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MEASUREMENT OF THE AVERAGE LIFETIME OF *B* HADRONS WITH THE DELPHI DETECTOR

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Abstract

A measurement of the average lifetime of *B* hadrons produced in $e^+ e^-$ interactions at the Z^0 pole is presented. The data were taken with the DELPHI detector, including a high precision silicon microstrip vertex detector, at LEP. In the analysis presented here, the *b* lifetime is extracted from the impact parameter distribution of high p_t muons.
The preliminary resulting *b* lifetime is $\tau_B = 1.30 \pm 0.12$ (*stat.*) $\pm$ 0.11 (*syst.*) *ps*

1. Introduction

Within the framework of the Standard Model, weak decays of hadrons containing *b* quarks indicate the mixing of the *b* quark with the lighter *d* and *s* quarks. This mixing is described by the Cabibbo-Kobayashi-Maskawa matrix which can be parametrized by 3 angles and one phase. These parameters are fundamental constants of the theory and must be determined experimentally. The *B* hadron lifetime is one of the experimental quantities, which allow determination of these parameters. In fact, in the spectator model, the lifetime of a B hadron is given by

$$\tau_B = \frac{192\pi^3}{G_F^2 m_b^5} f_{QCD}\, BR_{sl}\left(|V_{bu}|^2 + f_{ps}|V_{bc}|^2 \right)^{-1}$$

where G_F is the Fermi constant, m_b is the *b* quark mass, f_{QCD} is a QCD correction factor, f_{ps} is a phase space factor and BR_{sl} is the $B \rightarrow \mu$ branching ratio. As $|V_{bu}| \approx 0.1|V_{bc}|$ [1,2], measuring the *b* lifetime constrains the value of $|V_{bc}|$, once its branching ratio for semi-leptonic decays and the mass of the *b* quark are given.

The present analysis, using data from the DELPHI detector at LEP, extracts the lifetime of *b* particles from the impact parameter distribution of muon candidates produced in semileptonic decays and characterized by their high transverse momentum with respect to the jet axis. Since this method of identifying *B* decays cannot distinguish between the various *B* hadrons, we measure the average lifetime of b hadrons produced in Z^0 decays, weigthed by the relative production rates and semileptonic branching ratios of the various states.

In this analysis the data from a silicon microstrip vertex detector (microvertex) are used, resulting in a high impact parameter resolution, that permits a clear lifetime signal to be seen.

2. The DELPHI detector

The DELPHI detector has been described in detail elsewhere [9] . Since this analysis is based on the information from the microvertex detector, only the properties of the barrel region are summarised here.

Muon identification in the barrel region is based on a set of muon chambers (MUB) consisting of seven planes of drift chambers, three inside the return yoke of the magnet after 90*cm* of iron (inner layer) and four outside after a further 20*cm* of iron (outer and peripheral layers). Each chamber measures the $R\Phi$ coordinate within ±6*mm*.

The background of misidentified hadrons in the selected muon sample was evaluated using the hadron calorimeter (HCAL), a sampling gas detector incorporated in the magnet yoke. The energy resolution of the detector is $100\% / \sqrt{E}$.

In the barrel region, the charged tracks are measured in the 1.23 T magnetic field by a set of cylindrical tracking detectors whose axes are parallel to the magnetic field and to the beam direction. The Time Projection Chamber (TPC) is the main tracking device, providing up to 16 space points for angles between 39° and 141° , at radii between 30 cm and 122 cm. The Outer Detector (OD) has five layers of drift cells at radii between 198 and 206 *cm* and covers polar angles from 42° to 138°. The Inner Detector (ID) is a cylindrical drift chamber having inner radius of 12 *cm* and outer radius of 28 *cm*. It covers polar angles between 29° and 151°. It contains a jet chamber section providing 24 $R\Phi$ coordinates surrounded by five layers of proportional chambers providing both $R\Phi$ and longitudinal coordinates.

The microvertex detector (VD) in the configuration used in this analysis [10] was installed at the beginning of 1990 and has been fully operational during the whole 1990 run. The detector was constrained to fit into the space between the beam pipe and the ID. It was consisting of two independent half-shells each of them containing two concentric layers of capacitatively coupled silicon microstrip detectors located at radii of 9 and 11 *cm* (Fig. 1). Each layer consists of 24 modules with about 10% overlap in Φ between the modules. Each module carries 4 detectors along z, with strips parallel to the beam and detector pairs wire bonded in series and read-out at the end. They measure $R\Phi$ coordinates over a length of 24 *cm*, and cover polar angles between 43° and 137°. The strip pitch is 25 μm and each second strip is read out by VLSI chips with serial analog outputs. The number of read-out strips is more than 54K. The measured intrinsic point resolution for single tracks is $\sigma_{intr} = 8\ \mu m$.

In order to fully exploit the high intrinsic resolution of the VD, a careful understanding of its internal alignment was needed. Position monitoring systems showed that the microvertex detector structure and position were stable within a few μm throughout the whole period of operation. The relative positions of the microstrip detectors were measured outside DELPHI to an accuracy of about 20 μm. Further alignment corrections were evaluated using Z^o events, especially $Z^o \rightarrow \mu^+ \mu^-$ events. The separation in the $R\Phi$ plane between a pair of tracks from $Z^o \rightarrow \mu^+ \mu^-$ decay at their closest approach to the beam spot, called the dimuon miss distance, provides a measure of the $R\Phi$ resolution at the vertex that is independent of the precise knowledge of the beam spot. Using only the two VD hits on each track and the beam momentum value and the θ and z values provided by the external tracking, the dimuons miss distance is well fitted by a single Gaussian of width $\sigma = 110\ \mu m$. Since the two VD hits are at radii of 9 and 11 cm., this corresponds to a precision on individual $R\Phi$ coordinates in the VD, including VD alignment errors, of

$$\sigma_{VD} = (110/\sqrt{2})/\sqrt{(9/2)^2 + (11/2)^2} \approx 11\ \mu m\ .$$

Thus the final alignement precision of the VD was

$$\sigma_{align.} = (\sigma_{VD}^2 - \sigma_{intr.}^2)^{\frac{1}{2}} \approx\ 8\ \mu m.$$

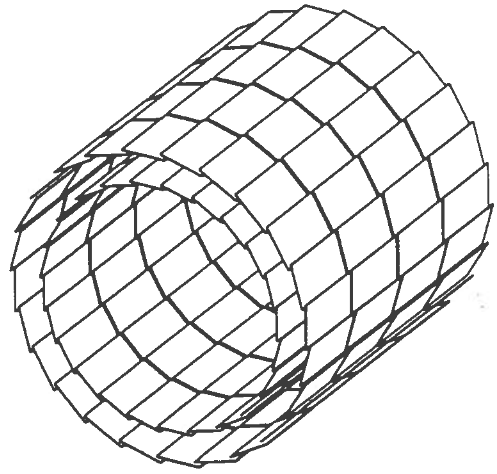

Fig.1 Layout of the DELPHI microvertex

3. Data Analysis

3.1 Event and track selection

The present analysis is based on about 120K hadronic Z^0 decays collected by the DELPHI detector at LEP during 1990. The sample of hadronic events was selected by requiring

- at least 5 detected charged particles with momentum $p > 0.2$ *GeV/c*,
- a total detected energy in charged particles greater than 15 *GeV*,
- a total detected energy in charged particles larger than 3 *GeV* in each of the two hemispheres, $\cos\theta < 0$ and $\cos\theta > 0$.

Events were further required to have $|\cos(\theta_{thrust})|$ below 0.85, where θ_{thrust} is the polar angle of the thrust axis of the event, and to have at least two jets reconstructed. Jets were reconstructed using only charged tracks with the LUND algorithm LUCLUS with default parameters [12]. Then only tracks belonging to a jet whose thrust axis was in the barrel region (defined by $|\sin\theta_T| > 0.5$) and containing at least two charged tracks with momentum above 2 *GeV/c* were used. These cuts ensured that the jet thrust axis direction was adequately defined. When computing the p_t, momentum of the track transverse to the jet thrust axis, the track was first removed from the jet and the axis was re-determined.

3.2 Impact parameter calculation

The impact parameter of a track is defined as its distance of closest approach to the primary vertex. It is signed according to the position of the intersection of the track with the jet thrust axis. This axis is taken to reproduce the parent particle direction. The sign is positive if the intersection point corresponds to a positive decay length. Because of the much higher reconstruction accuracy in the $R\Phi$ plane, only the projection of the impact parameter on this plane is used. The projected impact parameter δ of a track originated from a particle with a proper decay time t is given by:

$$\delta = \beta\gamma ct \sin\psi \sin\theta$$

where θ is the polar angle of the track and ψ is its angle with respect to the flight direction of the parent particle, projected in the $R\Phi$ plane. For large values of the $\beta\gamma$ factor, the kinematic effects cancel on average and $<\delta>$ is proportional to $c\tau$, where τ is the average proper lifetime.

To determine the impact parameter, tracks reconstructed in the barrel tracking detectors were associated with hits in the VD and then extrapolated to the interaction region.

The impact parameter resolution is the convolution of the track extrapolation accuracy σ_{extr} and the precision on the determination of the primary vertex position σ_{vtx}, giving

$$\sigma_{impact} = \sigma_{extr} \oplus \sigma_{vtx}$$

For the calculation of the primary vertex a two step procedure was used. First, primary vertices were reconstructed for all hadronic events [11] and used to measure the average position of the interaction region that was reconstructed to better than $20\ \mu m$ in both x and y, for each LEP fill.

As these mean beam positions were reconstructed using a large number of vertices, they can be considered to be independent of any individual event. Therefore, in a second step, an optimal estimation of the vertex position was obtained by including a beam constraint in the vertex fit. The mean beam position in the fill was used to initialize the fit. Subsequently, tracks were tested for compatibility with this vertex position before being included in the final primary vertex estimation. The impact parameter was therefore computed with respect to the fitted vertex. To avoid the bias due to the inclusion of the track in the fit, each track was removed from the fit before computing its impact parameter.

Events were used in the following analysis only if four or more tracks contributed to the vertex fit.

3.3 Impact parameter and extrapolation resolution

The impact parameter resolution using the primary vertex reconstructed for each event, as described above, was studied as a function of the track momentum component in the *RΦ* plane. The resolution degrades towards low momenta due to the effect of multiple scattering. Above 10 *GeV/c*, multiple scattering is negligible and the fitted width of the impact parameter distribution gives the value of its intrinsic resolution σ_{impact}. Using the primary vertex reconstructed event by event this asymptotic value is 84 μm (Fig.2).

The height of the LEP beam spot, $\sigma_{y,beam}$, is small ($\sigma_{x,beam} \approx 15 \mu m$, $\sigma_{y,beam} \approx 200\ \mu m$) So the effect of the error in the vertex position on the impact parameter is minor for tracks at a small angle to the horizontal plane. This allows the contributions to the impact parameter resolution σ_{impact} from the track extrapolation error σ_{extr} and the vertex reconstruction error σ_{vtx} to be distinguished. Tracks within 15° of the horizontal plane were used to study the extrapolation resolution as a function of the track momentum component in the *RΦ* plane. For high momentum tracks a width of 72μm was measured. The asymptotic track extrapolation resolution was then computed by unfolding from this measured width the residual effect of the horizontal beam width and of the error on the average beam position. It results in an estimation of $\sigma_{extr} = 62\ \mu m$ as extrapolation accuracy for high momentum tracks. These results imply then a resolution on the

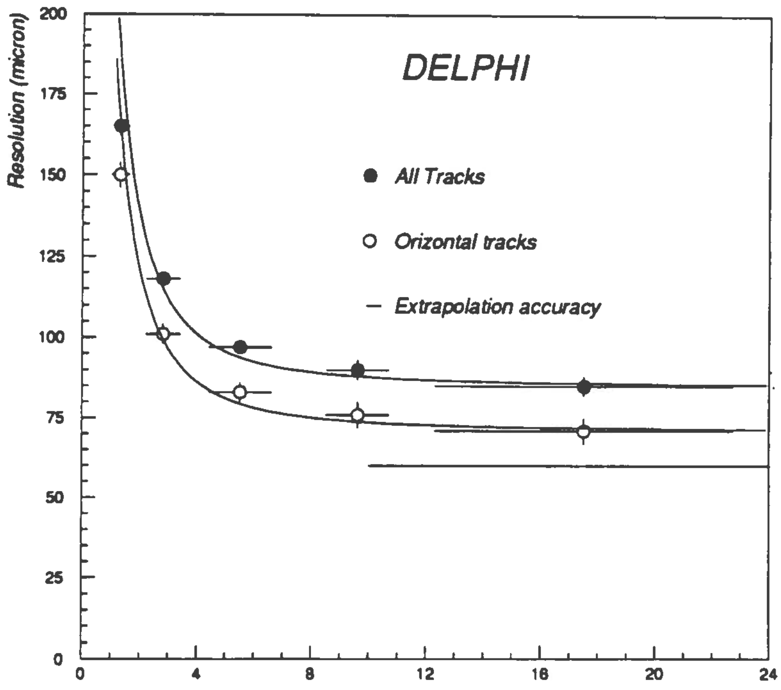

Fig.2 Impact parameter resolution

reconstruction of the event primary vertex $\sigma_{vtx} = \left(\sigma^2_{impact} - \sigma^2_{extr}\right)^{\frac{1}{2}} = 60\ \mu m$ including the beam constraint in the vertex fit.

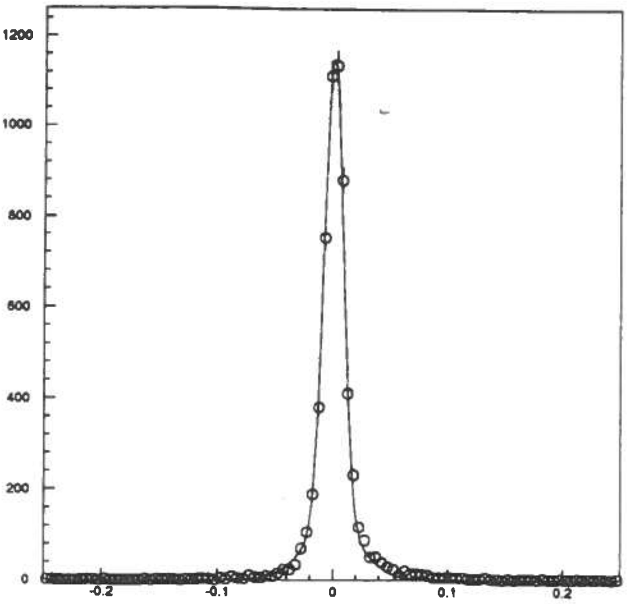

Fig.3 I.p. for tracks with pt parallel to z axis

The impact parameter resolution for the tracks used in the present lifetime analysis was measured on the data. Tracks were selected satisfying the standard reconstruction quality and kinematical cuts as in the analysis following. Further they were required to have a high p_t component oriented along the z axis. These were selected by requiring $|\sin \psi_{pt}| < 0.5$ where ψ_{pt} is the angle between the p_t vector and the plane defined by the thrust direction and the z axis. Such tracks carry only a minimal lifetime contribution to the impact parameter in the $R\Phi$ plane. Their distribution was parametrized as the sum of two Gaussians (Fig. 3). Both were well centred near zero. The narrower Gaussian had a width of 82 μm reflecting the intrinsic resolution while the wider Gaussian of width 245 μm containing 22% of the tracks described the tail due to residual misalignments in the tracking detectors and to ambiguities in the pattern recognition.

3.4 Muon Identification

All hits reconstructed in the MUB and compatible with the extrapolated track position were tested for association and the combination giving the smallest χ^2 was taken. Muon candidates were then selected by requiring the track to be linked to two layers of the muon chambers, or at least to the peripheral one, and the track extrapolation at the level of the muon chamber to be within 3 σ of the associated hit both in $R\Phi$ and in the ϕ angle. For muons above 3 *GeV/c*, the efficiency of this selection ε_μ was found to be *(78.5 ± 3.5)%* and to have no significant dependence on the energy of the muon or its momentum transverse to the jet axis. The contribution from π and K decays to the candidate muon sample was also obtained from the Monte Carlo simulation.

The contamination from hadrons was measured from the real data. For high energy pions from $\tau \to 3\pi$ decay, the misidentification probability $\varepsilon_{\mu,\pi}$ was found to be *(1.1 ± 0.3) %*. At low energy, between *3* and *5 GeV/c*, $\varepsilon_{\mu,\pi}$ was found to be below 1% for pions from $K^0_s \to \pi^+\pi^-$ decay. Both these evaluations are limited by statistics. To improve the precision we have used the behaviour of the candidates inside the HCAL. For tracks in the range between *10* and *15 GeV/c*, this procedure gave $\varepsilon_{\mu,\pi} = (0.91 \pm 0.12 \pm 0.14)\ \%$, where the second error is the estimated systematic uncertainty.

4. B lifetime determination

The composition of the sample was evaluated as a function of the momentum of the muon candidate transverse to the thrust axis of the jet requiring the track to have momentum greater than $3\ GeV/c$. The integrated composition for the $p > 3\ GeV/c$ and $p_t > 1\ GeV/c$ cuts used in the analysis is : 48% from b,10% from bc, 9% from c, 8% from decay background and 25% from misidentified hadronic background.

After applying all the above cuts to the muon sample, 759 candidates with two associated VD hits remained. Their impact parameter distribution was shifted towards positive values, having a mean value of $161 \pm 14\ \mu m$. The b lifetime information was extracted by an unbinned maximum likelihood fit.

The likelihood function used was the product of the probability density functions for the individual events, corresponding to the observation of a muon with a given value of impact parameter:

$$L = \prod_i P(\delta_i, \tau_B)$$

For each track, i, the fitting function $P(\delta_i, \tau_B)$ was defined as the sum of the contributions from five sources:

- prompt muons from direct $b \to \mu$ decays,
- prompt muons from cascade $b \to c \to \mu$ decay,
- prompt muons from direct c decays,
- muons from the decay of long lived hadrons (π, K, ...),
- misidentified hadrons,

each weighted by the fraction of muons arising from that source:

$$P(\delta_i;\tau_B) = f_b(p_t)\ P_b(\delta_i;\tau_B) + f_{bc}(p_t)\ P_{bc}(\delta_i;\tau_B) + f_c(p_t)\ P_c(\delta_i) + \\ f_{dec}(p_t)\ P_{dec}(\delta_i) + f_{mis}(p_t)\ P_{mis}(\delta_i)$$

The fractions $f_j(p_t)$, with $j=(b,bc,c,dec,mis)$, are the probabilities that a muon candidate of given transverse momentum p_t came from each of these sources, as discussed above. The P_j are the probability density functions describing the impact parameter distributions for the various sources.

The probability density functions for prompt leptons were evaluated in two steps. Firstly the impact parameter distribution expected for a reference lifetime τ_0 was computed by Monte Carlo, disregarding tracking resolution effects. Hadronic events were generated using the Lund JETSET 7.2 Parton Shower model [12] with retuned parameters, the Peterson fragmentation scheme [13], and an improved description of b and c decays. Muons were required to pass the same selection criteria as in the data. The impact parameter of each surviving muon track was evaluated using the exact trajectory and primary vertex position, as generated in the Monte Carlo, but its sign was determined using the reconstructed jet thrust axis. The distributions were then parametrized as the sum of four exponentials giving a corresponding ``physics function" F_j with $j=(b,bc,c)$. The distribution for any arbitrary lifetime τ was then found by scaling the reference distribution by the factor τ/τ_0. The F_{bc} function was scaled with only the b lifetime since the b lifetime dominates its shape. The charm physics function F_c was fitted to the impact parameter of muons produced in simulated charm decays. The uncertainties on the individual charm lifetimes and semileptonic branching ratios contribute to

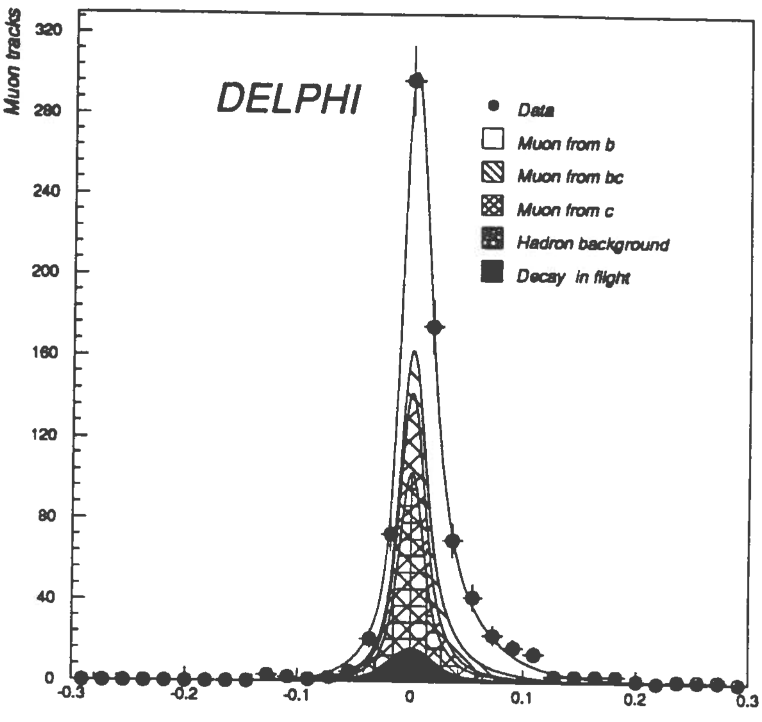

Fig.4 Muon Impact Parameter

the systematic error. The second step in evaluating the prompt muon probability density function was to convolute these functions analytically with the experimental resolution function described above

$$P_x(\delta,\tau_b) = F_x(\delta,\tau_b) \otimes R(\delta) .$$

The background probability density function due to misidentified hadrons P_{mis} was determined from the data, using the tracks that satisfy the same selection criteria as the muon candidates, except the muon identification requirement. That due to decays P_{dec} of long-lived hadrons was studied by Monte Carlo. The apparent impact parameter distributions of both decaying and non decaying mesons were simulated for single tracks originating at the primary vertex and passing through the full DELPHI detector simulation. Muons were identified using the same procedure as on the data and the tracks were refitted through associated hits of the microvertex detector. This enables the effect of the kink at the decay to be studied. In real hadronic data these tracks have some lifetime contribution from the b and c decays. To include this a convolution function was found which gives the non decaying mesons the same impact parameter distribution as that measured on data for misidentified hadrons. The decaying mesons were then convoluted with this function to give the best estimate of their impact parameter distribution.

5. Discussion

5.1 Results

The result of the fit was $\tau_B = (1.30 \pm 0.12\ )\ ps$. The fitting procedure was tested using Monte Carlo data generated with different lifetimes. There was good agreement over the whole range of input lifetimes (*1* to *1.8* *ps*). Fig.4 shows the result of the fit, including the contributions from the different muon sources, superimposed on the data. The size of the statistical error is determined by the event statistics, by the impact parameter resolution and by the purity of the muon sample. This last factor affects the statistical error in two ways: first, it determines the useful event statistics, second, since the flavour content is known only in a statistical sense, there is a further deterioration as the purity decreases.

5.2 Consistency checks

The *b* lifetime was evaluated for various subsamples of the data, giving the results summarized in table 1.

Table 1: Summary of consistency checks

Selection	N_{event}	$\tau_B[ps]$
Standard selection	759	1.30±0.12
Positive charge tracks	392	1.33±0.18
Negative charge tracks	367	1.28±0.17
$\cos\phi > 0$	378	1.24±0.17
$\cos\phi < 0$	381	1.35±0.18
Mean beam Position	759	1.31±0.13

The results obtained from muons of positive and negative charge agreed. Because of the good spatial resolution of the VD, the track extrapolation to the interaction region is determined mainly by the VD information. To check whether possible misalignments of a single VD half-shell affect the result, tracks measured in the two half-shells were separated by a cut in $\cos\phi$. The results agreed. To check for any possible bias arising from the use of a primary vertex position reconstructed individually for each event, the analysis was repeated using a fixed beam spot given by the average beam position measured for each fill. In this case the resolution function was reevaluated to account for the degraded impact parameter resolution. The value obtained agreed with the previous result, showing that no systematic effects derive from our procedure.

5.3 Systematic error

The systematic errors for the final sample are summarized in Table 2. There are two main contribution to the systematic error. The first is connected with the residual uncertainty affecting the knowledge of the muon sample composition. The other derives from the choice of the parametrization of the physics functions and with the evaluation of the impact parameter resolution for the likelihood fit. The value quoted for the error from the sample composition accounts for an estimated *20%* uncertainty in the hadronic background, for a *20%* difference in the ratio between the misidentified hadron and decay in flight background, for the uncertainty on the value of the $b \to \mu$ branching ratio measured at the Υ threshold and in the continuum and for uncertainties on the *b* fragmentation. The effect of the uncertainty in the parametrization of the resolution function was evaluated as follows. The resolution function is represented by the sum of two gaussians centered around the zero and is described by three parameters: σ_1, σ_2 (the two widths) and f, the ratio of the areas of the two gaussians (Fig.3). The systematic effect on the measured lifetime due to the uncertainties on this parametrization has been evaluated by varying independently of one standard deviation the central value of the parameters and taking into account the correlation between them. The same kind of analysis has been applied to evaluate the systematic errors due to the uncertainties of the parametrization of the Physics functions, of the hadronic background P_{mis}, of the decay background P_{dec}. For the decay in flight, we also evaluated the effect of changing the K/π ratio and the momentum spectrum of decaying particles. Adding all contributions in quadrature, the total systematic error is *0.11 ps*.

Table 2: Systematic error evaluation

Source	Systematic error [*ps*]
Muon sample composition	0.080
Physics functions	0.030
Hadronic background parametrization	0.020
Decay background parametrization	0.040
Resolution function	0.050
Average τ_C	0.015
Fragmentation	0.010
Total	0.110

6 Conclusion

In summary, from the analysis of the impact parameter distributions of high p_t muons, the average lifetime of B hadrons produced in Z^o decays is found to be

$$\tau_b = 1.30 \pm 0.12 \pm 0.11\ ps$$

where the first error is statistical, the second systematic. The result is preliminary.

This measured lifetime can be used to constrain the Cabibbo Kobayashi Maskawa matrix element $|V_{bc}|$. Assuming a b quark mass m_b of 5.00 ± 0.25 GeV/c^2 and a semileptonic branching ratio $BR_{B \to \mu}$ of (11. ± 0.5)% and that $|V_{bu}|$ is negligible, this result corresponds to

$$|V_{bc}| = 0.041 \pm 0.003^{+0.006}_{-0.005}$$

where the first error is associated to this measurement of τ_b and the second one to the uncertainties in m_b and the semi-leptonic branching ratio.

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