EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

July 30, 1997

Measurement of the B_d^0 Meson Lifetime using the Decay $\bar{B}_d^0 \to D^{*+} X \ell^- \bar{\nu}$.

L3 Collaboration

Abstract

From data recorded by L3 in 1994 which correspond to 1.5 million hadronic Z decays we measure the decay $\bar{B} \to D^{*+} X \ell^- \bar{\nu}$ using an inclusive method to reconstruct the D^{*+} meson in its decay to $D^0 \pi^+$. With this data sample the lifetime of the B_d^0 meson is measured to be

$$\boldsymbol{\tau_{B^0} = 1.74 \pm 0.12 \text{ (stat.) } \pm 0.04 \text{ (sys.) ps.}}$$

This result is preliminary.

Submitted to *Summer Conferences 1997*

1 INTRODUCTION

In this paper we describe a method to reconstruct the decay $\bar{B}_d^0 \to D^{*+}X\ell^-\bar{\nu}$[1)]. The reconstructed decays are used to measure the lifetime $\tau_{B_d^0}$of the B_d^0 meson. The measurement presented uses 1.5 million hadronic events collected at the Z resonance with the L3 detector in 1994. Efficiencies have been estimated with 3.3 million hadronic events, generated with the JETSET 7.3 Monte Carlo program, passed through a full detector simulation.

2 Analysis Method and Event Reconstruction

A detailed description of the L3 detector is provided in reference[1, 2]. The trigger requirements and the selection criteria for hadronic events have been described previously[3]. The analysis method is the following: The decay $\bar{B} \to D^{*+}X\ell^-\bar{\nu}$ is reconstructed by combining the lepton with the bachelor pion (π_s^+) from the subsequent decay $D^{*+} \to D^0\pi_s^+$. The D^0 meson is not exclusively reconstructed. In b- and c-quark jets the daughter particles from the heavy quark hadron tend to line up near the center of the jet. Thus, these particles have, on average, higher values of rapidity with respect to the jet axis while particles from fragmentation have lower rapidities. By selecting only high rapidity particles in lepton jets, while excluding the lepton, we inclusively reconstruct the D^0 meson [4]. The signal is best measured in the distribution of the mass difference

$$\Delta\mathrm{m} \; = \mathrm{m}(D^0\pi_s^+) - \mathrm{m}(D^0),$$

where $\mathrm{m}(D^0)$ and $\mathrm{m}(D^0\pi_s^+)$ are the invariant masses of the corresponding particle combinations, respectively.

The key elements of the analysis are: Event reconstruction, leptons, inclusive D^0 reconstruction, and slow pion (π_s^+) kinematics. A complete event reconstruction classifies all available detector signals into particles such as muons, electrons, tracks, photons, and hadrons. Muons and electrons will be described in detail below. Tracks have to come from the interaction vertex and have at least 50% of all hits possible for the given trajectory. All tracks (except those belonging to leptons) are assigned the pion mass. Photons are clusters in the electromagnetic BGO calorimeter consistent with an electromagnetic shower shape and isolated from tracks. Neutral hadrons are clusters in the electromagnetic- and hadron calorimeter which are not assigned to one of the above categories. The spatial resolution of the calorimeters does not allow to separate neutral particles from nearby lying charged tracks. Thus, considerable excess energy in clusters with respect to the summed energy of their assigned tracks is added to the neutral hadron list. Overall multiplication factors of the neutral hadron energies, in each of nine different detector regions, are recalibrated by minimizing the energy resolution of the events with respect to the beam energy. These particles are combined into jets using the JADE algorithm with a y-cut of 0.03. Selecting only particles which have a rapidity larger than 1.5, recalculating the jet directions, and iterating to become independent of the initial jet direction, improves the angular jet resolutions of the heavy-quark jets.

[1)] Charge conjugate decays are always implied.

Muons are identified and measured in the muon chamber system. We require that a muon track contains track segments in at least two of the three layers of muon chambers, and that the muon track points back to the interaction region. Electrons are identified using the electromagnetic calorimeter and the central tracking system. Only electrons in the barrel region $|\cos(\theta)| < 0.74$, where θ is the polar angle with respect to the beam axis, have been considered. The BGO cluster has to be consistent with having an electromagnetic shower shape. The associated track has to match the electromagnetic cluster in azimuthal angle ϕ and transverse energy. In addition we require less than 5 GeV of energy to be deposited in the hadron calorimeter in a cone of half angle 7^o behind the electromagnetic cluster.

The momentum of muon candidates is required to be larger than 4 GeV while the electron candidates are required to have momentum larger than 3 GeV. The b flavor of the event is tagged by selecting only leptons with a transverse momentum larger than 0.7 GeV. The transverse momentum is defined with respect to the nearest jet, using the heavy-quark jet direction.

The charmed hadron, assumed to be the D^0 meson, is reconstructed inclusively in all jets where a lepton candidate has been found. All particles in this jet - excluding the lepton - are ordered according to their rapidity. We combine the two particles with the highest rapidity, and keep adding particles until the invariant mass of the system exceeds 2.5 GeV. This cut has been chosen above the mass of the weakly decaying charm hadrons to allow for mass resolution and dilution due to fragmentation particles. We accept all charmed hadron candidates which have at least three constituent particles. This procedure is iterated to become independent of the initial jet direction.

In all jets with a lepton and a D^0 candidate we combine the D^0 with all charged tracks in the same jet, having a momentum in the range 0.5 GeV to 2 GeV, to form D^{*+} candidates. We also require that the track has at least one hit in the silicon microvertex detector (SMD) which improves the measurement of the polar angle. The following kinematic cuts have been applied. Since the π_s^+ coming from the D^{*+} decay has only 39 MeV momentum in the rest frame of the D^{*+} it is well lined up with the D^{*+} direction in the lab frame. In $b\bar{b}$ events there is an additional contribution coming from the direction of the D^{*+} with respect to the B meson. We require that the squared transverse momentum of the π_s^+ with respect to the jet axis is less than 0.05 GeV^2. Signal event purity is also improved by projecting the π_s^+ and the lepton onto the plane perpendicular to the heavy-quark jet axis. $\bar{B}_d^0 \to D^{*+}\ell^-\bar{\nu}$ events are expected to have, in this plane, the lepton pointing opposite to the π_s^+ whereas random pions from fragmentation have a flat distribution. The resolution is dominated by the missing neutrino and we require that this angle is larger than 120^o.

We calculate the invariant mass difference Δm between the D^{*+} and the D^0 candidate. If the π_s^+ candidate is one of the D^0 decay products, the D^0 candidate is first stripped of the π_s^+ track and its invariant mass is recalculated. Two classes of events are defined according to the relative charges of π_s^+ and the lepton: Signal events have oppositely charged pairs and are called right-sign events. The background can be studied with same charged pairs, which are called wrong-sign events. In Fig. 1a) we compare the shape of the Δm distribution for wrong-sign data and Monte Carlo simulation, whereas in Fig. 1b)

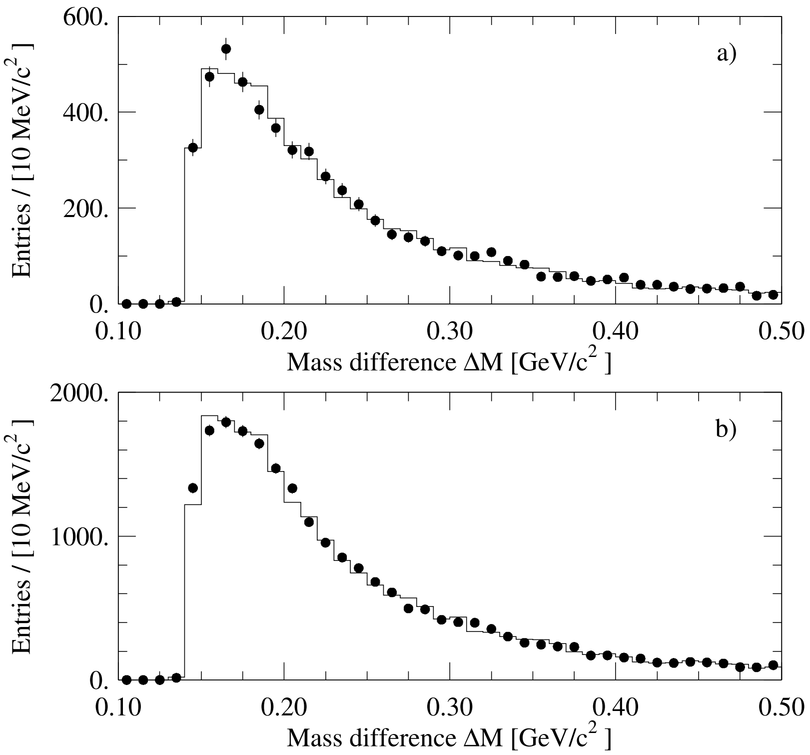

Figure 1: a) Δm distribution in the wrong-sign data (dots) compared to the simulated wrong-sign combinations (histogram). b) Δm distribution of the simulated combinatorial background (dots) compared to the simulated wrong-sign combinations (histogram). In a) and b) the histograms have been scaled to the same number of entries.

we show the shape of the simulated combinatorial non-D^{*+} background and wrong-sign background samples. For both comparisons the histograms have been scaled to the same number of entries. Good agreement is observed, thus justifying the description of the combinatorial background by the wrong sign-data. Figure 2 shows the Δm distribution for right- and wrong-sign events. An excess of events at low mass difference for right-sign events is clearly visible. In the wrong-sign data sample each Δm-bin has been multiplied by the ratio of the right-sign combinatorial over the wrong-sign background as obtained from the Monte Carlo simulation. In the Δm range below 0.20 GeV we select 4905 combinations. There are 1855 $\pm$ 95 D^{*+} candidates in this region out of which 1329 $\pm$ 68 combinations are attributed to $\bar{B}_d^0 \to D^{*+}\ell^-\bar{\nu}$ decays.

3 Lifetime Fit

The lifetime $\tau_{B_d^0}$ of the neutral B_d meson is measured using the signed impact parameter of the corresponding leptons. We select a lifetime sample from the 4905 reconstructed D^{*+}-lepton combinations by imposing the following additional requirements: The Δm

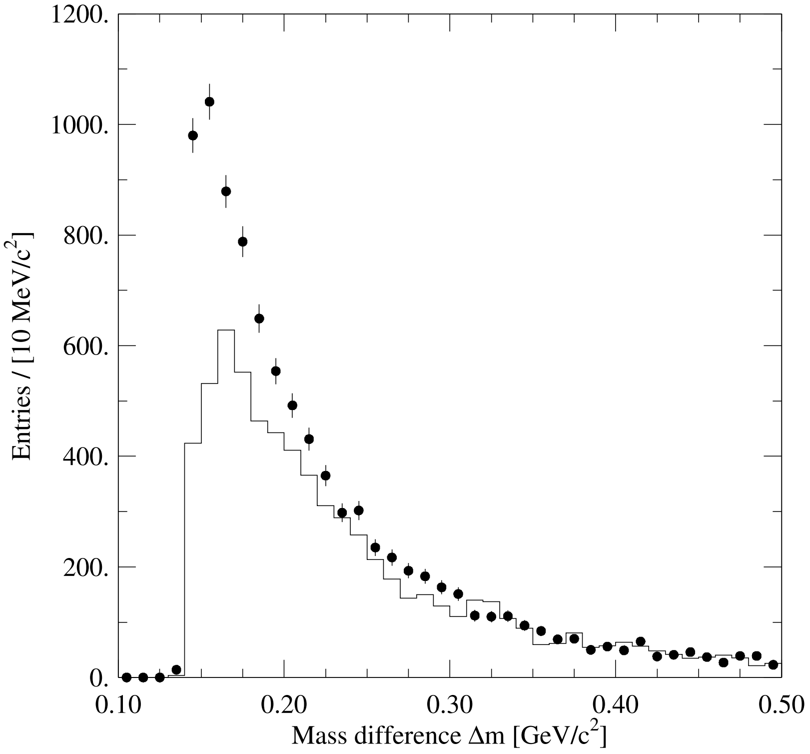

Figure 2: Δm distribution in the data for right-sign combinations (dots) and wrong-sign combinations multiplied in each Δm-bin by the right-sign/wrong-sign ratio of the background simulation (histogram).

mass range is tightened to 0.170 GeV to improve the signal fraction of events. We select only leptons which have a track in the inner detector system that has at a hit in the inner layer of the SMD and we require that the signed impact parameter of the lepton track is between -2.5 mm and 5 mm. These requirements yield 2306 right-sign and 1238 wrong-sign D^{*+}-lepton combinations, respectively.

The impact parameter δ of each lepton is defined as the absolute value of the distance-of-closest-approach (DCA) in the $r-\varphi$ plane with respect to the primary vertex with a sign that is positive (negative) if the track intersects the direction of the accompanying jet in (opposite to) the direction of the jet's total momentum, respectively. The lepton track has been excluded when calculating the primary vertex.

An unbinned likelihood fit to the signed impact parameter distribution is used to measure the B_d^0 meson lifetime $\tau_{B_d^0}$. For the signal D^{*+}-lepton combinations, the π_s^+ originates from a real D^{*+} and the probabilities of the different lepton sources ($\mathrm{f_{B_i}}$ or $\mathrm{f_{fbc}}$) have to be estimated. Otherwise the event has a probability $\mathrm{f_{comb}}$ to originate from the combinatorial background. The impact parameter distribution for the lepton is expressed as a convolution of two functions: the true impact parameter distribution $\mathcal{P}_\mathrm{i}(\delta^\mathrm{t})$, which for B mesons depends on their lifetime, and the resolution function which describe the smearing

$\delta = \mathcal{R}(\delta^{\rm t})$ due to the finite resolution of the lepton track and beam spot measurements. The likelihood function $\mathcal{L}(\tau_{B_d^0})$ is defined as follows:

$$\begin{aligned}\mathcal{L}(\tau_{B_d^0}) \quad = \quad & \prod_{i}^{\rm leptons} \{(1-{\rm f_{comb}})\{{\rm f_{B_d^0}}\mathcal{P}_{\rm B_d^0}(\tau_{B_d^0};\delta_{\rm i}^{\rm t}) \\ & + {\rm f_{B^+}}\mathcal{P}_{\rm B^+}(\tau_{B^+};\delta_{\rm i}^{\rm t}) + {\rm f_{B_s^0}}\mathcal{P}_{\rm B^+}(\tau_{B_s^0};\delta_{\rm i}^{\rm t}) + {\rm f_{fbc}}\mathcal{P}_{\rm fbc}(\tau_b;\delta_{\rm i}^{\rm t})\} \\ & + {\rm f_{comb}}\mathcal{P}_{\rm comb}(\delta_{\rm i}^{\rm t})\} \otimes \mathcal{R}(\delta_{\rm i}^{\rm t})\end{aligned}$$

where $\mathcal{P}_{\rm B_i}$, $\mathcal{P}_{\rm fbc}$, and $\mathcal{P}_{\rm comb}$ are the true impact parameter distributions for the different lepton sources. These distribution are parameterized using the Monte Carlo simulation. The convoluted distributions $\mathcal{P}_{\rm i} \otimes \mathcal{R}$ are normalized to unity in the selected δ range.

The true impact parameter $\delta^{\rm t}$ already includes the occasional mis-signing due to approximating of the B hadron direction by the heavy-quark jet axis. When the lepton originates from a direct semileptonic decay of a B meson we fit the simulated true impact parameter distribution to a sum of three (two) exponential functions ($\mathcal{P}_{\rm B_i}$) for positive (negative) $\delta^{\rm t}$, respectively. The lifetime of each B-hadron is introduced by rescaling each exponential coefficient of $\mathcal{P}_{\rm B_i}$ with the ratio of $\tau_{B_i}/\ \tau_{\rm MC}$ where τ_{B_i} are the lifetimes of the B_d^0, B^+, and B_s^0 mesons, and $\tau_{\rm MC} = 1.55$ ps is the lifetime used for all B hadrons in the Monte Carlo simulation. The validity of this procedure has been checked on inclusive lepton samples generated with different lifetimes.

The resolution function $\mathcal{R}(\delta^{\rm t})$ is parameterized as a superposition of three Gaussian functions. The parameters of the resolution function have been evaluated using the higher statistics of the inclusive lepton sample. For Monte Carlo events, we fit the true impact parameter density function $\mathcal{P}_\ell(\delta^{\rm t})$ to the signal sample, only. For data events, $\mathcal{P}_\ell(\delta^{\rm t})$ is the sum of the underlying true impact parameter density functions for the fractions of direct $b \to \ell$ decays, leptons from cascade decays ($b \to c \to \ell$), charm meson semileptonic decays, and background (fake) leptons. $\mathcal{P}_\ell$ has been determined using the simulation. In data, the lifetime of B mesons has been set to 1.59 ps as obtained by the measurement of τ_b in the 1994 lepton sample [5]. The parameters of the resolution function σ_j and the corresponding fraction of events ${\rm g}_j$, where ${\rm g}_1 = 1$ - ${\rm g}_2$ - ${\rm g}_3$, have been obtained by fitting the measured δ distribution to the convolution of $\mathcal{P}_\ell \otimes \mathcal{R}$ and are shown in Table 1.

	Data	Monte Carlo
σ_1	58 μm	43 μm
σ_2	143 μm	97 μm
σ_3	590 μm	330 μm
${\rm g}_2$	0.26	0.27
${\rm g}_3$	0.027	0.041

Table 1: Parameters of the resolution function for data and MC simulation.

The fractions ${\rm f_{B_i}}$ are determined by the different production rates of B_d^0, B^+, and B_s^0 mesons and by the relative production rates of charged D^{*+} in their semileptonic decays. About 74% of all true-D^{*+} lepton combinations are estimated to originate from the decay $\bar{B}_d^0 \to D^{*+}\ell^-\bar{\nu}$. The other contribution originate from D^{**} decays and produce all three types of B mesons. Reference [6] has compiled the existing data to estimate these production rates and their errors. Following their procedure we obtain:

$$\begin{aligned} \mathrm{f_{B^+}} &= 13.6 \pm 3.4\ \% \\ \mathrm{f_{B_d^{**}}} &= 7.8 \pm 1.6\ \% \\ \mathrm{f_{B_s^0}} &= 1.0 \pm 1.0\ \%\ . \end{aligned}$$

The value of $\mathrm{f_{B_d^0}}$ is equal to (1 - $\mathrm{f_{B^+}}$ - $\mathrm{f_{B_s^0}}$ - $\mathrm{f_{fbc}}$) and comprises the fraction $\mathrm{f_{B_d^{**}}}$ of D^{*+} produced in D^{**} decays. Contributions from b baryon semileptonic decays are expected to be negligble.

When the lepton originates from a cascade decay ($b \to c \to \ell$), right-sign combinations can be produced if there are two charmed mesons in the B decay chain. Their rate is estimated to be 2.4 $\pm$ 0.2 % of all true-D^{*+} lepton combinations, which is smaller than in the inclusive lepton sample where this value is about 10%. The contribution from true-D^{*+} with fake leptons is 1.3 $\pm$ 0.2 % and is also smaller than in the inclusive lepton sample, because the *uds* events produce only very few D^{*+} (via gluon splitting). The fake lepton and the cascade lepton distribution are taken together with $\mathrm{f_{fbc}} = 3.7 \pm 0.4$ % and their true impact parameter distribution $\mathcal{P}_{\mathrm{fbc}}$ is estimated from the simulation by fitting the measured δ distribution using the resolution function $\mathcal{R}$.

The probability of a D^{*+}-lepton combination arising from combinatorial background is $\mathrm{f_{comb}} = 0.537 \pm 0.021$ calculated by multiplying each Δm-bin in the wrong-sign data sample by the ratio of the simulated right-sign combinatorial non-D^{*+} over the wrong-sign background. The error is statistical only. The true impact parameter distribution $\mathcal{P}_{\mathrm{comb}}$ is estimated in two ways by using the wrong-sign sample (data and Monte Carlo) and by using the simulated non-D^{*+} combinatorial background sample. For both samples, $\mathcal{P}_{\mathrm{comb}}$ is a sum of up to three exponential functions for positive and negative δ^{t}. Its parameters are determined by fitting the measured δ distribution to $\mathcal{P}_{\mathrm{comb}} \otimes \mathcal{R}$ using the corresponding resolution function for data and Monte Carlo samples, respectively.

The measured δ distribution for data is shown in Figure 3 where the result of the lifetime fit using the Monte Carlo non-D^{*+} combinatorial background sample for $\mathcal{P}_{\mathrm{comb}}$ has been overlayed. Also shown are the contributions from the combinatorial background (dashed) and from the contribution from cascade and fake leptons (dotted). We obtain:

$$\tau_{B_d^0} = 1.74 \pm 0.12 \ \ \mathrm{ps}$$

4 SYSTEMATIC ERRORS

Various sources of systematic errors are estimated, generally by varying parameters by their measured or estimated errors. The different contributions taken into account for the systematic error are listed in Table 2.

No bias from the fitting procedure has been detected when fitting only the simulated sample of $\bar{B}_d^0 \to D^{*+} X \ell^- \bar{\nu}$ decays. For these events which have been generated with a

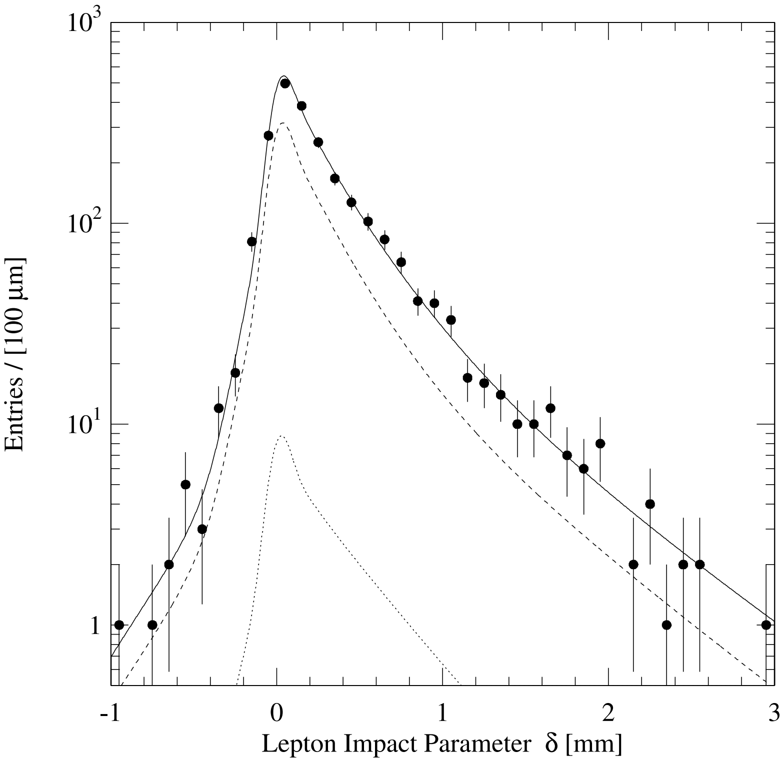

Figure 3: Lepton impact parameter δ distribution for data (dots). The curves overlayed show the fitted δ distribution for all (solid line) combinatorial background (dashed line) and cascade/fake lepton (dotted line) contributions.

lifetime of 1.55 ps, the measured lifetime is $\tau_{B_d^0} = 1.549 \pm 0.033$ ps. The background fraction f_{comb} has been determined using the wrong-sign data in the Δm signal range multiplied by the ratio of the simulated right-sign combinatorial non-D^{*+} over the wrong-sign background. Thus f_{comb} has a statistical uncertainty from data and Monte Carlo. The systematic uncertainty due to the description of the background ($\mathcal{P}_{comb}$) has been estimated by repeating the lifetime fit in data and Monte Carlo when either the background is taken from the combinatorial non-D^{*+} simulation (comb.) or from the corresponing wrong sign (w.s.) sample . The result are shown in Table 3. The wrong-sign sample has a δ distribution which is more shortlived than the combinatorial background thus resulting in higher lifetimes. This bias is 106 fs and 92 fs in data and Monte Carlo simulation, respectively. To account for an incomplete description of the combinatorial background in data we assign the above difference as systematic error. The fraction of cascade and fake leptons f_{fbc} has been varied by a relative 25%. The lepton transverse momentum has been smeared by 15 %. The uncertainty due to the simulation of the heavy-quark jet direction has been estimated by smearing the azimuthal jet angle by 1^o.

The systematic uncertainties due to differences between data and simulation in the impact parameter distribution have been estimated by using different resolution functions which have also been obtained by fitting the inclusive lepton spectra, e.g. by changing

Source	variation	$\Delta\tau_{B_d^0}$ [fs]
Background normalization	$\mathrm{f_{comb}} = 0.537 \pm 0.021$	$\pm$ 15
Background parametrization	$\mathcal{P}_{\mathrm{comb}}$	$\pm$ 14
Resolution function	systematic changes	$\pm$ 19
	statistical error	$\pm$ 16
Cascade and fake leptons	$\mathrm{f_{fbc}} = 3.7 \pm 1.0$ %	$\pm$ 1
Lepton transverse momentum	15 % smearing	$\pm$ 5
Angular jet resolution	1^o smearing	$\pm$ 7
B^+ meson lifetime	$\tau_{B^+} = 1.65 \pm 0.05$ ps	$\mp$ 6
B_s^0 meson lifetime	$\tau_{B_s^0} = 1.52 \pm 0.07$ ps	$\mp$ 1
D^{**} production	$\mathrm{f_{B^+}} = 13.6 \pm 3.4$ %	$\pm$ 3
	$\mathrm{f_{B_d^{**}}} = 7.8 \pm 1.6$ %	$\mp$ 1
	$\mathrm{f_{B_s^0}} = 1.0 \pm 1.0$ %	$\pm$ 2
B hadron fragmentation	$\mathrm{x_E} = 0.704 \pm 0.09$	$\pm$ 11
Total systematic error		36

Table 2: Systematic uncertainties.

Data/background sample	$\tau_{B_d^0}$ [ps]
Data/comb.	1.744 ± 0.121
Data/w.s.	1.850 ± 0.121
Simulation/comb.	1.565 ± 0.050
Simulation/w.s.	1.657 ± 0.049

Table 3: Comparison of lifetimes obtained in data and simulation by using different background parametrizations.

the input lifetime to 1.55 ps. The maximum change of $\tau_{B_d^0}$ is 19 fs. In addition, the parameters of the resolution function have been varied by their statistical error resulting in a systematic uncertainty of 16 fs.

The following systematic uncertainties are due to the incomplete knowledge of the production and decay of B hadrons. Parameters are varied according to recommendations of references [7, 8]. We have varied the lifetime of the B^+ meson $\tau_{B^+} = 1.65 \pm 0.05$ ps and of the B_s^0 meson $\tau_{B_s^0} = 1.52 \pm 0.07$ ps, respectively. The fractions $\mathrm{f}_{\mathrm{B_d^{**}}}$ $\mathrm{f}_{\mathrm{B^+}}$, and $\mathrm{f}_{\mathrm{B_s^0}}$ of B_d^0, B^+, and B_s^0 mesons in the true-D^{*+} sample which are produced via D^{**} have been varied according to their errors estimated above. The mean fractional beam energy $\mathrm{x_E}$ carried away by the weakly decaying B hadron has been varied from 0.695 to 0.713. This changes the shape of the underlying impact parameter description as well as the background fraction. Thus the total systematic uncertainty amounts to 36 fs. We get the following result:

$$\tau_{B_d^0} = 1.74 \pm 0.12 \pm 0.04 \ \ \text{ps}$$

where the first and second error are statistical and systematic, respectively.

5 CONCLUSIONS

We have reconstructed the decay $\bar{B} \to D^{*+} X \ell^- \bar{\nu}$ by selecting jets with a high transverse momentum lepton and using the mass difference distribution Δm = m($D^0 \pi_s^+$) - m(D^0) of an inclusively reconstructed D^0 meson signed with the slow pion π_s^+. In the Δm range below 0.20 GeV we find 1855 $\pm$ 95 D^{*+} candidates out of which 1329 $\pm$ 68 are attributed to $\bar{B}_d^0 \to D^{*+} \ell^- \bar{\nu}$ decays.

Using leptons with accurate SMD measurements in the Δm range below 0.17 GeV we measure the lifetime of the neutral B_d^0 meson to be

$$\tau_{B_d^0} = 1.74 \pm 0.12 \pm 0.04 \ \ \text{ps}$$

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

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