A Measurement of the Tau Lifetime

DELPHI Preliminary

Abstract

The tau lepton lifetime has been measured using two different methods with the DELPHI detector. The signed impact parameter distribution of one prong decays yielded a lifetime of $\tau_\tau = 304 \pm 11(stat) \pm 6(sys)$ fs while the decay length distribution of three prong decays gave the result $\tau_\tau = 303 \pm 13(stat) \pm 7(sys)$ fs. The combined result, accounting for correlations, was $\tau_\tau = 304 \pm 9$ fs. The ratio of the Fermi coupling constant from tau decay relative to that from muon decay was found to be 0.972 ± 0.017, compatible at the two standard deviation level with the hypothesis of lepton universality.

Submitted to the Rochester Conference (Dallas, August 1992).

1 Introduction

The tau lepton is a fundamental constituent of the Standard Model and its lifetime can be used to test the model predictions. In particular, lepton universality can be tested using the relationship:

$$\tau_\tau = \tau_\mu \left(\frac{\mathrm{G}_\mu}{\mathrm{G}_\tau}\right)^2 \left(\frac{\mathrm{m}_\mu}{\mathrm{m}_\tau}\right)^5 \times \mathrm{BR}\left(\tau^- \to e^- \bar{\nu}_e \nu_\tau\right), \tag{1}$$

where $\tau_{\mu,\tau}$ and $\mathrm{m}_{\mu,\tau}$ are the lifetimes and masses of the muon and tau respectively and $\mathrm{G}_{\mu,\tau}$ are the Fermi constants determined from muon and tau decay [1] .

The lifetime measurements presented here were derived from the data taken by the DELPHI experiment at LEP during 1991. The $\tau^+\tau^-$ data was the same as that used for the $\mathrm{Z}^0 \to \tau^+\tau^-$ lineshape measurement [2]. An improved, 3 layer, silicon Microvertex Detector, installed in the experiment in February 1991, was used to provide the precise $r\phi$ [1] track measurements necessary to observe the short tau decay distance.

Two techniques were used to measure the lifetime. The first method was applied to taus which decayed to produce single charged particles. The lifetime was extracted from a measurement of the distance of closest approach of the decay particle trajectory to the centre of the interaction region, referred to as the impact parameter. The other method reconstructed the decay vertex for taus which decayed to produce three charged particles and whose tracks were observed in the Microvertex Detector. As the interaction region of the LEP beams was small compared to the decay length, the production point of the taus could be taken as its centre, allowing the decay length to be determined and the lifetime calculated.

The Monte Carlo program KORALZ [3] was used to model tau decays in all of the above analyses.

The DELPHI detector is described in [4]. This analysis uses the DELPHI charged particle tracking system in the polar angle range $43^o < \theta < 137^o$. This consists of four tracking detectors in a 1.2 Tesla solenoidal magnetic field:

1. the Microvertex Detector (VD) which is discussed in more detail in section 2;
2. the Inner Detector. This is a gas detector with a jet-chamber geometry. It produces 24 points per track, yielding a track element with an $r\phi$ resolution of 60 μm;
3. the Time Projection Chamber (TPC). This is the main tracking detector of DELPHI, situated between radii of 30 cm and 120 cm. Up to 16 points per track produce a track element with an $r\phi$ resolution of 250μm;
4. the Outer Detector. This consists of 24 modules containing 5 layers of drift tubes operating in limited streamer mode and situated at a radius of 2 m. A typical charged particle produces 5 points yielding a track element with 300μm precision in $r\phi$.

Sections 4 and 5 describe the impact parameter and vertex analyses respectively, while section 6 presents the combined result, including correlations, and conclusions.

[1] r, ϕ and z define a cylindrical co-ordinate system where $+z$ coincides with the electron beam direction and the origin coincides with the interaction point.

2 The Microvertex Detector

The DELPHI Microvertex Detector [5] used in this analysis consists of three concentric layers of silicon strip detectors at average radii of 6.3, 9.0 and 11.0 cm respectively, giving full azimuthal coverage in the polar angle region $43^o < \theta < 137^o$. Each layer has 24 sectors with a 10-15% overlap in ϕ. A sector is subdivided along the beam direction into 4 silicon strip detectors. The silicon strips are parallel to the beam direction and have a pitch of 25 μm with every second strip read out by capacitive pick-up. With this geometry an intrinsic resolution in the $r\phi$ plane of 6μm has been obtained using charge division. The relative position of the modules was surveyed to an accuracy of 20μm in three dimensions before installation in DELPHI. Movement with respect to the rest of the DELPHI detector was monitored using lasers and found to be less than 5μm over the running period.

The final alignment was carried out using tracks from the dimuon decay channel of the Z^0, selected as described in [6]. The two track elements for the muons in the Outer Detector were used to define a circle with a radius obtained from the momentum known from the beam energy. This was used to obtain the global alignment of the VD relative to the DELPHI coordinate system. The alignment of the corresponding sectors in the layers relative to one another was then improved using a least squares circle fit to the VD hits alone. The alignment was cross-checked using a sample of light quark Z^0 decays. The decay vertices of the two jets were reconstructed and the the distance between these, in principle zero for light quarks decays, was measured. The distribution was centred on zero and consistent with the expected detector resolution.

3 Tracking Performance

The muon and electron miss distance, the distance of closest approach of the two leptons, calculated using the VD, TPC and ID had a standard deviation of 37$\pm$3μm, corresponding to a track extrapolation resolution at the vertex $\sigma_{ext} = 37\mu\mathrm{m}/\sqrt{2} = 26 \pm 2\mu$m. The VD dominated this measurement. Its single point resolution was determined to be 8μm. This included 6μm from the intrinsic detector resolution and 5μm from the alignment procedure.

Generalizing to all momenta, a track extrapolation uncertainty, σ_i (in μm), of the form:

$$\sigma_i = \sqrt{26^2 + \left(\frac{65}{p_i}\right)^2}$$

was obtained. The second term is a parameterisation of the multiple scattering in the $r\phi$ plane due to the beam-pipe wall and the first layer of the VD; p_i is the transverse momentum, with respect to the beam axis, in GeV/c of particle i.

In all of the following analyses the tau production point was taken as the centre of the interaction region measured for each DELPHI run by minimizing the distance of closest approach of high momentum tracks in Z^0 decays to hadrons. The centre was determined for every 100 Z^0s with a precision of 10μm. Using the dimuons, it was found that the x and y projections of the interaction region were well represented by Gaussian distributions with $\sigma_x = 145\mu$m and $\sigma_y = 7\mu$m. The effects of this finite interaction region were accounted for using a resolution function based on $Z^0 \rightarrow \mu^+\mu^-$ and e^+e^- events as described below.

4 The Impact Parameter Method.

For tau decays producing a single charged particle, the impact parameter is the distance of closest approach of the extrapolated track to the production point in the $r\phi$ plane. Its sign is positive if the extrapolated track intersects the tau direction before reaching the point of closest approach and negative otherwise. If the geometry of the production and decay could be reconstructed perfectly, the signed impact parameter would always be positive. Because of resolution effects and uncertainties in the tau direction it can be negative, however the distribution of signed impact parameters retains sensitivity to the tau lifetime. The geometric impact parameter, used below in the calculation of the resolution function, differs in that its sign is defined as the sign of the z component of the vector cross-product of the projections on the rϕ plane of the track vector at the point of closest approach and the vector from the centre of the interaction region to the point of closest approach. This distribution should be symmetric about zero.

The tau production point was taken as the centre of the interaction region. The decay track in the opposite hemisphere was used as an estimate of the tau direction for the sign of the impact parameter. Monte Carlo simulation showed that the difference between this track direction and the tau direction was centred on zero with a width of about 2^o.

The lifetime was extracted from the signed impact parameter distribution using a maximum likelihood fit. The signed impact parameter probability distribution was determined as a function of the tau lifetime as follows: an impact parameter distribution, for different lifetimes, was generated assuming perfect detector resolution and a point interaction region using Monte Carlo generated events in which the effects due to tau decay kinematics and experimental cuts for tau selection were included. In order to account for the smearing due to the beam size and the track extrapolation resolution, this impact parameter distribution was convoluted with a resolution function obtained from the geometric impact parameter distribution of the $Z^0 \rightarrow \mu^+\mu^-$ and e^+e^- events. The geometric impact parameter distributions for particles in such events, with the same VD selection criteria as for taus, is shown in fig. 1 and fig. 2.

For this analysis only events where both taus decayed into single charged particles were considered. This gave a sample of 4096 events. Tracks selected for this analysis (including the di-electron and di-muon events used to measure the resolution function) had to satisfy the following criteria:

1. At least 11 points in the TPC;
2. at least two layers with hits in the VD;
3. a χ^2 probability for the track fit in the TPC and VD greater than 0.01;
4. the increase in the χ^2 of the track fit when the VD points were added had to have a probability greater than 0.01, where the number of degrees of freedom was taken as the number of hits in the VD. This cut, while strongly correlated with the previous cut, ensured that all tracks in the sample had a extrapolation uncertainty

consistent with the VD resolution quoted above. Both χ^2 probability distributions were uniform;

5. there be at most one other layer with a hit within 7.5 degrees of the track in ϕ. This removed a small number of events with conversions, delta-rays and 3-prong decay where the other two tracks were unassociated in the VD.

6. if the track had hits in only 2 layers of the VD, it should not have any other hit within 400 μm, in order to reduce mis-association of hits to the track.

The final data sample comprised 6113 tau decays, 11029 muon tracks and 7819 electrons. The above criteria for $Z^0 \rightarrow e^+e^-, \mu^+\mu^-$ and $\tau^+\tau^-$ data samples showed no significant biases to the impact parameter distributions.

The effect of multiple scattering was accounted for by smearing the physics function decay by decay with the amount described in section 3. A contribution to the physics function was included to account for the small number of elastic hadronic interactions expected in the beam pipe and layers of the VD. The uncertainty in the lifetime due to uncertainty in the multiple scattering term was found to be negligible.

The background contamination of the sample was determined from Monte Carlo to be $1.9 \pm 0.4\%$, due to $Z^0 \rightarrow e^+e^-$, $Z^0 \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow (e^+e^-)X$ events. A background contribution represented by the resolution function, suitably normalised and centred on zero, was included in the probability distribution.

The impact parameter was determined as the distance of closest approach between the centre of the interaction region and a track fit through the VD points and the TPC track element. Each decay was assigned a probability P_i using the probability function described above and the log likelihood, $\Sigma \ln(P_i)$, calculated as a function of the lifetime. To obtain the optimal statistical uncertainty, the data was grouped into six bins in ϕ. Each bin included the four regions, each 15 degrees wide, in the four quadrants which mapped on to each other under reflection in the x and y axes. These should see the same beam profile. In each bin a combined maximum likelihood fit of the lifetime and the resolution function was made. The resolution function was parameterised as a Gaussian. The lifetime was taken as the weighted mean of the results of the six binned fits.

The lifetime was found to be 304 ± 11 fs. Figure 3 shows the measured impact parameter distribution with the probability distribution calculated for this lifetime superimposed. The result obtained using only muons for the resolution function was 305 fs and that obtained using only electrons was 302 fs, showing no evidence of remaining systematics because of differences in track reconstruction due to particle type.

The analysis procedure was tested for bias by performing fits on 100 Monte Carlo simulated datasets consisting of 3000 $Z^0 \rightarrow \tau^+\tau^-$ events and 6000 $Z^0 \rightarrow \mu^+\mu^-$ events for the resolution function. This showed that the systematic effects in the analysis method were less than 3 fs, and provided a cross-check of the statistical uncertainty for this measurement. Systematic uncertainties arose from: the uncertainty in the radial alignment of the VD (3 fs); the uncertainty on the contamination in the sample of taus (2 fs); bias in the p_t spectrum due to event and track selection criteria (2 fs); the effect of hadronic scattering (2 fs); uncertainties in the tau branching fractions (1 fs). Added in quadrature, these gave a total systematic uncertainty of 6 fs. As a further check on the consistency of the data, the lifetime has been calculated for positively and negatively charged decay particles, for various cutoff values of p_t, for positive and negative z and for different impact parameter fit ranges. All values of the lifetime obtained were consistent. The final result from the impact parameter method was:

$$\tau_\tau = 304 \pm 11(stat) \pm 6(sys)\ \text{fs}$$

5 The Vertex Method

In the sample of tau decays to three charged particles, the decay vertex was reconstructed allowing a direct measurement of the lifetime. In such events the other tau was required to decay to a single charged particle in order to reduce hadronic backgrounds. Monte Carlo studies showed this to be less than 0.2%. A total of 1400 events occurring between a polar angle of 40° and 140° were selected for the analysis.

In order to achieve the necessary precision on the vertex determination, VD hits had first to be associated to the external tracks, which were composed of track elements from the TPC and the ID. The inclusion of the ID here was necessary to remove hit association ambiguities among the three tracks present in the VD in each decay. The tracks were extrapolated to the VD and all combinations of hits occurring within a road of suitable dimensions are considered. The width of this road was set to three times the calculated extrapolation uncertainty. For each combination of hits a circle fit was made in the transverse plane, taking account of multiple scattering. The χ^2 probability distribution was flat showing that the point resolution in the various detectors and the multiple scattering was correctly determined. There was a peak near χ^2 probabilities near zero corresponding to incorrect hit associations. A cut on χ^2 probability of 0.01 removed them. In general only one good combination of VD hits existed for each of the three tracks. In the case that more than one combination existed all were considered and the possible ambiguity was solved at the next stage.

To reduce false associations, to solve ambiguities in the track fits and to remove conversion background, the constraint that the three tracks produced a good vertex was imposed. The decay vertex position (x, y) was estimated by minimizing the function:

$$\chi^2(\mathrm{x,y}) = \sum_i \left(\frac{d_i}{\sigma_i}\right)^2$$

where d_i is the distance of closest approach to the primary vertex in the $r\phi$ plane of particle $i(i = 1, 2, 3)$, and σ_i is the extrapolation uncertainty at the decay vertex as calculated from the track fit.

The χ^2 probability distribution for the reconstructed decay vertex was flat except for a peak towards zero corresponding to incorrect associations and background events. Again a cut on χ^2 probability at 0.01 was made and all the remaining possible vertices for a given event were considered. In general there was only one, but where two or more existed the event was rejected unless the decay vertex error ellipses overlap at the 2σ level.

Of the initial 1400 events, 391 had insufficient VD hits resulting from the finite angular acceptance of the detector and from dead regions and inefficiencies. 1009 had vertex hits associated to each of the three tracks. Of these 856 produced a satisfactory vertex and 823 did so with no ambiguity.

To determine the projected decay distance, d_i, the production point was taken to be the centre of the interaction region. The laboratory decay distance D_i was calculated from

$$D_i = \frac{d_i}{\sin\theta_i}$$

where θ_i is the polar angle of the tau which was approximated as that of the thrust axis of the three charged particles in the decay. The distribution of D_i is shown in fig. 4. The uncertainty on this, σ_{D_i}, was calculated from the covariance matrix for the position of the decay point and from the uncertainty in the actual production point.

The typical uncertainty on the decay distance is 750μm, which is about one third the size of the mean decay distance.

The decay time in the rest frame of the tau T_i is given by

$$T_i = \frac{D_i}{\beta\gamma \mathrm{c}}$$

where $\beta\gamma = (p_\tau/\mathrm{m}_\tau)$ with p_τ was determined from the beam energy taking account of radiative corrections. The lifetime was extracted from the distribution of decay times using the maximum likelihood method. For each event, the probability P_i of the event having a decay time T_i was calculated as a function of the lifetime using an exponential lifetime distribution convoluted with a Gaussian distribution of width σ_{D_i}. The lifetime corresponding to the maximum of the log likelihood, $\Sigma \ln(P_i)$, was found to be 303$\pm$13 fs. The procedure was tested by analysing simulated events with five known lifetimes between zero and twice the world average. The results showed that the systematic effects associated with the analysis technique were less than 3 fs. The systematic uncertainty arising from uncertainty in the association of the VD hits was estimated to be 5 fs from an examination of the cases in which ambiguous constructions could occur. Uncertainties in the effect of initial and final state radiation (2 fs), in the determination of the tau direction (1 fs) and in the radial and azimuthal alignment of the VD (3 fs) have also been included. By adding all contributions in quadrature the total systematic uncertainty was estimated to be 7 fs.

The final result of the vertex method was:

$$\tau_\tau = 303 \pm 13(stat) \pm 7(sys)\mathrm{fs}$$

6 Summary and Conclusions

The lifetime of the tau has been measured in two statistically independent ways. Of the systematic uncertainties only those arising from the VD alignment were common. Combining the two results by weighting them with the reciprocal of the quadratic sum of the statistical and independent systematic uncertainties and retaining the common systematic uncertainty unaltered, a tau lifetime of

$$\tau_\tau = 304 \pm 8(stat) \pm 5(sys)\ \mathrm{fs}$$

was obtained. This result agrees with the value of 287 $\pm$ 3 fs predicted by equation 1 using $BR(\tau \to e\nu\nu) = 17.93 \pm 0.26\%$ and $\mathrm{m}_\tau = 1784 \pm 3$ MeV/c^2 [7]. Alternatively the measured lifetime may be used to determine the relative strengths of the Fermi coupling constants (G_τ/G_μ). This ratio was found to be 0.972 $\pm$ 0.017, consistent, at the two standard deviation level, with lepton universality.

Table 1 shows a compilation of recent measurements of the tau lifetime [8]. The agreement among the measurements, including the one described here, is good. The measurements presented here are becoming systematics limited, although they will still benefit from the increased statistics expected from ongoing LEP running. They approach the level of precision where further clarification of the tau mass is necessary. This will then leave us in a position to make very precise ($< 1\%$) tests of lepton universality.

Tau Lifetime (fs)	Experiment
$291 \pm 13 \pm 6$	ALEPH
$314 \pm 23 \pm 9$	DELPHI (90)
$309 \pm 23 \pm 30$	L3
308 ± 13	OPAL
$304 \pm 8 \pm 5$	This measurement

Table 1: *Recent measurements of the tau lifetime*

7 Acknowledgements

We are greatly indebted to our technical staff and funding agencies for their support in building and operating the DELPHI detector, and to members of the SL division for the excellent performance of the LEP collider.

References

[1] Y.S.Tsai, Phys. Rev. **D4** (1971) 2821.
H.B. Thacker and J.J. Sakurai, Phys. Lett. **B36** (1971) 103.

[2] DELPHI Collaboration, submitted to this conference.

[3] S.Jadach and Z.Was, Comp. Phys. Com. **36** (1985) 191.
S.Jadach et al., CERN **89-08**, volume 3 (1989) 67.

[4] DELPHI Collaboration, Nucl. Instr. and Meth. **A303** (1991) 233.

[5] H. Borner et al., submitted to this conference and Nucl. Instr. and Meth.

[6] DELPHI Collaboration, P. Aarnio et al., Phys. Lett. **B260** (1991) 240.

[7] Particle Data Group, M.Aguilar-Benitez et al., Phys. Rev. **D45**, part 2, (1992).

[8] ALEPH Collaboration, D. Decamp et al., Phys.Lett. **B297** (1992) 411. DELPHI Collaboration, P. Abreu et al., Phys.Lett. **B267** (1991) 422. L3 Collaboration, B. Adeva et al., Phys.Lett. **B265** (1991) 451.
OPAL Collaboration, P.D. Acton et al., Phys.Lett. **B273** (1991) 355.

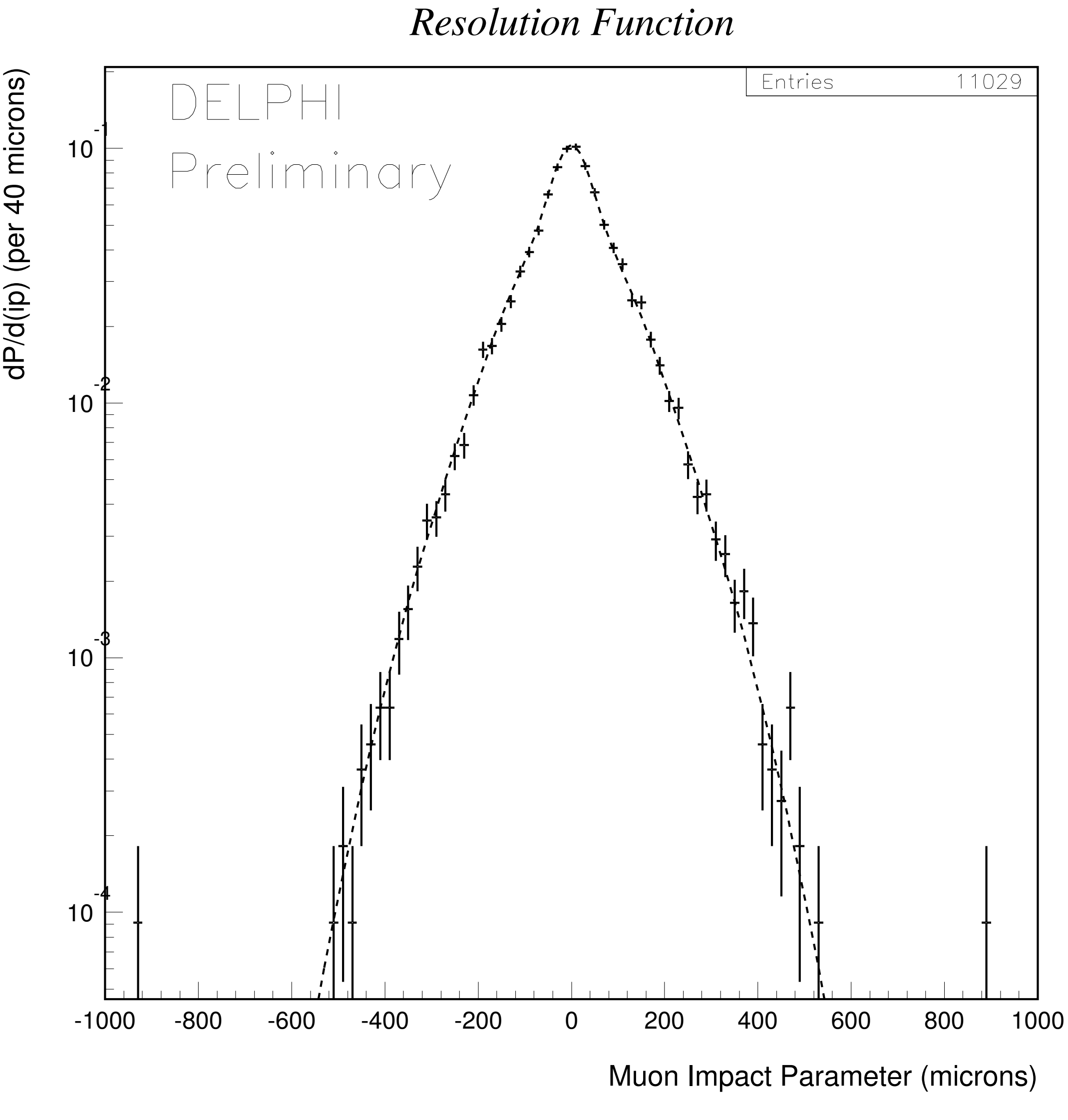

Figure 1: The data points are the observed geometric impact parameter distribution for muons in $\mu^+\mu^-$ events. The curve is the best fit to a sum of three Gaussians.

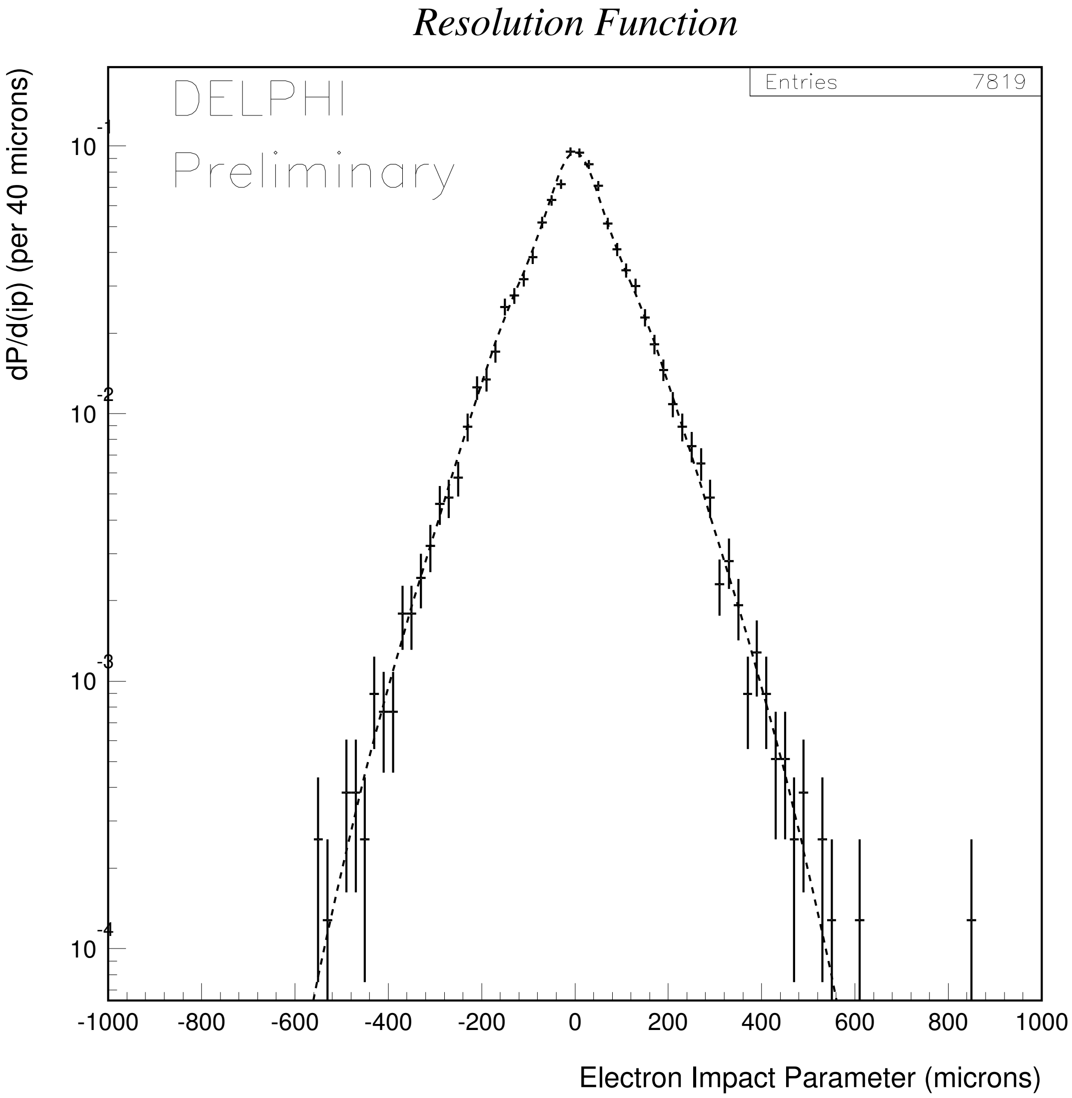

Figure 2: The data points are the observed geometric impact parameter distribution for electrons in e^+e^- events. The curve is the best fit to a sum of three Gaussians.

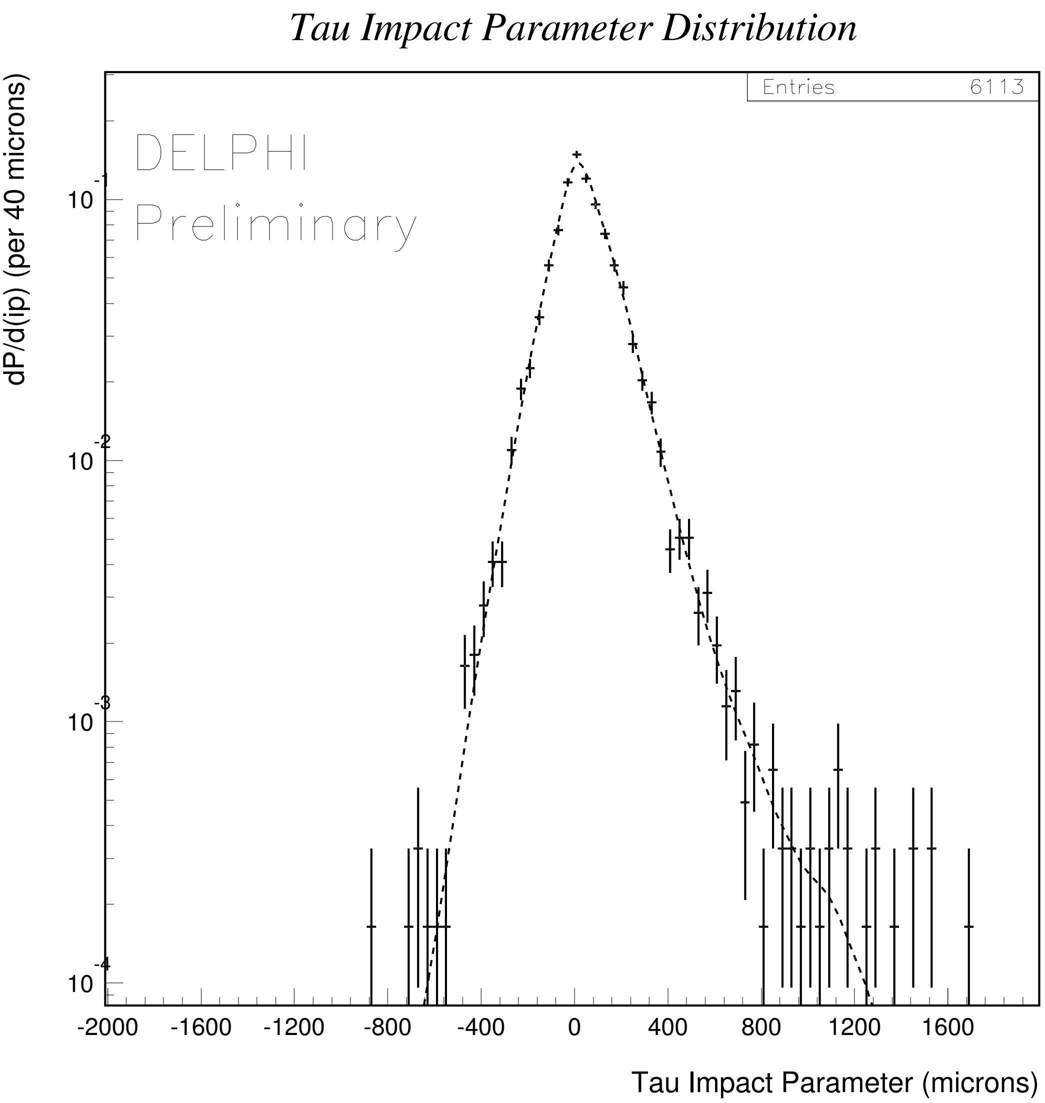

Figure 3: The data points are the observed lifetime signed impact parameter distribution for taus. The curve shows the probability distribution for the fitted value of the tau lifetime, scaled to the number of tracks in the data sample.

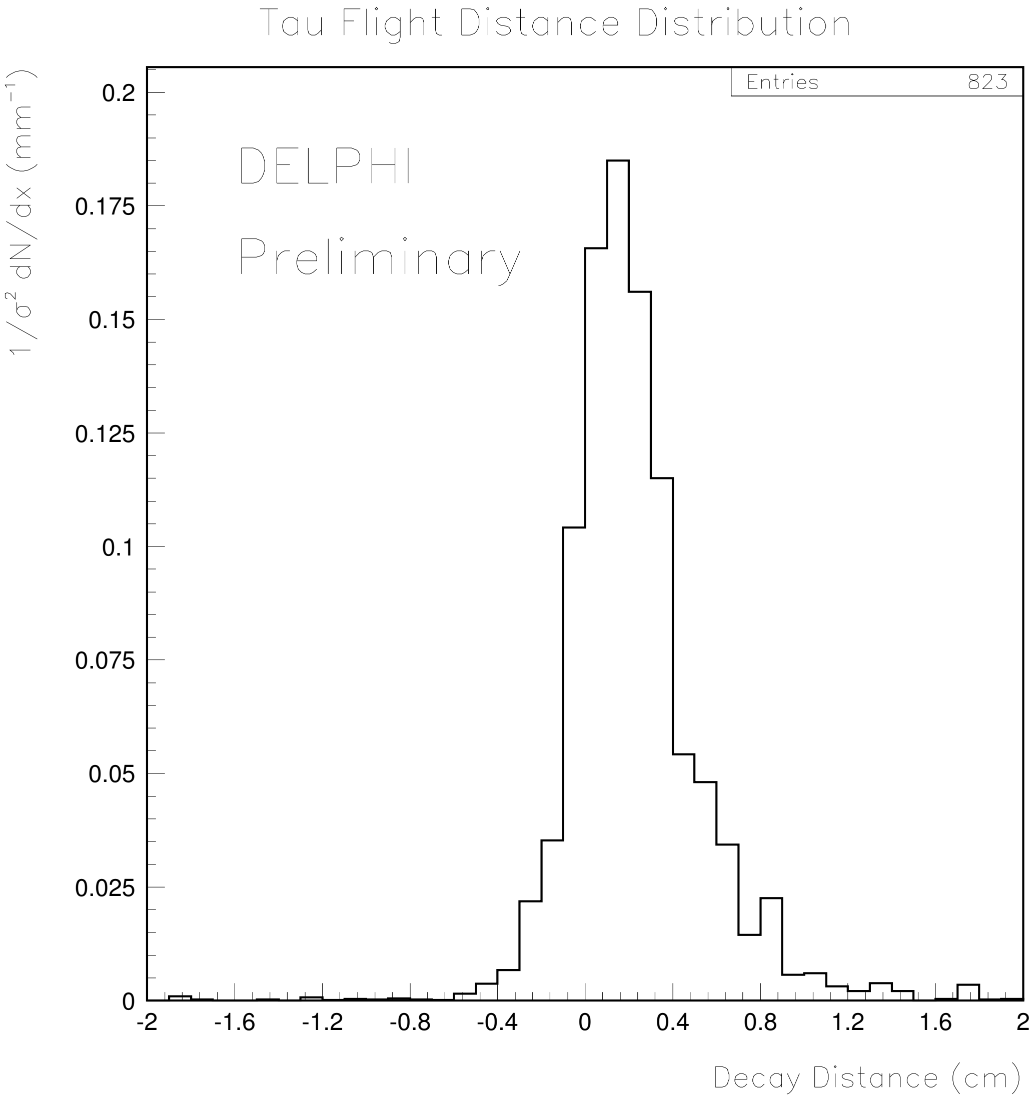

Figure 4: The observed decay distance distribution for taus using the vertex method.