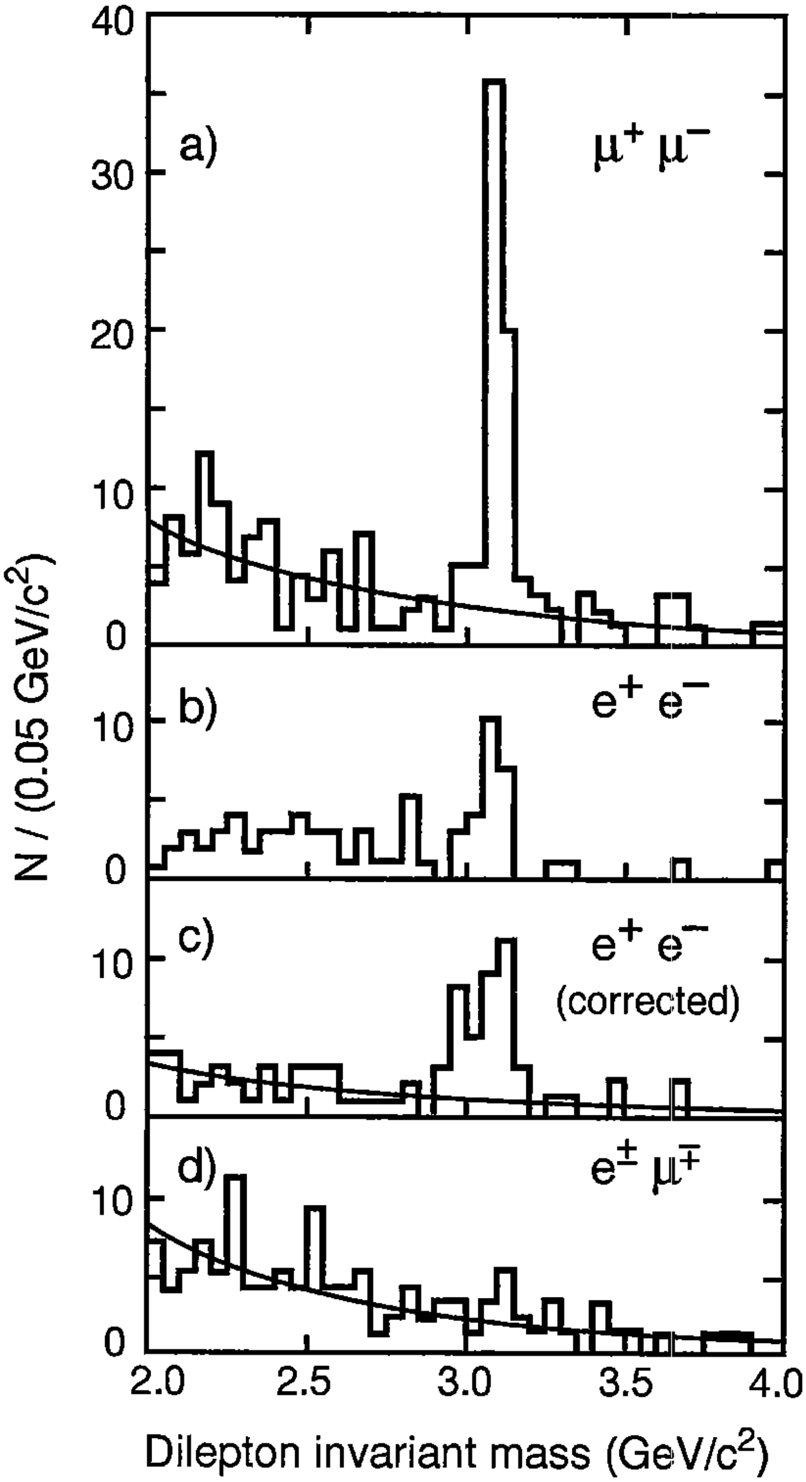

Figure 1: Di-lepton invariant mass spectra (a) $\mu^+\mu^-$, (b) raw e^+e^- , (c) e^+e^- with correction applied when a bremsstrahlung photon is observed, (d) $e^\pm\mu^\mp$. The curves are fitted exponential functions, whose shapes are obtained from the $e^\pm\mu^\mp$ spectrum as described in the text.

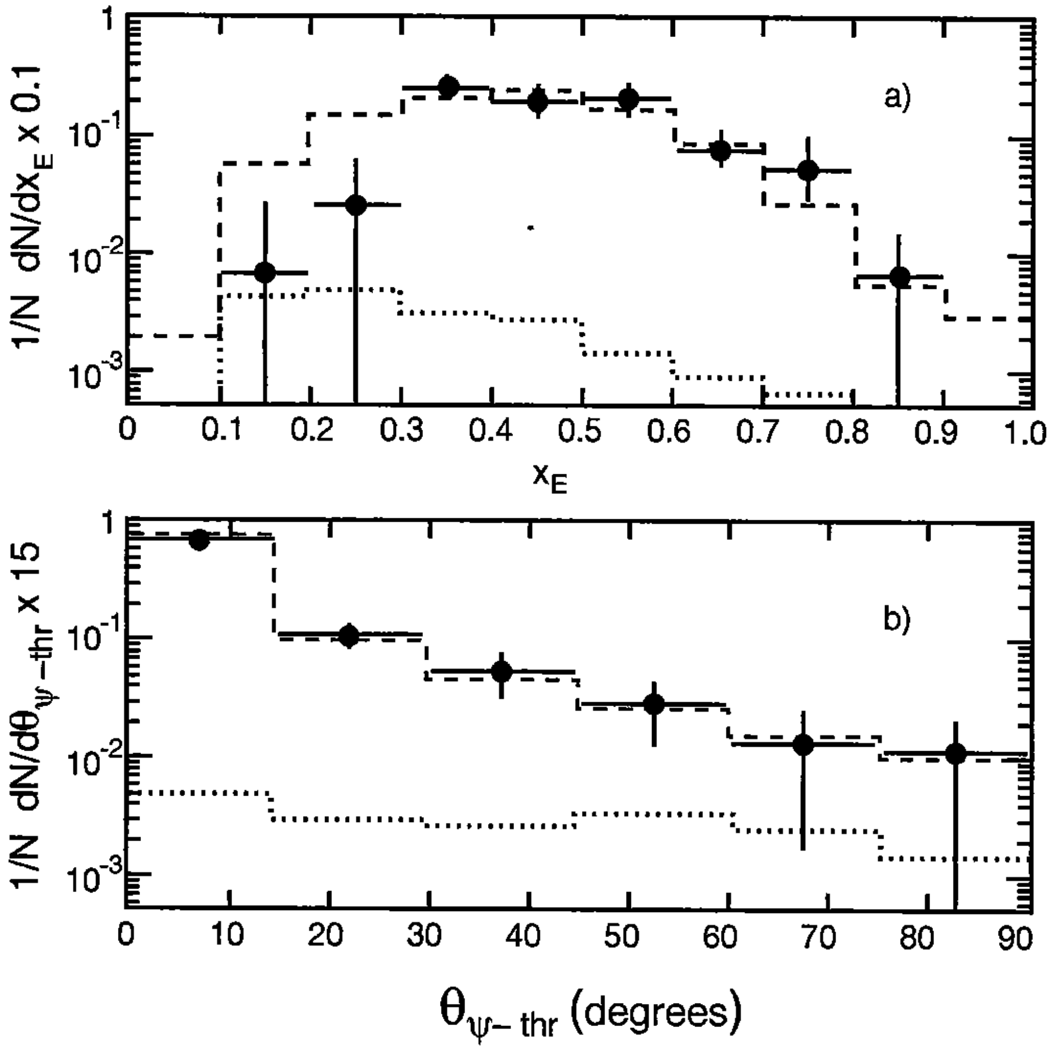

Figure 2: Distributions of J/ψ events for : (a) $1/N\ dN/dx_E$, where the J/ψ scaled energy $x_E = E_\psi/E_{beam}$; (b) $1/N\ dN/d\theta_{\psi-thr}$, where $\theta_{\psi-thr}$ is the angle between the J/ψ direction and the event thrust axis. For these distributions no requirement is made on the J/ψ momentum. The data are plotted as points and the Monte Carlo predictions for J/ψ's originating from $b\bar{b}$ and gluon events as dashed and dotted lines respectively. The Monte Carlo predictions are normalized to the total number of J/ψ events.

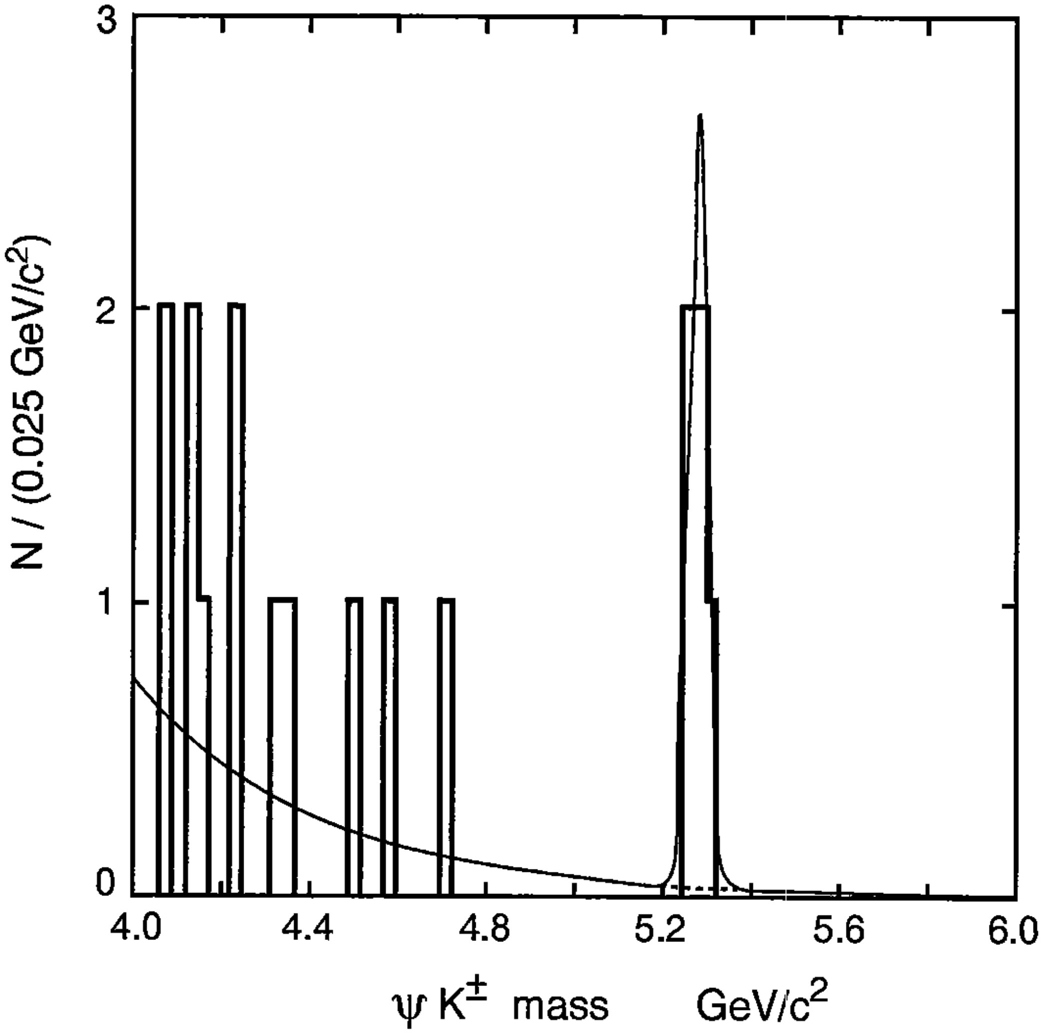

Figure 3: $J/\psi\ K^{\pm}$ invariant mass spectrum. The curve is a fit as described in the text.

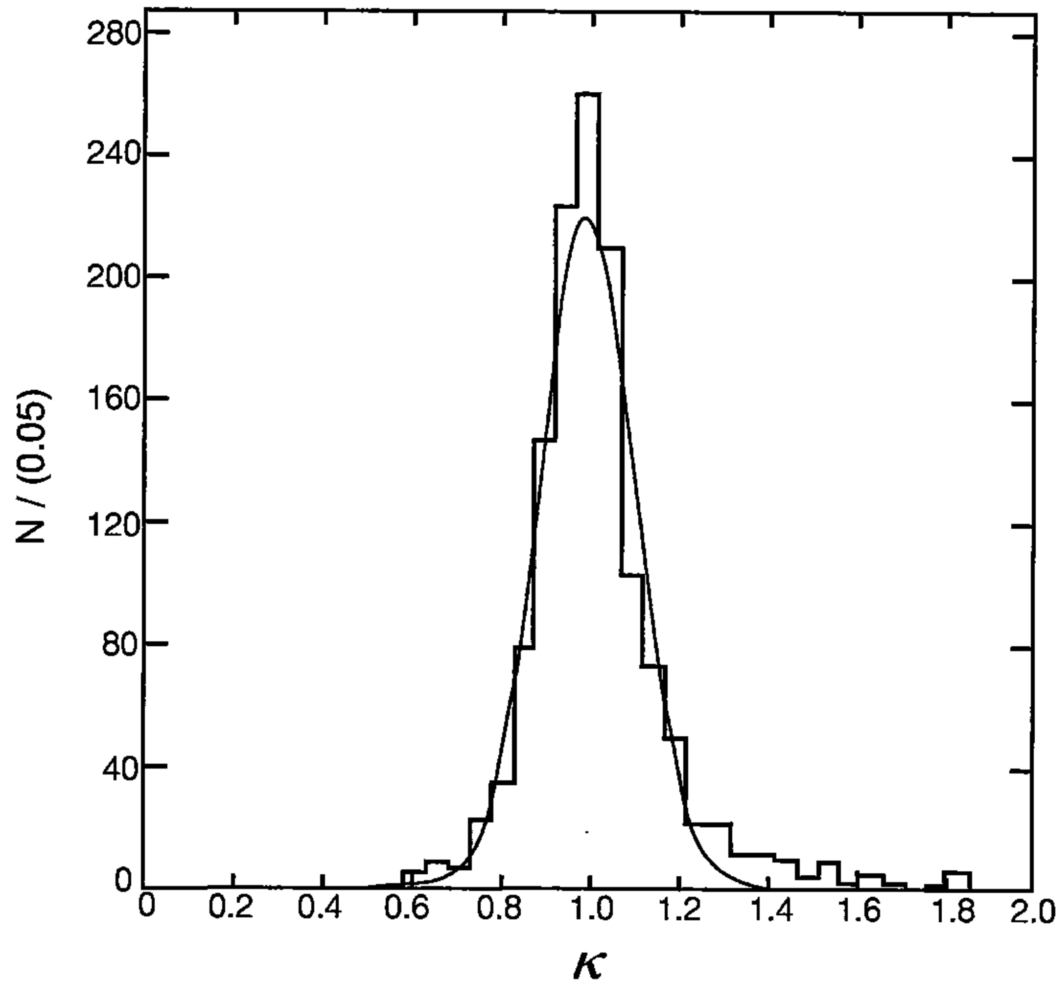

Figure 4: Monte Carlo simulation of the algorithm used to reconstruct the B boost. The distribution shows the quantity: $\kappa = (\gamma\beta)_{jet}/(\gamma\beta)_B^{true}$ and the solid line is a fit with a Gaussian function.

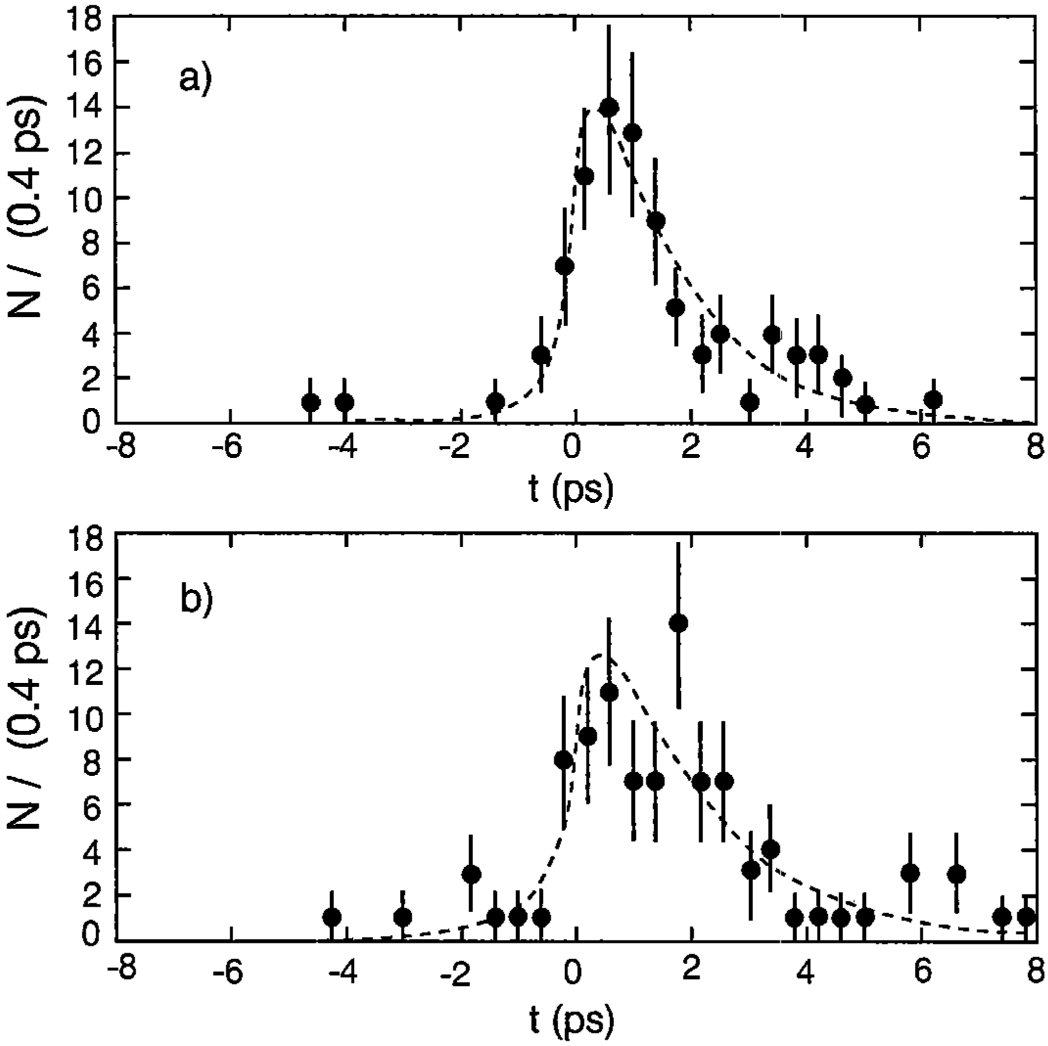

Figure 5: (a) Proper-time distributions for signal events: e^+e^- and $\mu^+\mu^-$ in the mass range 3.0−3.2 GeV/c^2. (b) Equivalent distributions for background events: sideband e^+e^- and $\mu^+\mu^-$ in the mass range 2.4−2.9 GeV/c^2, plus $e^\pm\mu^\mp$ in the mass range 2.4−4.0 GeV/c^2. The dashed lines are the fits described in the text.