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Updated Measurement of the Tau Lifetime at SLD*

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Abstract

We present an updated measurement of the tau lifetime at SLD. 4316 τ-pair events, selected from a $150k$ Z^0 data sample, are analyzed using three techniques: decay length, impact parameter, and impact parameter difference methods. The measurement benefits from the small and stable interaction region at the SLC and the precision CCD pixel vertex detector of the SLD. The combined result is: $\tau_\tau = 288.1 \pm 6.1(stat) \pm 3.3(syst)$ fs.

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1 Introduction

Within the framework of the Standard Model[1], all lepton flavors couple to the W boson in a similar fashion. A measurement of the τ lifetime provides a test of this hypothesis. The lifetime of the τ is related to that of the muon according to:

$$\frac{\tau_\tau}{\tau_\mu} = \left(\frac{m_\mu}{m_\tau}\right)^5 \mathcal{B}R(\tau^- \to e^- \bar{\nu}_e \nu_\tau)\ [1 - \delta_r], \tag{1}$$

where m_μ is the muon mass, m_τ the τ mass, $\mathcal{B}R(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$ the τ electronic branching fraction, and δ_r radiative and electroweak corrections[2].

The SLC with its small and stable interaction region and the SLD with its excellent tracking and vertexing resolution provided by its CCD pixel vertex detector represent a well suited environment for measuring the τ lifetime. Three techniques are utilized: the decay length method using three-prong τ decays, the impact parameter method using one-prong decays, and the impact parameter difference method using decay correlations in 1 vs. 1 τ-pair events.

A description of the SLD detector components and their performance can be found elsewhere[3, 4]. The vertex detector (VXD), the central drift chamber (CDC), and the lead–liquid-argon calorimeter (LAC) represent the main elements used in this analysis. For infinite-momentum tracks, the combined VXD-CDC tracking system achieves an impact parameter resolution of 11 (76) μm in the transverse (longitudinal) direction with respect to the beam axis. Its momentum resolution can be parametrized as a function of the track transverse momentum p_T as: $\left(\frac{\delta p_T}{p_T}\right)^2 = 0.01^2 + (0.0026\ p_T)^2$. The energy resolution of the LAC for electromagnetic showers is $\frac{\sigma_E}{E} = \frac{15\%}{\sqrt{E(\mathrm{GeV})}}$.

In an earlier publication[3], we have reported a measurement based on 1671 τ-pair events from a $60k$ Z^0 data sample. The present measurement relies on the same analysis, with a few improvements, and a data sample about 2.5 times larger.

2 Final State Selection

The events used in this analysis were selected from a sample of 5.35 pb^{-1} collected at a center-of-mass energy of 91.2 GeV in 1994 and 1995. At this energy, τ-pair events are characterized by two low-multiplicity, collimated, back-to-back jets, and by missing energy. In addition, the background which consists of muon-pair, wide-angle Bhabha scattering, two-photon, and multihadron events, is easily reduced to a reasonable level. The event selection criteria are based mainly on tracking and calorimetry information; a detailed description can be found in Ref.[3].

Candidate events are required to have at least two but fewer than seven tracks. The total visible energy in the event must be greater than 10 GeV, the total electromagnetic energy must be less than 62.5 GeV, and the polar angle Θ_{miss} of the missing momentum vector must satisfy $|\cos\Theta_{miss}| < 0.88$. In each hemisphere, tracks are required to lie within 15° of the jet axis, and the invariant mass be less than 2.3 GeV/c^2. The jet axes in the two hemispheres must be back to back within 20°, and the sum of two largest track momenta in the event must be less than 65 GeV/c. Two-prong events are required to have a minimum acolinearity of 10 mrad. A total of 4316 τ-pair candidates are selected. From a Monte Carlo program based on the τ-pair event generator KORALZ 4.0 [5] and the detector simulation package GEANT 3.21 [6], the selection efficiency is estimated to be 62.7%. The purity of the sample is estimated to be 97.5%.

Further requirements are applied in order to select events used in each of three analysis techniques, namely the 1 vs. 1 and the 1 vs. 3 topologies. After exclusion of tracks consistent with originating from a photon conversion, the event is required to have exactly two or four tracks. In the decay length (DL) method, which uses 1 vs. 3 events, tracks on the three-prong side are required to pass track quality cuts (at least 25 hits in the CDC, at least one hit in the VXD, a track fit χ^2 per degree of freedom less than 5 for two of the tracks and less than 15 for the third) and are fit to a common vertex (the χ^2 probability for the vertex fit must be less than 0.04%). In this fashion, 702 events are selected for the decay length method, with a negligible contamination from background.

Both the single-impact parameter (IP) method and the impact parameter difference (IPD) method use events in the 1 vs. 1 topology. Both tracks in the event must satisfy these track quality requirements: momentum greater than 1 GeV/c, at least 40 CDC hits, at least one VXD hit, a track fit χ^2 per degree of freedom less than 5, a polar angle in the range $|\cos\theta| < 0.72$, and a distance of closest approach along the beam direction less than 2.5 mm. In addition, in order to further reduce the background from two-photon, wide-angle Bhabha scattering, and muon-pair events, the two-prong invariant mass is required to be greater than 3 GeV/c^2, the total invariant mass in the event must be less than 75 GeV/c^2, and the missing momentum vector must satisfy

$|\cos\Theta_{miss}| < 0.80$. A total of 1945 events in the 1 vs. 1 topology are selected, with a background contamination of 1.15% consisting of two-photon, wide-angle Bhabha scattering, and muon-pair events in almost equal amounts. For the IP method, each event contributes two measurements. Thus, 3890 tracks are used in the analysis.

3 Decay Length Method

In this technique, τ-pair events in the 1 vs. 3 topology are selected as described above, a vertex fit in three dimensions is performed on the three-prong side of the event, and a decay length is calculated for each event as the distance from the interaction point to this three-prong vertex. The average decay length is extracted from an unbinned maximum likelihood fit using an exponential decay distribution convoluted with a Gaussian resolution function:

$$P(l_i,\sigma_i;l_0,s_0) = \frac{1}{l_i s_0 \sigma_i \sqrt{2\pi}} \int \exp\left(-\frac{x}{l_0}\right) \exp\left(-\frac{(x-l_i)^2}{2s_0^2\sigma_i^2}\right) dx, \qquad (2)$$

where the l_i are the measured decay lengths, l_0 is the parent decay length, and s_0 is a scale factor on the calculated decay length errors σ_i. The average decay length error is calculated to be 407 ± 6 μm. The fit returns a value of 2.14 ± 0.08 mm for the average decay length, with a scale factor of $s_0 = 1.20 \pm 0.09$. In Fig. 1(a), the distribution of measured decay lengths in the data is shown, with the fit function represented by the solid curve. Fig. 1(b) shows the decay length distribution for the Monte Carlo.

Systematic effects	Error (%)
Decay length resolution	0.5
Track and vertex quality cuts	0.5
Initial and final state radiation	0.3
Beam energy and energy spread	0.3
Total	0.8

Table 1: Systematic errors for decay length method.

A summary of the systematic errors is given in Table 1. The decay length resolution contributes an uncertainty of 0.5%. This was determined by repeating the fit with various fixed values of the scale factor s_0. The selection cuts, the track quality requirements, and various parameters in the three-prong vertex fit were varied in the data. The combined effect from these sources on the lifetime corresponds to a systematic uncertainty of 0.5%. The uncertainty in the calculation of initial- and final-state radiation in the Monte Carlo simulation was estimated to contribute a systematic error of 0.3% in the average boost of the τ's. The effect on this average boost due to the beam energy spread and the uncertainty in the beam energy measurement was also studied in the Monte Carlo; it contributes a systematic error of 0.3%. Combined in quadrature, these various uncertainties amount to a total systematic error on the τ lifetime of 0.8%.

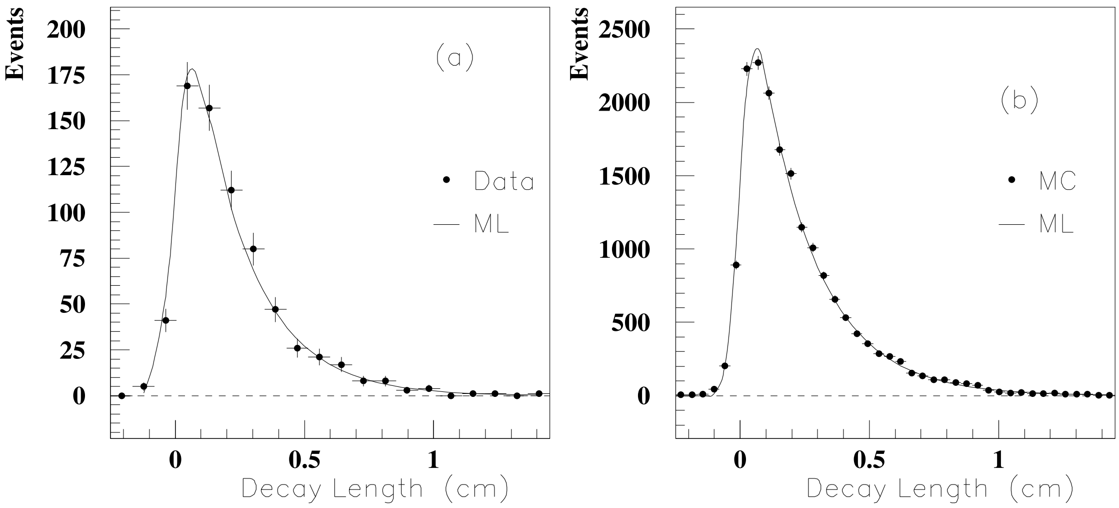

Figure 1: Three-prong decay length distribution for the final event samples in (a) the data and (b) the Monte Carlo. The solid curve in the two figures corresponds to the maximum likelihood fit described in the text.

Several cross-checks on both data and Monte Carlo were performed. Data samples from various run periods yielded consistent results for the lifetime. The effect of a possible misalignment between the VXD and the CDC was studied by dividing the data into four samples by azimuthal quadrants of the detector where decay vertices were found. No significant effect was observed. The effect of non-Gaussian tails in the distribution of beam positions was also investigated and found to be negligible. Finally, the measurement procedure was applied to a large number of Monte Carlo samples with comparable statistics to the data sample, and the various fits yielded lifetime values with an average consistent with that input in the Monte Carlo and a spread consistent with the statistical error obtained in the data. Thus, no bias associated with the measurement technique is observed.

From the above average decay length obtained from the maximum likelihood fit in the data and the average boost factor $< \beta\gamma >= 25.44 \pm 0.01$ determined from Monte Carlo, a value of the τ lifetime for the decay length method is derived:

$$\tau_\tau = 280 \pm 11 \pm 2 \text{ fs},$$

where the first error is statistical and the second systematic.

4 Impact Parameter Method

In the impact parameter method, the τ lifetime is inferred from the average track impact parameter in one-prong decays. In the present analysis, only 1 vs. 1 events (1945 events) are used and each event contributes two measurements (3890 tracks). The distribution of impact parameters measured in these events is shown in Fig. 2. The impact parameter is assigned a positive (negative) value if the extrapolated track crosses the event thrust axis before (after) its point of closest approach to the interaction point. Negative impact parameters result from finite tracking errors and uncertainties in the beam position determination.

The τ lifetime is extracted from this impact parameter distribution using a binned maximum likelihood fit. More details are given below in the description of the IPD analysis, where a similar approach is used. The fit function is represented by the impact parameter distribution in the Monte Carlo where the normalized content of each bin represents the likelihood probability of that bin. A likelihood function, defined as the product of these probabilities, is computed for all data points and for several τ lifetime values simulated by re-weighting in the Monte Carlo the impact parameter in each decay according to the proper time of the τ. The τ lifetime is derived as the value for which the likelihood function is maximum.

The maximum likelihood fit was limited to the impact parameter range from -0.3 mm to +0.6 mm, as shown in Fig. 2, and a bin size of 10 μm was used. Proper care was taken that in the tails of the data distribution a minimum of ten entries per bin is satisfied, by combining contents of neighboring bins. The result of the fit is:

$$\tau_\tau = 290.4 \pm 8.2 \text{ fs}.$$

The impact parameter distribution corresponding to the best fit lifetime in the Monte Carlo is shown as the solid histogram in Fig. 2. Good agreement between data and Monte Carlo is seen, and the comparison between the two distributions gives a χ^2 per degree of freedom of 1.2.

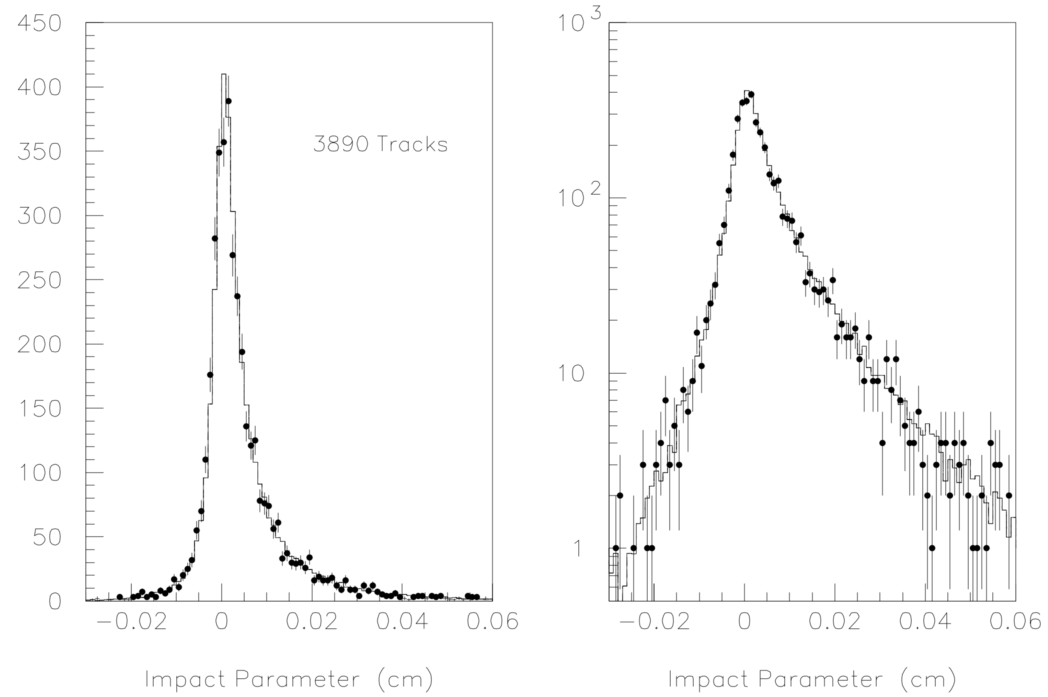

Figure 2: Impact parameter distribution for data (data points) and Monte Carlo (histogram) shown in both linear and logarithmic scale.

The dominant systematic error in this analysis comes from the fitting procedure. Both the bin size and the fit interval were varied over a large range. From the observed deviations in the measured lifetime, systematic errors of 1.0% and 0.9% were assigned for the binning and fit range, respectively. An additional systematic error of 0.5% is assigned due to Monte Carlo statistics. The sensitivity of the lifetime to the event selection and track quality requirementS was found to contribute a systematic uncertainty of 0.6%. As in the previous method, an error of 0.3% associated with the calculation of initial- and final-state radiation in the Monte Carlo is assigned, as well as an additional error of 0.3% due to the beam energy measurement uncertainty and beam energy spread. These systematic errors are listed in Table 2, and when combined in quadrature result in an overall systematic uncertainty of 1.6%.

Other systematic checks included dividing the data into various run periods, studying the alignment of the tracking detectors, and evaluating the effect of tails in the beam position measurement; all were found to have no significant effect.

Systematic effects	Error (%)
Binning	1.0
Fit range	0.9
Monte Carlo Statistics	0.5
Event selection and track quality	0.5
Initial and final state radiation	0.3
Beam energy and energy spread	0.3
Total	1.6

Table 2: Systematic errors for the impact parameter method.

The above measured value for the τ lifetime was corrected for background which was taken to have a zero lifetime. This was checked by merging events from the various sources that compose the background with the Monte Carlo sample that was used in the fit, with the proper normalization. The change in the lifetime was as expected within the statistical error. Including the systematic error, the lifetime measured with the impact parameter method is:

$$\tau_\tau = 293.7 \pm 8.2 \pm 4.6 \text{ fs}.$$

5 Impact Parameter Difference Method

The impact impact parameter difference technique[7] is based on the linear correlation that exists between the impact parameter difference and the acoplanarity of the two tracks in 1 vs. 1 τ-pair events:

$$< d_1 - d_2 >= \beta\gamma \, (c\tau_\tau) \, [1 - \lambda] \; \sin\theta \; \delta\phi. \tag{3}$$

In each event, one measures the impact parameters d_1 and d_2 and azimuths ϕ_1 and ϕ_2 of the two tracks. The acoplanarity is defined as $\delta\phi = \phi_1 - \phi_2 + \pi$, and θ is the polar angle of the thrust axis of the event. The term $[1 - \lambda]$ can be represented by the following expansion:

$$1 - \lambda = 1 - \frac{(\psi_1 - \psi_2)^2}{24} - \frac{(\psi_1 + \psi_2)^2}{8} + \frac{(\psi_1 - \psi_2)^2}{1920} + \frac{(\psi_1 + \psi_2)^2}{384} - \ldots, \tag{4}$$

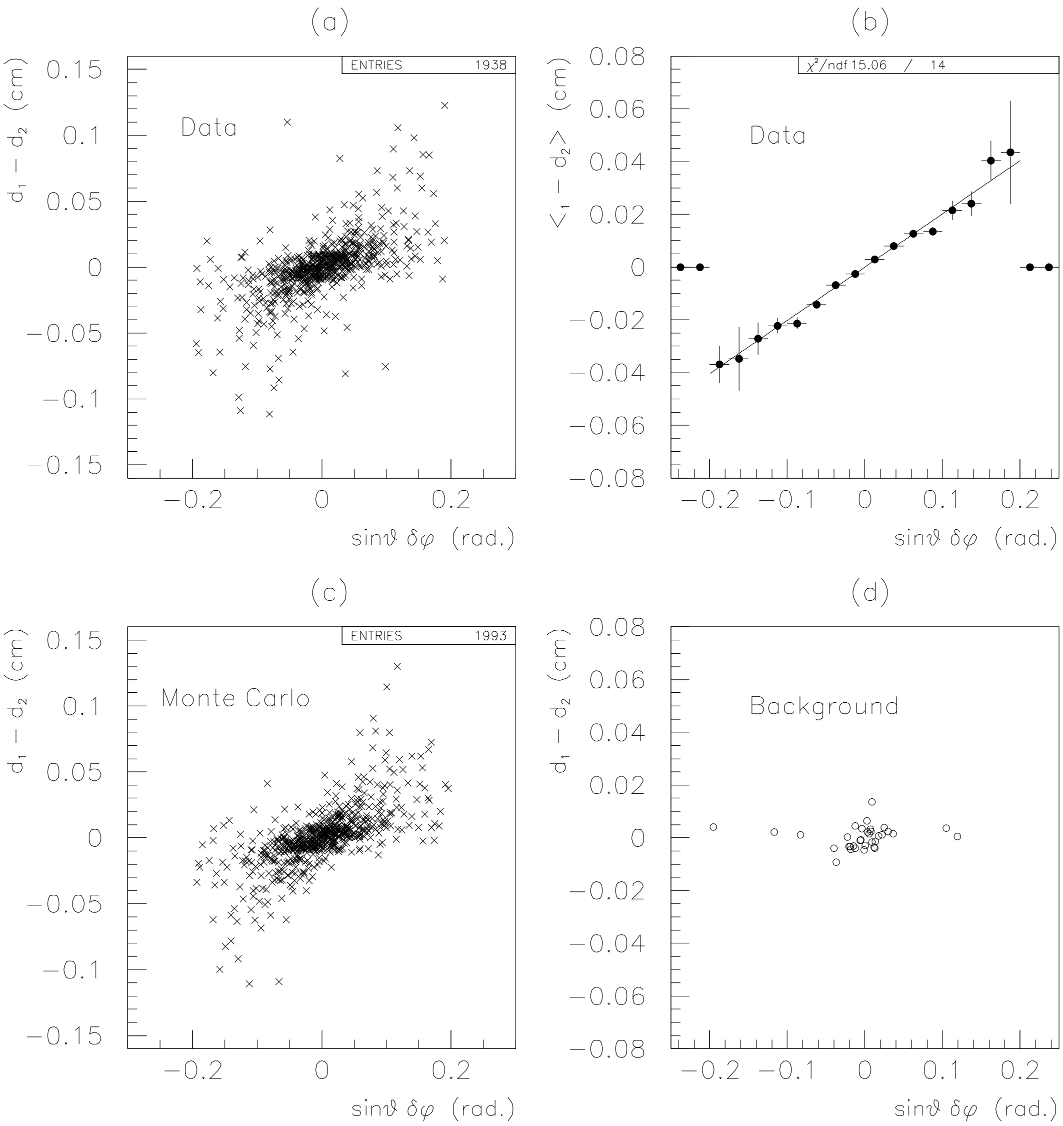

Figure 3: Scatter plots of impact parameter difference vs. acoplanarity for the data (a)-(b), Monte Carlo (c), and background (d).

where ψ_1 and ψ_2 are the decay angles of the two tracks in the event with respect to their respective parent τ flight direction. Effectively, $(\psi_1 - \psi_2)$ is equal to the acoplanarity $\delta\phi$. For small values of acoplanarity, λ represents a (constant) correction to the linear correlation of Eq. 3. It is very small at LEP/SLC energies and of the order of a few percent[8] at CESR energies where the decay angles ψ_1 and ψ_2 can be quite large. For larger values of $\delta\phi$, the higher-order terms in the expansion of Eq. 4 become important and the correlation between the impact parameter difference and the acoplanarity is no longer linear.

As mentioned above, 1945 events in the 1 vs. 1 topology were selected. A scatter plot of the impact parameter difference vs. acoplanarity for these events is shown in Fig. 3(a). A clear correlation between the two measured quantities is observed. Fig. 3(b) represents the same distribution in a profile histogram where each data point for a given acoplanarity bin corresponds to the mean impact parameter difference in that bin. A sample of τ-pair Monte Carlo events with comparable statistics to the data are shown in Fig. 3(c). The scatter plot in Fig. 3(d) represents wide-angle Bhabha scattering and muon-pair events selected from the data. Here, the events lie on a straight horizontal line, corresponding to a null lifetime as expected in these data samples.

It is worthwhile stressing the fact that in both Eq. 3 and Fig. 3, a correlation exists only between the *average* impact parameter difference and the *average* acoplanarity in any given slice in acoplanarity. There is no intrinsic correlation on an event-by-event basis. Furthermore, all the available lifetime information is contained in the impact parameter difference which is exponentially distributed (the acoplanarity follows a Gaussian distribution).

We choose to extract the τ lifetime by performing a binned maximum likelihood fit to the data. A large Monte Carlo sample is utilized to simulate two-dimensional distributions in impact parameter and acoplanarity for several τ lifetime values by weighting each event according to the proper times t_1 and t_2 at which the two τ's were produced. The weighting factor employed is given by:

$$\text{weight} = \frac{\tau_0^2}{\tau^2} \frac{\exp\left(-\frac{(t_1+t_2)}{\tau}\right)}{\exp\left(-\frac{(t_1+t_2)}{\tau_0}\right)}. \tag{5}$$

τ_0 is the nominal lifetime in the Monte Carlo sample ($\tau_0 = 291.6$ fs), τ is the desired alternative lifetime. For each value of τ, a likelihood function is defined as:

$$\ln L = \sum_i \sum_j Y_{ij} \ln p_{ij}, \tag{6}$$

where the two sums run over the total number of bins in impact parameter difference and acoplanarity, Y_{ij} is the number of entries in the bin (i, j) for the data, and p_{ij} is the normalized content of bin (i, j) in the Monte Carlo.

In order to minimize the effect of entries lying in the tails of the impact parameter difference and acoplanarity distributions, the events in the data and Monte Carlo that were used in the fit were required to lie within a square region defined by: $|\sin\theta\ \delta\phi| \leq 0.2$ rad and $|d_1 - d_2| \leq 1.6$ mm. Seven events (0.35% of the total) in the data were rejected this way. Furthermore, the bin size was chosen so that a minimum of five entries were contained in each Monte Carlo bin contributing to the likelihood calculation. A single bin size (80 mrad) was used for the acoplanarity, whereas two bin sizes (80 μm in the core and 400 μm in the tails) were applied for the impact parameter difference. The result of the fit is:

$$\tau_\tau = 284.5 \pm 7.7 \text{ fs.}$$

Systematic effects	Error (%)
Binning	0.6
Fit range	0.4
Monte Carlo Statistics	0.5
Event selection and track quality	0.5
Lifetime of background	0.5
Initial and final state radiation	0.3
Beam energy and energy spread	0.3
Total	1.2

Table 3: Systematic errors for the impact parameter difference method.

A correction of +1.15% due to the background contamination is applied, assuming the lifetime of the background to be zero (see Fig. 3(d)). A conservative systematic error of 0.4% is assigned due to the uncertainty in the lifetime of the two-photon portion of the background. Systematic uncertainties in the fitting procedure were thoroughly studied both in the data and Monte Carlo. The measurement was found to be slightly sensitive to the fit range and binning which contribute systematic errors of 0.6% and 0.4%, respectively. An additional systematic error of 0.5% was assigned due to Monte Carlo statistics; it was estimated by varying the minimum number of entries required in each bin in the Monte Carlo sample. The event selection and track quality requirements were varied and were found to contribute an uncertainty of 0.5%.

A systematic uncertainty of 0.3% was assigned to account for initial- and final-state radiation effects in the Monte Carlo. The beam energy spread and the uncertainty in the beam energy determination contribute an additional systematic error of 0.3%. These systematic uncertainties are summarized in Table 3, the overall systematic error for the impact parameter difference method is 1.2%.

The measurement technique was tested for any potential bias. It was applied on several Monte Carlo samples and the average measured lifetime was consistent with the input Monte Carlo value, while the spread in the answers was consistent with the statistical error in the data. A number of other cross-checks were performed. No effect was observed due to the alignment of the tracking detectors (VXD and CDC). Non-Gaussian tails in the distribution of beam positions in the data ($\simeq 0.25\%$) were simulated in the Monte Carlo and found to have no effect on the measured lifetime.

With the correction mentioned above and including the systematic error, the τ lifetime obtained from the impact parameter difference measurement is:

$$\tau_\tau = 287.8 \pm 7.7 \pm 3.5 \text{ fs}.$$

6 Summary and Conclusions

The τ lifetime has been measured using three different techniques giving results consistent with one another. The decay length method is independent of the other two methods since it uses a completely separate set of events. Though the measurements in the impact parameter and impact parameter difference methods are based on exactly the same events, because the two techniques make use of different information, they are not entirely correlated. The correlation between them has been evaluated following the procedure described in Ref. [9] to be 59.9%. The combined result of these two techniques is: $\tau_\tau = 291.7 \pm 7.3 \pm 3.9$ fs. With the inclusion of the decay length measurement, a τ lifetime of

$$\tau_\tau = 288.1 \pm 6.1 \pm 3.3 \text{ fs}$$

is derived, where the first error is statistical and the second systematic. This result is consistent with other recent measurements[10, 11, 12, 13].

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