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Production cross section and topological decay branching fractions of the τ lepton

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We report new measurements of the production cross section for the reaction $e^+e^- \to \tau^+\tau^-$ at $\sqrt{s} = 29$ GeV, as well as the topological decay branching fractions of the τ lepton. The data were taken with the High Resolution Spectrometer at the SLAC e^+e^- colliding-beam facility PEP. The measured cross section yields $R_{\tau\tau} = 1.044 \pm 0.014 \pm 0.030$ [where the first (second) error is statistical (systematic)], consistent with QED and corresponding to QED cutoff parameters of $\Lambda_+ > 129$ GeV and $\Lambda_- > 284$ GeV at the 95% C.L. The fractions of τ decays into one and three charged particles are $B_1 = 0.864 \pm 0.003 \pm 0.003$ and $B_3 = 0.135 \pm 0.003 \pm 0.003$.

The study of τ decay is of particular interest in view of the long-standing discrepancy[1] between the inclusive decay branching fraction into one charged particle B_1 and the sum of the branching ratios of the exclusive one-prong final states S_1. A recent compilation[2] of the experimental data on B_1 shows two clusters of values, the lower value $B_1^{\text{low}} = 0.847 \pm 0.006$ is the mean of the values obtained by three groups, whereas the higher value $B_1^{\text{high}} = 0.869 \pm 0.003$ results from the measurements of six other groups. If confirmed, the lower value would significantly reduce the discrepancy with the exclusive sum S_1, which is measured to be between 0.79 and 0.82 (Ref. 1).

We report new measurements of the production cross section of τ leptons, $R_{\tau\tau}$, and the topological decay branching fractions of the τ to one and three charged particles, denoted by B_1 and B_3. The results are based on data collected by the High Resolution Spectrometer (HRS) at the SLAC e^+e^- storage ring PEP. The data correspond to an integrated luminosity $\int L\,dt = 291 \pm 7$ pb^{-1}, and were taken at a center-of-mass energy $\sqrt{s} = 29$ GeV. Our group has previously published measurements of the production cross section[3] and the topological branching fractions[4] using data samples corresponding to integrated luminosities of 106 and 176 pb^{-1}, respectively. The present analysis is based on the full data sample and, therefore, supersedes the old results.

The HRS (Ref. 5) consisted of a solenoidal magnet of 4.5 m diameter, with a central field of 1.6 T, containing 17 layers of drift chambers, providing a momentum resolution for large-angle tracks of $\sigma_p/p = 0.2p\%$ (p in GeV/c). The magnetic volume also contained 40 barrel shower counter modules, constructed with alternate layers of lead and scintillator, with each module subtending an angle of 9° in azimuth. Each module was segmented in depth into a $3X_0$ and an $8X_0$ section with a single layer of 14 proportional wires (PWC) separating the two regions. The PWC layer was at a radius of 2.03 m from the e^+e^- beam axis. The energy resolution of the shower counters can be parametrized as

$$\left[\frac{\sigma_E}{E}\right]^2 = \frac{0.16^2}{E} + 0.06^2 + 0.011^2 E \quad (E \text{ in GeV}) , \tag{1}$$

where the first term comes from sampling fluctuations, the second term from calibration systematics, and the last term from shower leakage. The z position of a shower, along the beam axis, was determined by current division in the PWC layer to an accuracy of $\sigma(z)=2.5$ cm. The forward and backward regions were covered by end-cap shower counters.

The cuts applied to select τ-pair events in the 1-1, 1-3, 3-3, and 1-5 charged-track topologies and to reject other annihilation channels have been described previously.[3,4,6] The number of events that passed these selection criteria are summarized in Table I. Also shown is the background from non-τ-pair events in the different topologies.

The background in the 1-1 data sample is dominated by radiative μ pairs ($e^+e^-\to\mu^+\mu^-\gamma$) and two-photon annihilation channels ($e^+e^-\to e^+e^-\mu^+\mu^-, e^+e^-\tau^+\tau^-$) and is quantitatively estimated by analyzing Monte Carlo–generated data for these processes.[7] In the 1-3 and 3-3 data samples, the background is predominantly due to low-multiplicity hadronic events and was measured from the 1-3 and 3-3 hadronic events in which one three-prong state had a mass above the τ mass. This technique assumes independent fragmentation of the two jets.[8] The background in the 1-5 sample is estimated to be significantly less than one event.[6]

The detection efficiencies for the four different topological final states have been calculated by use of a Monte Carlo simulation of τ production and decay including the α^3 QED radiative corrections.[7] The generated events were subject to the same cuts as were applied to the data, and the resulting detection efficiencies are displayed in the last column of Table I. The errors correspond to the statistical uncertainty of the Monte Carlo- (MC-) generated events. The MC simulation includes the effects of migration between topologies: for example, a 1-3 event will sometimes be observed in the 1-1 topology. The detection efficiencies given in Table I are calculated as the ratio of events selected in a particular topology, irrespective of their origin, to the number of events generated in that topology. The event migration is at the few-percent level[4] since the radiation thickness of the detector from the e^+e^- interaction point to the first layer of the tracking chambers was only 0.017 radiation lengths, and the large magnetic bending gave good charged-track separation. In calculating the efficiencies, the decays

$$\begin{array}{l}\tau^-\to K^{*-}\nu_\tau\\ \quad\hookrightarrow \pi^-K^0_S\\ \qquad\quad\hookrightarrow \pi^+\pi^-\end{array}$$

were classified as three-prong final states, whereas decays such as

$$\begin{array}{l}\tau^-\to \rho^-\nu_\tau\\ \quad\hookrightarrow \pi^-\pi^0\\ \qquad\quad\hookrightarrow e^+e^-\gamma\end{array}$$

were considered as one-prong final states.

Two methods were applied to extract the production cross section and the topological branching fractions from the numbers given in Table I. In order to simplify the calculations, B_5 was fixed at the value obtained in an earlier analysis of HRS data, $B_5=0.0012$ (Ref. 6). With the constraint $B_1+B_3+B_5=1$, this reduces the unknown variables to either B_1 or B_3 and N_τ, the efficiency corrected number of produced τ pairs.

(a) A maximum-likelihood fit was performed to minimize the difference between the measured numbers of events with charged topology ij after background subtraction, N_{ij}, and the predicted numbers, $E_{ij}=N_\tau\epsilon_{ij}B_iB_j$, as a function of the topological branching ratios and the number of produced τ pairs. Assuming the errors on the measurements are given by Poisson statistics, the likelihood can be written as

$$\mathcal{L}=\prod_{ij}\frac{E_{ij}^{N_{ij}}}{N_{ij}!}e^{-E_{ij}} .$$

It is more convenient to maximize $\ln\mathcal{L}$, since

$$\ln\mathcal{L}=\sum_{ij}(N_{ij}\ln E_{ij}-E_{ij})+\text{constant terms} .$$

Once the optimal values for the topological branching fraction B_1 and the numbers of N_τ of produced τ pairs were found, the statistical errors were estimated by varying $B_1(N_\tau)$ and subsequently remaximizing $\ln\mathcal{L}$ with respect to $N_\tau(B_1)$. The one-standard-deviation limits were then given by the set of values corresponding to a decrease of $\ln\mathcal{L}$ by half a unit.

(b) A χ^2 defined as

$$\chi^2=\sum_{ij}\frac{(N_{ij}-E_{ij})^2}{E_{ij}+U_{ij}}$$

was minimized, where $E_{ij}=N_\tau\epsilon_{ij}B_iB_j$ is the expected number of events, and U_{ij} is the background from other annihilation channels with topology ij. Statistical errors in the fitted parameters N_τ and B_1 are given by the set of values corresponding to a unit increase in χ^2.

The results obtained with the two methods were identical: $B_1=0.864\pm0.003$, $B_3=0.135\pm0.003$, and N_τ

TABLE I. Data and background summary.

Topology	Number of events	Background (%)	Corrected number of events	Detection efficiency (%)
1-1	3643	7.8±0.3	3359	11.07±0.12
1-3	2693	5.8±1.1	2537	26.42±0.29
3-3	158	7.4±2.4	146	21.85±0.91
1-5	13	1.4±0.6	13	15.98±0.82

$=40\,512 \pm 543$ (Ref. 9). The production cross-section ratio to the QED prediction up to order α^3 is given by

$$R_{\tau\tau} = N_\tau / N_{\tau_{\rm calc}} = 1.044 \pm 0.014 \ ,$$

where $N_{\tau_{\rm calc}} = \sigma_{\tau\tau_{\rm rad}} \int L\, dt = 38\,800$ is the calculated total number of τ pairs produced. For the radiatively corrected cross section for τ-pair production at $\sqrt{s} = 29$ GeV, we have used $\sigma_{\tau\tau} = 133.35$ pb.

Since the measurements were performed using the excellent charged-particle tracking system of the detector with minimum exploitation of the information from the shower-counter system, the systematic errors are small and well understood.

The following contributions to the systematic error on $R_{\tau\tau}$ were considered.

(i) The uncertainty in the measurement of the integrated luminosity, which was done using wide-angle Bhabha events, yields an error on $R_{\tau\tau}$ of 2.4%.

(ii) The efficiency calculations are dependent on the exact τ-decay branching ratios. Varying the individual branching ratios inside reasonable limits while constraining their sum to be 100% changed the production cross section by up to 1.7%.

(iii) The limited statistics of the Monte Carlo–generated events leads to an uncertainty in the efficiency calculation corresponding to 0.4% of the cross section.

(iv) The uncertainty in the determination of the fraction of background from other annihilation channels than τ-pair production corresponds to an error of 0.2%.

These contributions to the systematic error are independent of each other and were therefore added in quadrature, yielding $\sigma_R^{\rm sys} = \pm 0.030$.

Since B_1 is determined as a ratio of events according to their charged topology, many systematic errors cancel. In particular, our result for B_1 does not depend on knowing the absolute value of the integrated luminosity for the experiment. The main contributions to the systematic error on B_1 come from the uncertainties in the efficiency calculation.

(a) Varying the τ-decay branching ratios inside conceivable limits, but constraining the sum to be 100%, changed B_1 by ± 0.002.

(b) The error in the efficiency calculation related to the limited Monte Carlo statistics corresponds to an error of ± 0.002 on B_1.

(c) The systematic error, due to the uncertainty in the track-finding efficiency and the Monte Carlo simulation of the photon conversion in the beam pipe, was estimated to be smaller than ± 0.001.

(d) Finally, the uncertainty in the fraction of background events in the data sample corresponds to an error of ± 0.001.

Because all systematic errors are independent of each other, the total systematic error on B_1 of ± 0.003 is obtained by adding the above contributions quadratically.

In conclusion, we have measured the total cross section for τ-pair production in e^+e^- annihilation at $\sqrt{s} = 29$ GeV. Our value divided by the α^3 QED prediction is $R_{\tau\tau} = 1.044 \pm 0.014 \pm 0.030$ [where the first (second) error is statistical (systematic)], in good agreement with the expectation from the standard electroweak theory. Since the effect of the weak interaction on $R_{\tau\tau}$ is negligible at $\sqrt{s} = 29$ GeV, we can use our measurement to test QED. With the QED cutoff parameters $\Lambda_\pm$ defined as

$$\sigma_{\rm meas} = \sigma_{\rm QED}[1 \mp s/(s' - \Lambda_\pm^2)]^2 \ ,$$

our cross-section result yields $\Lambda_+ > 129$ GeV and $\Lambda_- > 284$ GeV at the 95% C.L.

We have measured the topological branching fraction of τ decays into one charged track $B_1 = 0.864 \pm 0.003 \pm 0.003$ and into three charged tracks $B_3 = 0.135 \pm 0.003 \pm 0.003$. Our value for B_1 is significantly larger than the sum of the experimental measurements of exclusive τ-decay modes into one charged particle S_1, which lies between 0.79 and 0.82 (Ref. 1). Thus, our new measurement does not support a solution to the one-prong puzzle involving a value of B_1 close to the current sum of the exclusive modes S_1.

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[9] The detection efficiencies given in Table I were calculated with a specific set of assumed exclusive τ-decay branching ratios. The numbers in Table I yield $N_{\tau}=40\,804$. However, since there is a discrepancy between B_1 and S_1, no unique choice of exclusive decay modes can be made. We have tried several sets of values constrained to our measured value of B_1, yielding an average value for $N_{\tau}=40\,512$.