Classical Impact Parameter Measurements of the Tau Lepton Lifetime

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We review the tau lepton lifetime measurements done at LEP, using the classical impact parameter method in one prong tau decays. After describing the general features of the method, we discuss in details the measurement done by the L3 and OPAL experiments and the systematic errors obtained.

1. INTRODUCTION

In the decay of the τ lepton into a charged particle, the "classical" impact parameter can be defined as the distance of closest approach (in the plane perpendicular to the beam axis) of the particle to a reference point which is assumed to be the production point of the τ. A positive sign is given to this quantity if the track crosses the tau direction in the same hemisphere, relative to the tau production point, in which it lays and a negative one otherwise.

The τ production point is assumed to be the beam position, while the τ direction is determined by the event thrust axis.

The impact parameter δ_O thus defined is linearly dependent on the τ lifetime since:

$$\delta_O = (\beta\gamma c sin\theta)\ t_i\ sin\Delta\phi_i$$

where t_i is the tau decay time and ϕ_i is the angle between the tau and the charged decay particle.

If the real tau production point (O) does not coincide with the beam position (V), the impact parameter is dependent on their relative position:

$$\delta_V = \delta_O + x_\tau sin\phi - y_\tau cos\phi$$

where δ_V is the impact parameter with respect to the beam position that we measure and ϕ is the azimuthal angle of the decay particle.

It is therefore evident that the knowledge of both the direction and the production point of the τ are important for the impact parameter measurement.

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2. THE MAXIMUM LIKELIHOOD FIT (L3)

For this determination of the tau lepton lifetime we use L3 data from 1992 and 1993. A sample of tau decays is selected with the same method as used for the tau polarization measurement [1]. Restricting to one prong tau decays, we find 20279 decays in the 1992 and 20286 decays in the 1993 data, respectively. These are then subjected to restrictive track quality cuts, which ensure that the observed charged particle from tau decay is well measured in the L3 Time Expansion Chamber (TEC). The requirements are:

- The ratio of the number of hits used in the track fit, normalized to the number of wire planes crossed by the track, is larger than 87%.
- At least two out of the eight innermost wire planes have a hit used in the track fit.
- The track lies in the region of maximum chamber resolution, at least 27 mrad (22 mrad) away from the anode plane of the inner (outer) chamber and 22 mrad away from the cathode planes.

After these cuts, 11122 and 10839 tau decays remain from 1992 and 1993, respectively.

The observed impact parameter distribution is analyzed in terms of a convolution between an underlying physics function and the detectors resolution function. The physics function is determined by Monte Carlo at the generator level. For the resolution function we investigate the sources of uncertainties on the determination of the impact parameter, namely the intrinsic resolution of the detector, the tau production point uncertainty (beam spot size) and the multiple scattering.

The main difference to previous L3 measurements of the tau lifetime lies in the fact that due to higher statistics and more elaborate calibration methods, the impact measurement from the TEC and its errors are better understood. This leads to a better resolution than in previous years as well as a better control of the resolution function, which is crucial for a systematically accurate measurement. To further improve these two aspects, we perform a recalibration of the impact measurement as well as the impact measurement error, using data from $e^+e^- \to \mu^+\mu^-$. The quality of this fine adjustment is controlled using an independent sample of events from $e^+e^- \to e^+e^-$. The determination of the chamber's resolution function is thus free of Monte Carlo simulation.

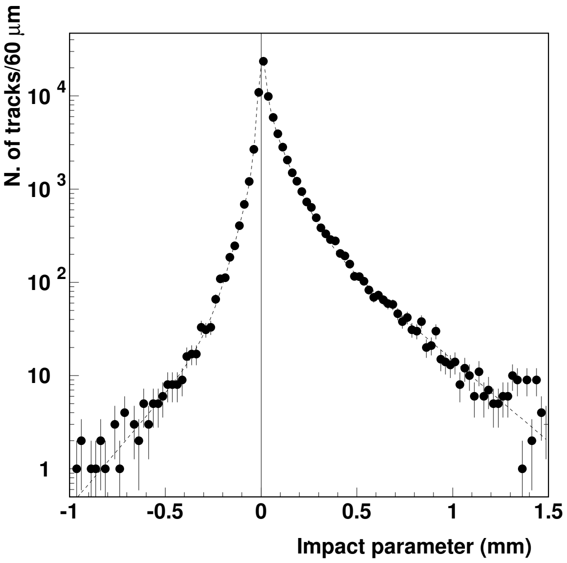

Figure 1. Underlying distribution of the signed impact parameter as determined from the Monte Carlo at generator level. The dashed line indicates the result of the fit.

2.1. Underlying Distribution

The physics function is determined from the distribution of the impact parameter of the charged track from the tau decay, as given by the Monte Carlo generator. We then attribute a sign to the impact parameter in order to take into account the error we have with the assumption that the tau direction is given by the event thrust.

The distribution is parameterized as a sum of three exponentials per each side (positive and negative impact parameter); the physics function is then found with a maximum likelihood fit to determine the slopes (λ_i) and relative fractions (F_i) of the exponentials. The distribution and the fitted function are shown in Fig. 1. The fit gives an excellent description up to large values of the impact parameter.

The assumption that the slopes are proportional to the lifetime is checked with samples of various lifetimes (see section 4.1).

2.2. Impact Parameter and Error Recalibration

The quality of the TEC calibration is checked with dimuon events, and corrected for effects which are either dependent on sector-by-sector distortions ("global" corrections) or on the position inside the sector ("local" corrections). With an iterative procedure to correct simultaneously for the two effects, we determine offsets to the distance of closest approach (DCA) of the tracks, and multiplicative factors to the errors on the DCA as given by the track fit.

We find offsets of the order of a few tens of microns for the DCA and a few percent correction to the errors coming from the fit.

It should be noted that these corrections are found on the dimuon sample, but then checked and used to find the resolution function on a different sample, the Bhabha events. This second sample is also used to estimate the uncertainties associated to this recalibration procedure.

2.3. Average Beam Position and Beam Spot Size

The production point of the τ is assumed to be the average beam position during a fill, which is determined from hadronic events.

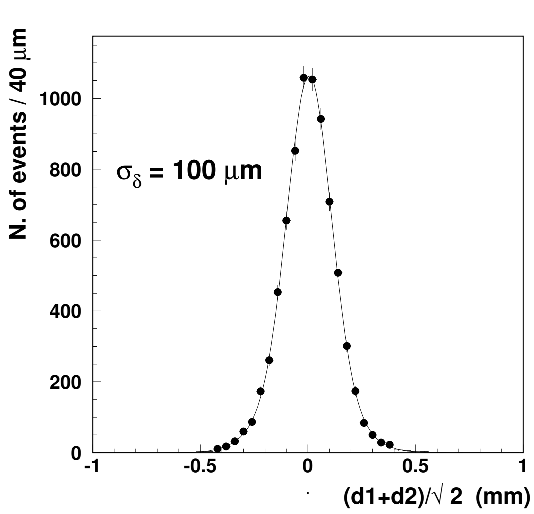

Figure 2. Miss distance distribution of Bhabha events after all corrections.

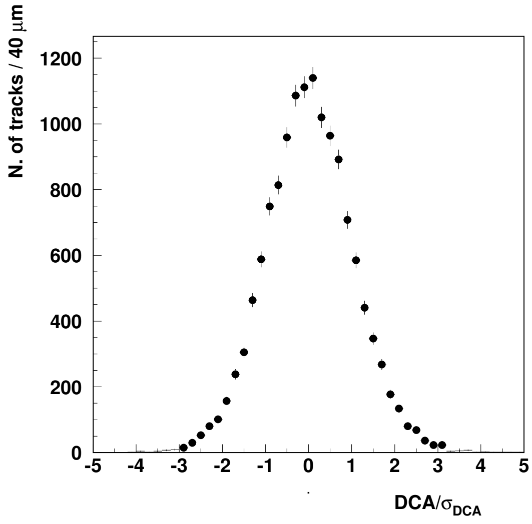

Figure 3. Distribution of DCA values divided by their errors after recalibration.

The beam spot size is determined through the distribution of the sum (S) and difference (D) of the DCA's of the two muons: if the two tracks are back-to-back the sum of DCA's is independent from the production point, while the difference is doubly dependent on it. The quadratic difference between the widths of D and S is therefore related to the beam spot size in the following way:

$$\sigma^2_{D/\sqrt{2}} - \sigma^2_{S/\sqrt{2}} = 2\sigma_x^2 sin^2\phi + 2\sigma_y^2 cos^2\phi$$

We obtain from the dimuon samples for 92 data:

$$\sigma_x = (97 \pm 3)\mu m \quad ; \quad \sigma_y = (0 \pm 11)\mu m$$

and for 93 data:

$$\sigma_x = (142 \pm 4)\mu m \quad ; \quad \sigma_y = (9 \pm 13)\mu m$$

Indeed the beam optics settings of LEP indicate that a larger beam envelop should be expected in 1993.

2.4. The resolution function

After having determined all the calibration parameters on the dimuon sample, we can study the resolution function on the Bhabha sample. We aim to describe it with a single Gaussian:

$$R(x, DCA, \phi, \sigma_{DCA}) =$$

$$= (\sigma_{DCA}\sqrt{2\pi})^{-1} exp[-(x - DCA)^2/(2\sigma^2_{DCA})]$$

where

$$\sigma_{DCA} = \sqrt{K^2 {\sigma^{cor}_{FIT}}^2 + \sigma_x^2 sin^2\phi + \sigma_y^2 cos^2\phi + \sigma^2_{MS}}.$$

The multiple scattering component is given by:

$$\sigma_{MS} = C/(< \sin\theta > \cdot p_t[\mathrm{GeV/c}])$$

where $C = \ 69\mu m$ for 1992 and $C = 118\mu m$ for 1993.

The factor K is an overall multiplicative factor to σ_{FIT}, with which we expect to take into account different resolution components. K is determined requiring that the distribution of the ratio between the DCA and its uncertainty σ_{DCA} (both calculated on a track by track basis) has a width of 1:

$$\sigma(DCA/\sigma_{DCA}) = 1.$$

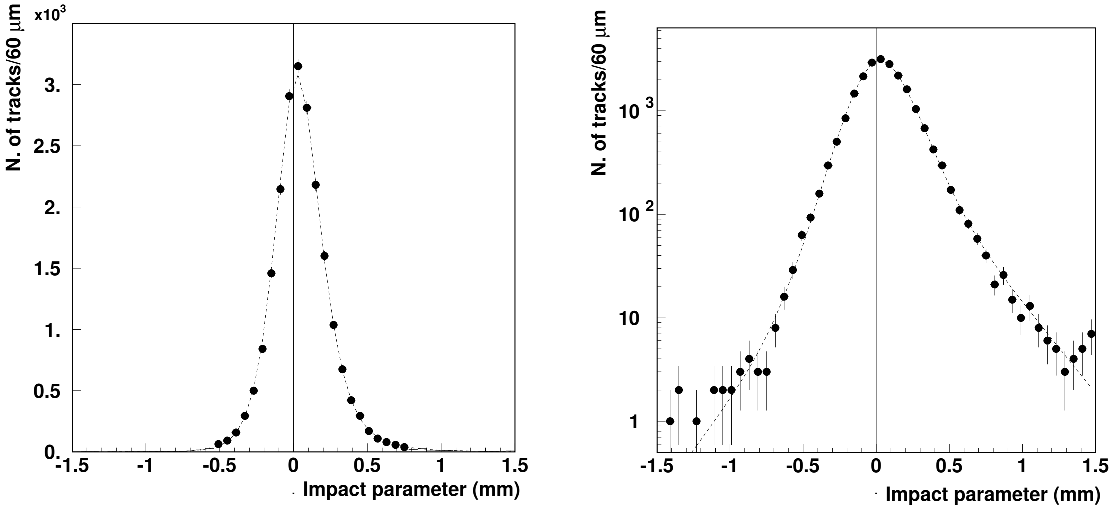

Figure 4. Experimental impact distribution from the sum of 1992 and 1993 data (data points). The dashed line represents the sum of the fitted functions, corresponding to the tau lifetime quoted in the text.

The accuracy on the K factor is defined as the variation which leads to a one standard deviation change in this width.

The distribution of the miss distance S measured from the Bhabha sample after all corrections (as determined from the $\mu\mu$ sample) is shown in Fig. 2. The distribution of DCA/σ_{DCA} is shown in Fig. 3. It is indeed well described by a single Gaussian of unit width, tails are negligible.

2.5. Determination of the Average Lifetime

The average τ lifetime is extracted from the observed impact parameter distribution with a maximum likelihood method. The probability to observe a certain impact parameter, δ, is a convolution between the underlying distribution, which gives the probability to have a certain true impact parameter, δ', given a certain lifetime, and the resolution function, which gives the probability to measure a certain impact parameter given a true impact parameter:

$$P(\delta|\lambda_i;\sigma) = P(\delta|\delta';\sigma) \otimes P(\delta'|\lambda_i;F_i).$$

We perform a binned maximum likelihood fit, with a likelihood defined by

$$\ln L = -\sum_I (N_I \ln Y_I - Y_I - \ln N_I!)$$

with

$$Y_I = \sum_K W_K P(\delta_I|\lambda_i;\sigma_K) C$$

where I runs through the bins of the impact parameter distribution, Y_I is the average expected number of events in the bin, δ_I is the center of the bin and C is a normalization factor. For the expected number of events, a weighted average is performed, with weights W_K given by the observed error distribution ($W_K = (1/N)dN/d\sigma_K$).

The fit is done separately for 1992 and 1993 data, and we obtain

$$\tau = (291.1 \pm 8.5)\ \text{fs} \quad (1992)$$

$$\tau = (303.2 \pm 9.7)\ \text{fs} \quad (1993)$$

where the error is statistical only.

In Fig. 4 we show the impact parameter distribution obtained from the whole sample. Overlaid is (for display purpose only) the result of the fit summed over the two samples. The distribution is shown in linear and log scale to demonstrate the excellent quality of the fit in both the bulk and the tails of the distribution.

3. THE TRIMMED MEAN (OPAL)

The average τ lifetime has been determined by OPAL through the comparison of the data and the Monte Carlo impact parameter distributions in terms of the trimmed mean: this is the average of the distributions which are left after 5% of the entries have been removed from each tail. The lifetime is therefore extracted by the relation:

$$\tau_\tau = \tau_{MC} \times \frac{\bar{x}_{meas}}{\bar{x}_{MC}}$$

where $\bar{x}_{meas}$ and $\bar{x}_{MC}$ are the trimmed means from data and Monte Carlo, respectively.

This method was already applied in previous measurements, which may be referred to for further details [3].

The impact parameter is measured in the central tracking system of the OPAL detector, which consists of a jet chamber, a vertex drift chamber and a silicon strip vertex detector; the latter provides a position measurement in the plane perpendicular to the beam axis with a resolution of about 9 μm, including the alignment uncertainties. The whole tracking system gives an impact parameter resolution of 16 μm as determined by μ-pair and electron-pair events.

3.1. Event and track selection

The τ events are selected requiring two collimated, back-to-back, low multiplicity jets [4]. After rejecting events satisfying μ-pair or electron-pair selection criteria and after restricting to an angular acceptance defined by $|cos\theta_{thrust}| \leq 0.9$, a total of 28792 and 26894 are left from the 1992 and the 1993 data, respectively. To select one-prong τ decays, it is then required that exactly one charged track exists in each event hemisphere (as defined by the thrust axis).

Additional cuts are applied to the tracks, requiring:

- at least one silicon hit and half the maximum possible number of hits in the central jet chamber;
- a total track impact parameter uncertainty of less than 0.1 cm;
- a χ^2 per degree of freedom less than 10 from track reconstruction.

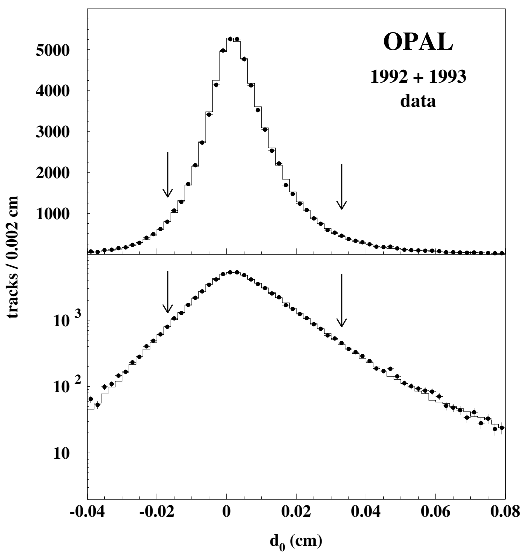

Figure 5. Data and Monte Carlo impact parameter distributions (OPAL).

In this way a total of 35168 and 32703 tracks are selected from the 1992 and the 1993 data, respectively.

3.2. Monte Carlo sample

For the comparison with the experimental distributions of the impact parameter, Monte Carlo samples with an input lifetime of 303.5 fs are used. The linearity between the trimmed mean and the τ lifetime has been verified with different Monte Carlo samples.

In order to extract the measurement from the comparison of the data and the Monte Carlo trimmed mean, the Monte Carlo has to be tuned to reproduce the spot size and tracking resolutions of the data. For this purpose, extra Gaus-

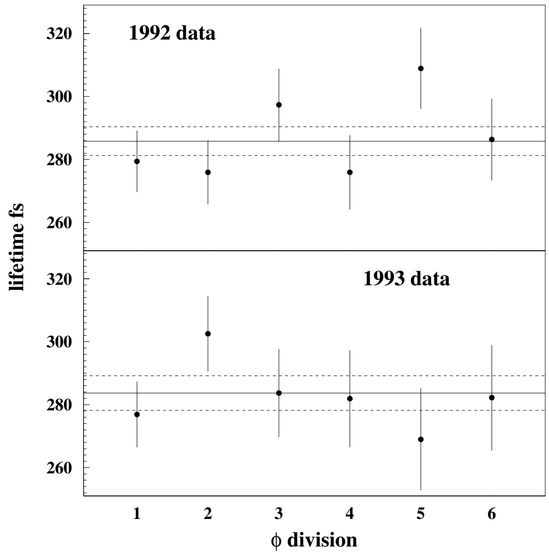

Figure 6. The τ lifetime measured in the ϕ divisions described in the text (OPAL).

sian smearing parameters are determined from independent samples of μ-pair Monte Carlo and data; these parameters are of the order of $20\mu m$ and are added in quadrature to the impact parameter resolution from tracking only. In Fig. 5 the data and Monte Carlo impact parameter distributions are shown; the arrows indicate where the 10% trimmed mean would act, while in reality the trimming is not applied to the overall distribution (see later).

3.3. Determination of the Average Lifetime

Since the beam spot ellipse is highly asymmetric (being much more spread in horizontal direction), the impact parameter distribution is strongly dependent on the azimuthal angle. For this reason the trimmed mean is not performed on the whole distribution, but both the 1992 and the 1993 data samples are divided into six regions in ϕ. For each of these distributions a trimmed mean has been performed and thus a lifetime extracted.

The final result is obtained by a weighted average of the six measurements, which gives

$$\tau = (285.8 \pm 4.4)\ \text{fs} \quad (1992)$$

$$\tau = (283.7 \pm 5.3)\ \text{fs} \quad (1993).$$

In Fig. 6 the lifetime measurements in ϕ bins are shown, together with the average.

4. SYSTEMATIC ERRORS

4.1. The L3 measurement

Since the lifetime estimation has two main components, underlying distribution and resolution function, systematic uncertainties fall into the same two main categories. For the underlying distribution, we first have to estimate the (statistical) uncertainty of its description by the above mentioned eleven parameters and their correlation. For this purpose, we determine the main axes of the error ellipsoid. We then systematically shift all eleven parameters in these directions by one standard deviation and re-evaluate the resultant lifetime. The largest variation observed, 1.8 fs, is taken as an estimate of the error from this source.

In addition, the underlying distribution contains a single element from detector simulation, namely the probability to obtain a negative impact parameter due to the approximation of the τ direction by the event's thrust axis. To estimate this error, we evaluate this probability directly from the experimental impact distribution by leaving it free in the fit. The resultant probability is in excellent agreement with the Monte Carlo prediction. Its error is used to estimate the systematic error from this source. Another source of uncertainty in this class is the composition of the one prong sample in terms of the branching fractions of one prong tau decays. Since these decays have a different number of neutrals and thus a different decay angular distribution, their relative amount may influence the relative importance of the three fit components. Also the relative normalization of these components is therefore left free in the fit to the experimental impact distribution. Again, the resulting normalizations agree with the Monte Carlo prediction within one

Table 1
The systematic error (L3 measurement)

Underlying Distribution	
Linearity Slopes-Lifetime	0.3 fs
MC Thrust Reconstruction and Branching Fractions	1.0 fs
MC Statistics	1.8 fs
Resolution Function	
Beam Spot Size and Beam Centroid	1.3 fs
Detector Calibration	3.3 fs (92) 4.0 fs (93)

standard deviation. From the errors obtained by the fit to the data, we estimate the systematic uncertainty. For these two errors, care has to be taken to avoid double counting with the Monte Carlo statistical error quoted above. Subtracting the statistical error in quadrature, we estimate a residual systematic error of 1.0 fs for the combined effect of tau direction uncertainty and sample composition.

A last source of systematics is the assumption made in the fit that the slopes of all components in the underlying distribution depend linearly on the lifetime. To test this assumption, Monte Carlo samples for six different lifetimes between 200 and 400 fs have been generated and the corresponding underlying distributions determined. The linearity of the slope parameters is confirmed with an accuracy of 0.1%, leading to a systematic error of 0.3 fs in the lifetime.

The second group of systematic errors relates to uncertainties in the experimental determination of the resolution function. First, the accuracy in the determination of the beam spot size and position have to be taken into account. These are taken as the errors on the horizontal and vertical size of the luminous region. Any error in the beam centroid position would be absorbed in the beam width itself. The combined error from this source is thus 1.3 fs.

The uncertainty in the recalibration of DCA errors has been determined in the recalibration procedure itself. It is dominated by the error on the overall error scale factor K. Due to the different size of the correction, this error is different for the two years and leads to a systematic error of 3.3 (4.0) fs for 1992 (1993).

In our previous studies [2] an additional systematic error was assigned due to uncertainties in the calibration (not re-calibration) of the TEC. This error, however, is found to be completely redundant with the error on the resolution function quoted above. A miscalibration of the chamber – at constant single point resolution assumed in the fit – leads to a widening of the $\sigma(DCA/\sigma_{DCA})$ distribution. Since the width of this distribution is used in the recalibration procedure, any miscalibration errors are already accounted for.

The contributions to the systematic error are summarized in tab. 1.

Among the two years of data taking, systematic errors are completely correlated. The total systematic error for the combined result of the two years are thus the quadratic sum of the errors mentioned above. We thus find a final combined result of

$$\tau_\tau = (296.4 \pm 6.4(\text{stat.}) \pm 4.4(\text{syst.}))\ \text{fs}$$

4.2. The OPAL measurement

The results have been checked to be independent of the selection cuts and also the division of the data according to other variables have been found to be consistent.

Table 2
The systematic error (OPAL measurement)

Source	1992		1993
resolution matching of MC	1.6 fs		1.0 fs
detector calibration and alignment	0.4 fs		0.3 fs
beam size uncertainties	1.2 fs		1.0 fs
beam position uncertainties	0.4 fs		0.3 fs
background fractions		0.8 fs	
MC branching ratios		0.5 fs	
MC statistics	1.4 fs		1.7 fs
total systematic error	2.7 fs		2.5 fs

The contributions to the systematic error from the knowledge of the detector resolution come from the uncertainties on the Monte Carlo smearing, on the detector calibrations and alignment, and on the beam parameters. The latter are varied in their ranges of uncertainties, while for the alignment contribution the impact parameter distributions from μ-pair events are used.

Uncertainties on Monte Carlo decay modes can influence the result since different decay modes give slightly different trimmed means: the Monte Carlo branching fractions are varied by their uncertainties to determine the effect on the measurement.

The effect from residual background in the data has been studied with Monte Carlo, and found to be $(+0.82 \pm 0.28)\%$.

The contributions of the various sources to the systematic error are summarized in tab. 2. The error from Monte Carlo uncertainties and from background uncertainties is common for 1992 and 1993; since the errors from detector calibration and alignment can be correlated for the two years, full correlation is assumed when computing the total systematic error. In this way the combined value for τ lifetime is:

$$\tau_\tau = (287.2 \pm 3.4(\mathrm{stat.}) \pm 2.0(\mathrm{syst.}))\ \mathrm{fs}$$

5. CONCLUSIONS

The latest LEP measurements of the τ lepton lifetimes from classical impact parameter have been reviewed.

The L3 experiment has obtained an improved systematic error by a better understanding of the calibration of the tracking device; future measurements will make use of the precise information from the new Silicon Microvertex Detector

The OPAL experiment has reached a very precise measurement, which is still statistically limited.

It is therefore possible to conclude that this method, although being sensitive to both tau production point and direction uncertainties, provides one of the most precise measurement of the tau lepton lifetime.

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