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Measurement of the τ-lepton mass

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Using data from the CLEO II detector at CESR, we measure the τ-lepton mass by exploiting the unique kinematics of events in which both τ's decay hadronically. The result is $m_\tau = 1777.8 \pm 0.7 \pm 1.7$ MeV/c^2. By comparing our result with other measurements near τ-pair threshold, we extract an upper limit on the τ-neutrino mass of 75 MeV/c^2 at 95% confidence level.

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The masses of quarks and leptons are fundamental parameters in the standard model (SM). We have obtained a new measurement of the mass of the τ, the heaviest of the three charged leptons. In the minimal SM, the rate for the purely leptonic decay of the τ via the charged weak current can be written

$$\Gamma(\tau^- \to e^- \bar{\nu}_e \nu_\tau) \equiv \frac{1}{\tau_\tau} \mathcal{B}_e = \frac{G_F^2 m_\tau^5}{192\pi^3}(1 + R_{\mathrm{EW}}) ,$$

where m_τ and τ_τ are the mass and lifetime of the tau lepton, respectively, $\mathcal{B}_e$ is its electronic branching fraction, $R_{\mathrm{EW}} \simeq -0.4\%$ is an electroweak correction [1], and massless neutrinos are assumed.

Current world averages [2] for τ_τ and $\mathcal{B}_e$ predict $m_\tau = 1762.3 \pm 8.6$, which is 2.3 standard deviations below the Particle Data Group average [2] (dominated by the 1978 DELCO m_τ measurement [3] near τ-pair threshold). Recent measurements by BES [4] at τ-pair threshold and ARGUS [5] at $E_{\mathrm{c.m.}} \simeq 10$ GeV indicate that m_τ is significantly below the previous world average value.

In addition to this precision test of the SM, the value of m_τ is needed to obtain the best limits on the τ-neutrino mass [6], and also to understand the hadronic spectral functions in τ decay. In this paper we report a measurement of m_τ using a novel method, with data from the CLEO II detector at the Cornell Electron Storage Ring (CESR) e^+e^- collider.

We consider two-body decays of the τ, $\tau^- \to h^- \nu_\tau$, where h^- is some hadronic system. Because the neutrino is undetected, the direction of the τ^- momentum vector cannot be completely determined. In the process $e^+e^- \to \tau^+\tau^-$, the two τ directions must lie on cones around the hadron directions, on half-angles $\theta_\pm$, given by the relation

$$P_\tau - P_h = P_\nu \Longrightarrow m_\tau^2 + m_{h^\pm}^2 - 2E_\tau E_{h^\pm} + 2p_\tau p_{h^\pm} \cos\theta_\pm = m_\nu^2 .$$

Here, $E_\tau = E_{\mathrm{bm}}$ (the beam energy) and $p_\tau = \sqrt{E_{\mathrm{bm}}^2 - m_\tau^2}$ under the assumption that there is no initial or final state radiation. $E_{h^\pm}$ and $p_{h^\pm}$ are the measured energies and momenta of the two hadronic systems (+ and −) and $m_{h^\pm} = \sqrt{E_{h^\pm}^2 - p_{h^\pm}^2}$. The half-angles θ_+, θ_- can thus be calculated.

In the absence of initial-state radiation, the two τ's have the beam energy and are back to back. Thus, the true τ directions must lie on the intersection of one cone and the parity inversion of the other cone. In general, two cones intersect in two rays (see Fig. 1). If one assumes a smaller τ mass, the two half-angles shrink; eventually, the two cones just touch. Since further shrinking of m_τ yields τ directions which cannot be back to back, this degenerate solution is the "minimum kinematically allowed τ mass" for the event, M_m. At this point, the directions of both τ and both hadronic systems lie in one plane, and one has $\theta_+ + \theta_- + \theta = \pi$, where θ is the angle between the two hadronic systems. With this relation, a simple quadratic equation can be solved for the value of M_m for that event.

At CESR energies, these half-angles are typically $\sim 8°$. Such angles are small enough that the value of M_m often lies close to m_τ (since all four true directions are close to being coplanar); however, the half-angles are large enough that uncertainties in M_m are not totally dominated by detector resolutions. Thus, this technique is most powerful at beam energies intermediate between threshold and high energies. Monte Carlo simulation studies [7] predict that in the absence of radiation, the M_m distri-

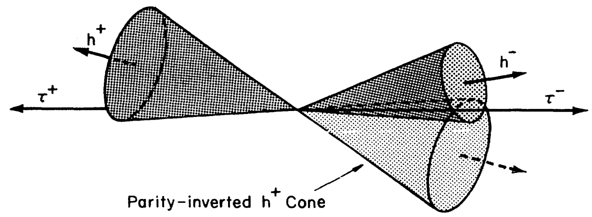

FIG. 1. The kinematics of $\tau^+\tau^- \to h^+\bar{\nu}_\tau h^- \nu_\tau$.

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bution in a perfect detector exhibits a pileup of events just below m_τ, followed by a sharp edge and a very small high-mass ($M_m > m_\tau$) tail (the "ideal" case).

Several factors can contribute to a softening of the sharp edge, to the high-mass tail, and potentially to a change in the position and slope of the edge: initial state radiation, final state radiation, missing and/or unreconstructed particles, misidentification of leptonic decays (which are three body), background from non-τ-pair events, detector resolution smearing of the kinematic quantities, π/K misidentification, and other mismeasurements of the hadronic system. In addition, uncertainties in the knowledge of the detector energy and momentum scales, the beam energy, the beam energy spread, and the τ neutrino mass contribute to the systematic error on the extraction of m_τ from the edge position. The impact of these effects will be discussed below.

The data were accumulated using the CLEO II detector [8] at the CESR e^+e^- collider. The analysis uses information from the 67-layer tracking system and the 7800-crystal CsI calorimeter, both of which are inside the 15 kG superconducting solenoidal magnet. A total luminosity of 1.43 fb^{-1} was used, accumulated on the peak of the $\Upsilon(4S)$ resonance and the continuum at center-of-mass energies $E_{\text{c.m.}} \sim 10.6$ GeV. This corresponds to 1.31 million τ pairs.

We select events in which each τ decays hadronically to one charged particle and 0, 1, or 2 π^0's. Events of 1-versus-1 topology with π^0's have large branching fractions and are relatively free of hadronic background compared with other topologies. The use of π^0's reduces the dependence of the M_m edge position on absolute knowledge of the momentum scale at the expense of increased dependence on knowledge of the energy scale.

Events are required to have exactly two reconstructed charged tracks, of opposite charge, separated in angle by $\geq 90°$. Both tracks must have more than 100 MeV/c of momentum transverse to the beam line. No more than one can have momentum exceeding 85% of E_{bm}. No particle identification is attempted; both tracks are assumed to be pions. To reject Bhabha scattering events, the total visible energy in the calorimeter must be less than 85% of $E_{\text{c.m.}} \equiv 2E_{\text{bm}}$. Showers in the calorimeter are used to make a π^0 if they are neutral (unmatched to the charged tracks), lie in the barrel region ($|\cos\theta| < 0.71$), and have energy exceeding 40 MeV. Shower pairs must lie within 3 standard deviations of the π^0 mass (typically, $\sigma_{\gamma\gamma} \simeq 7$ MeV/c^2). The event is rejected if any unused neutral showers of more than 100 MeV remain. A reconstructed π^0 is then associated with the charged track nearest to it in angle. We require at least one π^0 in an event. The explicitly selected topologies are $\pi^\pm$ vs $\pi^\mp\pi^0$, $\pi^\pm$ vs $\pi^\mp 2\pi^0$, $\pi^\pm\pi^0$ vs $\pi^\mp\pi^0$, and $\pi^\pm\pi^0$ vs $\pi^\mp 2\pi^0$.

Each charged track unassociated with a π^0 must leave a shower in the calorimeter with energy less than 85% of its momentum (to reject $e^\pm$), and not penetrate 4 interaction lengths of material in the outer muon detection system (to reject $\mu^\pm$). In order to reject background from two-photon collision processes, the visible energy in the event ($\pi^\pm$'s and π^0's) must exceed 40% of $E_{\text{c.m.}}$, and the visible momentum transverse to the beam must exceed 500 MeV/c. Approximately 10% of the events passing these cuts appears with more than one valid combination of photons in π^0's; all such combinations are used in the analysis. A total of 35 255 combinations pass all cuts.

For each combination, each π^0 is kinematically constrained to the π^0 mass. The value of M_m is calculated from the four-vectors of the two hadronic systems. Approximately 11% of all combinations yield no solution because missing particles from one hadronic sysetem force a value of M_m which is smaller than the invariant mass of the other system. These combinations are discarded.

The M_m distribution in the data is shown in Fig. 2(a). The predicted pileup just below m_τ, the sharp drop, and the high-mass tail, are apparent. Figure 2(b) is a closeup of the region around the edge. Also shown is the distribution obtained from a realistic Monte Carlo simulation, with $m_\tau = 1784.1$ MeV/c^2. The properties of the signal events are studied using the τ-pair Monte Carlo simulation KORALB/TAUOLA [7], with detector simulation using the GEANT [9] package. There is good qualitative agreement between data and simulation on the shape of the distribution.

From Monte Carlo simulations, the background from hadronic events is expected to be negligible. The background from two photon events is less than 1%. It has been verified, by loosening cuts, that none of these backgrounds produce structure in the M_m distribution in the region of interest.

The invariant mass distributions of the hadronic $\pi^\pm\pi^0$ and $\pi^\pm 2\pi^0$ systems are dominated by the $\rho^\pm$ and $a_1^\pm$ resonances, and no events appear above the nominal τ mass. The shape of the M_m distribution is the same in both data and simulation, including the high mass tail. KORALB

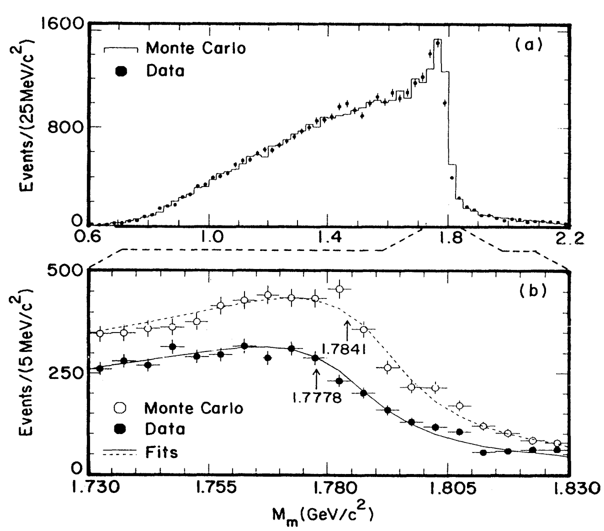

FIG. 2. (a) The M_m distribution in the data and in the simulation. (b) An expanded view of (a), with the fit function superimposed. The vertical scale for the simulation is shifted so that it can be visually compared with the data points.

predicts that all the events in the tail have unreconstructed or misidentified particles, the former due primarily to the photon from initial state radiation which follows the beam direction and falls outside the detector acceptance.

Both the data and simulation M_m distributions are fitted with an empirical shape composed of an arctangent curve, falling from 1 to 0 in the vicinity of the edge, with its position and slope as fit parameters, a fourth-order polynominal multiplying the arctangent curve, to model the falloff at masses below the edge, and a first-order polynominal to model the high-mass tail.

The parameters governing the two polynomials are determined from the M_m distribution in the simulation. Only the overall normalization and position of the arctan curve are varied to fit the data. The fits are shown as curves superimposed on Fig. 2. Here, $m_\tau = 1784.1$ MeV/c^2 was assumed in the simulation. It can be see that the data and simulation have very similar shapes. We have verified that in the simulation the fitted position of the edge linearly follows the generated value of m_τ over the entire relevant range. The fitted simulation edge position, relative to the generated value of m_τ, is used as an offset to extract the measured value of m_τ from the fitted edge position in the data.

The calculation of M_m for each event is determined completely from measurements of the kinematical quantities of the observed tracks and showers and the beam energy. Mismeasurements of any of these quantities can potentially lead to changes in the position and slope of the edge in the M_m distribution. Contributions to the systematic error on the measured m_τ come from uncertainties in the momentum scale; calorimeter energy scale; the beam energy and energy spread; resolutions in momentum, energy, and angle; the statistical error on the edge position from the simulation; different cut values and fit procedures; and the assumed mass of the τ neutrino.

The dependence of the fitted edge position on shifts of scale was studied by varying the appropriate scale, in both data and simulation, and refitting the M_m distributions. In all cases, the dependence of the edge position on fractional changes of scale was in good agreement between data and simulation.

The momentum scale in data and simulation is established by comparing measured values of various multiparticle decay invariant mass peaks in the data with Monte Carlo simulations in which world average values [2] were used as input. The decays used for these comparisons included $K_S \to \pi^+\pi^-$, $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $\Lambda \to p^+\pi^-$, and $J/\psi \to \mu^+\mu^-$. The resulting uncertainty in the momentum scale is $\pm 0.1\%$, which corresponds to an uncertainty in the fitted edge position, and therefore on the measured m_τ of 0.8 MeV/c^2.

The calorimeter energy scale is established by studying the distribution of $\gamma\gamma$ invariant mass $m_{\gamma\gamma}$ in the decay $\pi^0 \to \gamma\gamma$ in the selected event sample. The calibration procedure minimizes the variation in position of the peak in the data as a function of time. After calibration, important features of the two photon system in the data are reproduced by the simulation, including the shape and peak position of the $m_{\gamma\gamma}$ distribution as well as the spectra in $\gamma\gamma$ opening angle, π^0 energy, and azimuth and polar angle. The energy scale is checked by comparing the mass of the D^0 measured in the decay $K^-\pi^+\pi^0$ with the known value [2]. The overall uncertainty in the difference between the data and simulation energy scales is $\pm 0.3\%$. This corresponds to an uncertainty in the measured m_τ of ± 1.2 MeV/c^2.

The CESR beam energy scale is established using precision measurements of the $\Upsilon(1S)$ and $\Upsilon(2S)$ resonances. Extrapolation to the vicinity of the $\Upsilon(4S)$ resonance introduces an uncertainty of ± 1.75 MeV in the absolute knowledge of the beam energy [10]. The position of the $\Upsilon(4S)$ resonance is observed to be stable to this level over the duration of our data taking. This corresponds to an uncertainty in the measured m_τ of ± 0.1 MeV/c^2.

Uncertainties in resolutions are studied by explicitly introducing degraded momentum, energy, and angular resolution, and beam energy spread, into the data and simulation. There is no significant effect on the fitted edge position. Various reasonable systematic angular errors also produced no significant effect.

The shape of the M_m distribution studied separately for each topology agrees well between data and simulation, as measured using both χ^2 and Kolmogorov tests [11]. The measured value of m_τ obtained using a particular topology always agrees within statistical errors with the value obtained from all accepted topologies. Varying cut values and fitting procedure produced shifts in the resulting measurement of m_τ by as much as ± 0.5 MeV/c^2. We use that figure as an estimate of the systematic error associated with such effects.

A τ neutrino mass different from zero will shift the position of the edge. The shift is linear in the square of the neutrino mass. Using the ARGUS limit [6] of 31 MeV/c^2, the m_τ measurement changes by $+0.9$ MeV/c^2.

Using the offset determined from fits to the simulation, the fit to the data yield $m_\tau = 1777.8 \pm 0.7$ MeV/c^2, where the error is the statistical error on the edge determined from these fits. The contributions to the systematic error detailed above are summarized in Table I. Added in quadrature, they total ± 1.7 MeV/c^2 (excluding the uncertainty from the τ neutrino mass). This measurement is 6.5 MeV/c^2 below the current world average, and it agrees well with the recent measurements from BES and ARGUS.

The BES and DELCO mass measurements, made at $\tau^+\tau^-$ threshold, are independent of the τ neutrino mass. Our measurement of m_τ increases if the τ neutrino mass is greater than zero. By requiring consistency between

TABLE I. Sources of error in the m_τ measurements.

Source of error	Scale uncertainty	m_τ uncertainty (MeV/c^2)
Energy scale	$\pm 0.30\%$	± 1.2
Momentum scale	$\pm 0.10\%$	± 0.8
Beam energy scale	$\pm 0.03\%$	± 0.1
Simulation statistics		± 0.8
Vary cuts, fit		± 0.5
τ-neutrino mass	< 31 MeV/c^2	$+0.9$

this measurement and the threshold measurements at the 1.64 standard deviation level (taking statistical and systematic errors from both measurements in quadrature), we derive a 95% confidence level upper limit on the τ neutrino mass of 75 MeV/c^2.

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[1] W. J. Marciano and A. Sirlin, Phys. Rev. Lett. **61**, 1815 (1988).

[2] Particle Data Group, K. Hikasa *et al.*, Phys. Rev. D **45**, S1 (1992).

[3] DELCO Collaboration, W. Bacino *et al.*, Phys. Rev. Lett. **41**, 13 (1978).

[4] BES Collaboration, J. Bai *et al.*, Phys. Rev. Lett. **69**, 3021 (1992). The BES Collaboration measures $m_\tau = (1776.9 \pm 0.4 \pm 0.3)$ MeV/c^2.

[5] ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. B **292**, 221 (1992). The ARGUS Collaboration measured $m_\tau = (1776.3 \pm 2.4 \pm 1.4)$ MeV/c^2.

[6] ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. B **202**, 149 (1988); D. Britton (ARGUS) and D. Cowen (CLEO), in *Proceedings of the Second Workshop on Tau Lepton Physics*, Columbus, Ohio 1992, edited by K. K. Gan (World Scientific, Singapore, in press).

[7] KORALB (v.2.1)/TAUOLA (v.1.5): S. Jadach and Z. Was, Comput. Phys. Commun. **36**, 191 (1985); **64**, 267 (1991); S. Jadach, J. H. Kühn, and Z. Was, *ibid.* **64**, 275 (1991); M. Jezakek, Z. Was, S. Jadach, and J. H. Kuhn, *ibid.* **70**, 69 (1992).

[8] Y. Kubota *et al.* Nucl. Instrum. Methods A **320**, 66 (1992).

[9] R. Brun *et al.*, GEANT 3, 14 CERN DD/EE/84-1.

[10] CLEO Collaboration, C. Bebek *et al.*, Phys. Rev. D **36**, 1289 (1987).

[11] See, for example, W. T. Eadie *et al.*, *Statistical Methods in Experimental Physics* (North-Holland, Amsterdam, 1971), p. 269.