Physics Letters B 292 (1992) 221-228
North-Holland

PHYSICS LETTERS B

# A measurement of the tau mass

ARGUS Collaboration

H. Albrecht, H. Ehrlichmann, T. Hamacher, R.P. Hofmann, T. Kirchhoff, A. Nau, S. Nowak [1], H. Schröder, H.D. Schulz, M. Walter [1], R. Wurth

*DESY, W-2000 Hamburg, FRG*

R.D. Appuhn, C. Hast, H. Kolanoski, A. Lange, A. Lindner, R. Mankel, M. Schieber, T. Siegmund, B. Spaan, H. Thurn, D. Töpfer, A. Walther, D. Wegener

*Institut für Physik, Universität Dortmund, W-4600 Dortmund, FRG* [2]

M. Paulini, K. Reim, H. Wegener

*Physikalisches Institut, Universität Erlangen-Nürnberg, W-8520 Erlangen, FRG* [3]

R. Mundt, T. Oest, R. Reiner, W. Schmidt-Parzefall

*II. Institut für Experimentalphysik, Universität Hamburg, W-2000 Hamburg, FRG*

W. Funk, J. Stiewe, S. Werner

*Institut für Hochenergiephysik, Universität Heidelberg, W-6900 Heidelberg, FRG* [4]

K. Ehret, W. Hofmann, A. Hüpper, S. Khan, K.T. Knöpfle, J. Spengler

*Max-Planck-Institut für Kernphysik, W-6900 Heidelberg, FRG*

D.I. Britton [5], C.E.K. Charlesworth [6], K.W. Edwards [7], E.R.F. Hyatt [5], H. Kapitza [7], P. Krieger [8,6], D.B. MacFarlane [5], P.M. Patel [5], J.D. Prentice [6], P.R.B. Saull [5], K. Tzamariudaki [5], R.G. Van de Water [6], T.-S. Yoon [6]

*Institute of Particle Physics, Canada* [9]

D. Reßing, M. Schmidtler, M. Schneider, K.R. Schubert, K. Strahl, R. Waldi, S. Weseler

*Institut für Experimentelle Kernphysik, Universität Karlsruhe, W-7500 Karlsruhe, FRG* [10]

G. Kernel, P. Križan, E. Križnič, T. Podobnik, T. Živko

*Institut J. Stefan and Oddelek za fiziko, Univerza v Ljubljani, 61111 Ljubljana, Slovenia* [11]

H.I. Cronström, L. Jönsson

*Institute of Physics, University of Lund, S-233 62 Lund, Sweden* [12]

0370-2693/92/$ 05.00 

V. Balagura, I. Belyaev, M. Danilov, A. Droutskoy, A. Golutvin, I. Gorelov, G. Kostina, V. Lubimov, P. Murat, P. Pakhlov, F. Ratnikov, S. Semenov, V. Shibaev, V. Soloshenko, I. Tichomirov and Yu. Zaitsev

*Institute of Theoretical and Experimental Physics, 117 259 Moscow, Russia*

Received 29 June 1992

Using the ARGUS detector at the DORIS II storage ring, a new measurement of the mass of the $\tau$ lepton has been obtained. An analysis of the tau pseudomass spectrum for decays of the type $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ finds $m_\tau = 1776.3 \pm 2.4 \pm 1.4$ MeV/$c^2$. This result also leads to an improvement of the upper limit on the $\nu_\tau$ mass to $m_{\nu_\tau} <$ 31 MeV/$c^2$ at the 95% confidence level.

To date, the only method which has been applied in determining the mass of the $\tau$ lepton is based on the behaviour of the total cross section $\sigma(e^+e^- \to \tau^+\tau^-)$ in the threshold region. The four existing measurements lead to an average value of $m_\tau = 1784.1^{+2.7}_{-3.6}$ MeV/$c^2$ [1]. However, the result is dominated by the measurement of the DELCO experiment, $m_\tau = 1782^{+2}_{-7}$ MeV/$c^2$ [2], which was later refined to $m_\tau = 1783^{+3}_{-4}$ MeV/$c^2$ after recalibration of the SPEAR energy scale [1] using a high precision $\psi(2s)$ mass measurement [3].

A more precise knowledge of the $\tau$ mass is highly desirable for several reasons.

– The most sensitive bounds on the mass of the $\nu_\tau$ can be derived from the analysis of the invariant mass spectrum of semihadronic $\tau$ decays, e.g. the present best limit of $m_{\nu_\tau} < 35$ MeV/$c^2$ (95% CL) [4] was obtained using the decay $\tau^- \to \pi^-\pi^-\pi^-\pi^+\pi^+\nu_\tau$ [#1]. Since this method depends on a determination of the kinematic end point of the mass spectrum, the current precision of the $\tau$ mass measurement will restrict the ultimate sensitivity on $m_{\nu_\tau}$ to about 10 MeV/$c^2$.

– In the framework of the standard model, the leptonic branching fractions of the $\tau$ lepton can be related to $\tau$ and $\mu$ lifetimes and masses. The leptonic width for the decay $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ can be written as

$$\Gamma(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = \frac{G_F^2 m_\tau^5}{192\pi^3}(1+r),$$

where $G_F$ is the Fermi coupling constant and $r \approx -0.4\%$ arises from radiative corrections and the nonlocal structure of the W-propagator [5]. The total decay width of the $\tau$ is known from measurements of the $\tau$ lifetime $\tau_\tau = 302.5 \pm 5.9$ fs [6]. Hence, the theoretically expected branching ratio for this decay $(B_e)_{theor}$ can be calculated:

$$(B_e)_{theor} = \tau_\tau \Gamma(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = (18.9 \pm 0.4)\%.$$

This is considerably larger than the current world average of the measured branching ratio for this decay $(B_e)_{exp} = (17.73 \pm 0.23)\%$ [6]. This discrepancy, at about the 2.5 standard deviation level, is commonly referred to as the "$\tau$ lifetime problem" [7]. If the problem persists it might be the first indication of a violation of lepton universality for the $\tau$ lepton. A pos-

1 DESY, IfH, 1650 Zeuthen, FRG.
2 Supported by the German Bundesministerium für Forschung und Technologie, under contract number 054DO51P.
3 Supported by the German Bundesministerium für Forschung und Technologie, under contract number 054ER12P.
4 Supported by the German Bundesministerium für Forschung und Technologie, under contract number 055HD21P.
5 McGill University, Montreal, Quebec, Canada H3A 2T8.
6 University of Toronto, Toronto, Ontario, Canada M5S 1A7.
7 Carleton University, Ottawa, Ontario, Canada K1S 5B6.
8 Supported in part by the Walter C. Sumner Foundation.
9 Supported by the Natural Sciences and Engineering Research Council, Canada.
10 Supported by the German Bundesministerium für Forschung und Technologie, under contract number 054KA17P.
11 Supported by the Department of Science and Technology of the Republic of Slovenia and the Internationales Büro KfA, Jülich.
12 Supported by the Swedish Research Council.

#1 References in this paper to a specific charged state also imply the charge conjugate state.

sible remedy for the problem would be a downward shift in the lifetime or mass of the tau.

In this paper we report a measurement of the $\tau$ mass using a new pseudomass technique [8]. The $\tau$ pseudomass is derived from the measured mass, energy and momentum of the three-pion system in the decay $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$, together with the beam energy. Tau-pair events are selected with the following combinations of decay modes:

$$
\begin{aligned}
e^+e^- \to \tau^+\tau^- &\to \pi^-\pi^-\pi^+\nu_\tau \\
&\hookrightarrow e^+\nu_e\bar{\nu}_\tau\,,\ \mu^+\nu_\mu\bar{\nu}_\tau\,, \\
&\qquad \pi^+\bar{\nu}_\tau + n\gamma \text{ or } K^+\bar{\nu}_\tau + n\gamma \\
&\qquad\qquad (0 \leqslant n \leqslant 4)\,.
\end{aligned}
$$

The measurement was performed with the ARGUS detector operating at the $e^+e^-$ storage ring DORIS II. The data sample, corresponding to 341 $pb^{-1}$ and containing about 325 000 produced $\tau$ pair events, was collected at centre-of-mass energies between 9.4 and 10.6 GeV. The $4\pi$ spectrometer ARGUS, its trigger requirements and particle identification capabilities have been described in detail elsewhere [9].

Events are required to have exactly four charged tracks with a zero net charge. In addition, each track must have a transverse momentum $p_T > 0.06$ GeV/$c$, a momentum $p < 4$ GeV/$c$ and point to the event's main vertex. To ensure a good detection efficiency the track must be found in a polar angle region defined by $|\cos\theta| < 0.92$. The characteristic 1-versus-3 topology of the charged particles is obtained by requiring $\cos(\boldsymbol{p}_1,\boldsymbol{p}_i) < 0$ $(i = 2,3,4)$ and $\cos(\boldsymbol{p}_1,\boldsymbol{p}_{3pr}) < -0.5$, where $\boldsymbol{p}_1$ denotes the momentum of the charged particle on the 1-prong side, $\boldsymbol{p}_i$ is momentum of each particle $i$ on the 3-prong side and $\boldsymbol{p}_{3pr} = \sum_{i=2}^{4} \boldsymbol{p}_i$ is the momentum of the 3-prong hemisphere. Contributions from radiative QED events with converted photons are reduced by rejecting events with a secondary vertex consistent with a converted photon. A suppression of two-photon and hadronic backgrounds is achieved by a cut on the relationship between the transverse momentum balance and the total visible momentum of charged and neutral particles [10]:

$$
\left|\sum_{i=1}^{n} \boldsymbol{p}_{Ti}\right| > \left[4.5\left(\sum_{i=1}^{n} |\boldsymbol{p}_i| c/E_{cms} - 0.55\right)^2 + 0.1\right] \text{GeV}/c\,.
$$

Note that the sum includes all charged particles and photons found in the event. Energy clusters in the calorimeter of more than 80 MeV with no associated track are accepted as photon candidates. The number of photons per event, $n_\gamma$, has been restricted to $n_\gamma \leqslant 4$, with no photons allowed in the 3-prong hemisphere of the event by requiring $\cos(\boldsymbol{p}_{\gamma_j},\boldsymbol{p}_{3pr}) < 0$ for $1 \leqslant j \leqslant n_\gamma$. An additional suppression of background from $\gamma\gamma$ events was achieved by a cut on the total visible momentum of the charged particles: $\sum_{i=1}^{4} |\boldsymbol{p}_i| > 2.7$ GeV/$c$. Background from Bhabha reactions has been further reduced by restricting the sum of the energy deposition by the charged particles on the 3-prong side to be less than 4 GeV. As a final requirement, all particles on the 3-prong side must be consistent with the pion hypothesis, by requiring that the corresponding likelihood ratio [9] exceed 1%.

A total of 10 959 events pass these selection criteria, including a tau-pair background contribution of 2161 ± 200 events which has been determined from a Monte Carlo study based on the KORALB 2.1/TAUOLA 1.5 [#2] program package [11]. The dominant fraction of this background originates from the decay $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$ where the photons of the $\pi^0$ escape undetected.

The background from $e^+e^-$ annihilation into multihadrons is 360 ± 80 events, as determined by a Monte Carlo study [10] using JETSET versions 6.2 and 6.3 [12] as generators. Other background sources, such as Bhabha reactions or two-photon processes, contribute at a level of less than 1% each.

The measured $3\pi$ invariant mass spectrum is shown in fig. 1. Note that the background from other $\tau$ decays has not been subtracted. The spectrum is compared with Monte Carlo predictions for the invariant $m_{3\pi}$ spectrum from the decays $\tau^- \to a_1^-\nu_\tau$ followed by $a_1^- \to \rho^0\pi^-$ and $\rho^0 \to \pi^+\pi^-$, and from the background sources. There is good agreement between data

[#2] All Monte Carlo studies on $\tau$ decays described in this paper are based on this program package.

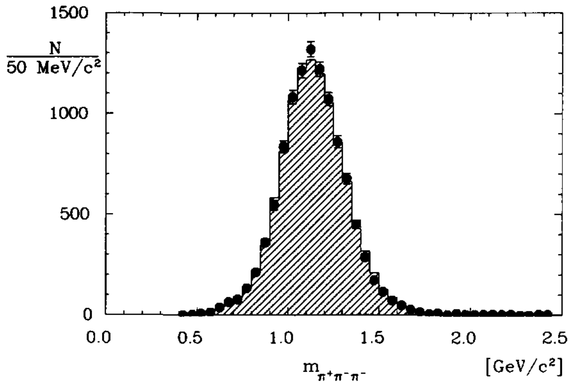


Fig. 1. Measured invariant $3\pi$ mass spectrum. The hatched histogram shows the result of a Monte Carlo calculation of the $m_{3\pi}$ spectrum for $\tau$ decays into $\pi^-\pi^-\pi^+\nu_\tau$ and for background (see text), normalized to the data.

and the Monte Carlo simulation. The small number of entries found for $m_{3\pi} > 1.8$ GeV/$c^2$ demonstrates that the background from non-$\tau$ events is indeed very small.

The $\tau$ mass itself cannot be calculated from the measured quantities since the $\tau$ flight direction is unknown. However, a $\tau$ pseudomass can be derived with the approximation that the flight direction of the $3\pi$ system is the flight direction of the $\tau$, i.e., setting $\cos(\boldsymbol{p}_\tau, \boldsymbol{p}_{3\pi}) = 1$. With $m_\tau^2 = E_\tau^2 - p_\tau^2$ and $E_\tau = \frac{1}{2}\sqrt{s}$, equal the nominal beam energy, it follows that only the $\tau$ momentum needs to be determined. Using the approximation noted above, a pseudo $\tau$ momentum, $p_\tau^* = p_{3\pi} \pm p_{\nu_\tau}$, can be derived from the momenta of the $3\pi$ system, $p_{3\pi} = |\boldsymbol{p}_{3\text{pr}}|$, and the tau neutrino, $p_{\nu_\tau}$. The solution $p_\tau^* = p_{3\pi} - p_{\nu_\tau}$ has been discarded since the case where $p_\tau < p_{3\pi}$ is true for only $\approx 2\%$ of the $\tau$ decays under consideration. In addition, a poor sensitivity to $m_\tau$ results from an analysis of such events. The energy of the tau neutrino, $E_{\nu_\tau}$, is derived from the energy difference between the $\tau$ and the $3\pi$ system: $E_{\nu_\tau} = E_\tau - E_{3\pi}$. With $p_{\nu_\tau} = \sqrt{E_{\nu_\tau}^2 - m_{\nu_\tau}^2}$ and $m_\tau^{*2} = E_\tau^2 - p_\tau^{*2}$ it follows that

$$m_\tau^{*2} = 2E_\tau E_{3\pi} - 2E_{3\pi}^2 + m_{3\pi}^2 + m_{\nu_\tau}^2$$
$$- 2p_{3\pi}\sqrt{(E_\tau - E_{3\pi})^2 - m_{\nu_\tau}^2}\,.$$

The mass of the tau neutrino is known to be very small: $m_{\nu_\tau} < 35$ MeV/$c^2$ (95% CL) [4]. The scale of its effect on the pseudomass determination is set by comparison with the other terms $m_{3\pi}^2$ and $(E_\tau - E_{3\pi})^2$. Since the $3\pi$ system is formed by the decay of an $a_1$ meson [13], $m_{3\pi}$ takes values above 0.9 GeV/$c^2$, i.e., large compared to 35 MeV/$c^2$. Due to the restriction of our choice for $p_\tau^*$ to $p_{3\pi} + p_{\nu_\tau}$, the $a_1$ meson has been emitted opposite to the $\tau$ direction of flight (as seen from the $\tau$ rest frame) for events where the approximation $\cos(\boldsymbol{p}_\tau, \boldsymbol{p}_{3\pi}) = 1$ holds true. Since almost no events with $m_{3\pi}$ masses close to the mass of the $\tau$ lepton (fig. 1) have been found, the difference between $\tau$ and $3\pi$ energies is large for the majority of events with $m_\tau^* \approx m_\tau$, so that here too $E_\tau - E_{3\pi} \gg 35$ MeV. Therefore, a finite but small tau neutrino mass has only a marginal influence on the determination of $m_\tau$ and will be neglected. Hence, $m_\tau^{*2}$ can be written as

$$m_\tau^{*2} = 2(E_\tau - E_{3\pi})(E_{3\pi} - p_{3\pi}) + m_{3\pi}^2\,.$$

The systematic error on $m_\tau$, imposed by this approximation, will be discussed later in detail. Another source of systematic uncertainty in the determination of $m_\tau^*$ is the precision by which the beam energy is known. The absolute energy scale of the DORIS II storage ring has been calibrated using the mass measurements of the $\Upsilon$ resonances [1,14] as reference. The long term stability of the centre-of-mass energy is known from data taking periods on the $\Upsilon$ resonances. In addition, the resonance energies have been well reproduced after a shutdown period or after a period of data taking in the nearby continuum. Hence, we conclude that the average beam energy is known with a precision of $\sigma_{E_{\text{beam}}} \simeq 3$ MeV, yielding a shift to $m_\tau^*$ of $\delta m_\tau^* \simeq 0.5$ MeV/$c^2$, as follows from the formula above. Since the influence of two major possible sources of uncertainty on the determination of the $\tau$ mass, a finite $\nu_\tau$ mass and a wrong beam energy, are very small, systematic errors of about 1 MeV/$c^2$ should be feasible using the pseudomass method.

The observed pseudomass spectrum after these requirements is shown in fig. 2 together with the normalized distribution for the background. The data exhibit a sharp threshold behaviour in the region close to the nominal value of the $\tau$ mass, while the background has only a very slight slope in the same area. The tail above the nominal $\tau$ mass cannot be explained by the presence of background, but is due to initial-state radiation processes which effectively reduce the $\tau$ energy. Since the beam energy is used in the calculation of the pseudomass, the true $\tau$ energy is over-

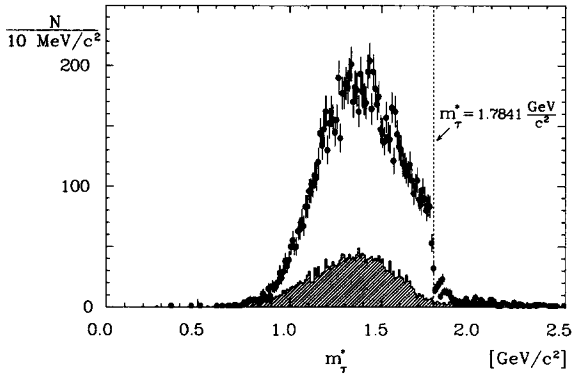


Fig. 2. Tau pseudomass spectrum of data (full dots with error bars) and background, normalized to the data (hatched histogram). The present nominal $\tau$ mass of $m^*_\tau = m_\tau = 1.7841\ \mathrm{GeV}/c^2$ [1] is indicated by the dotted line.

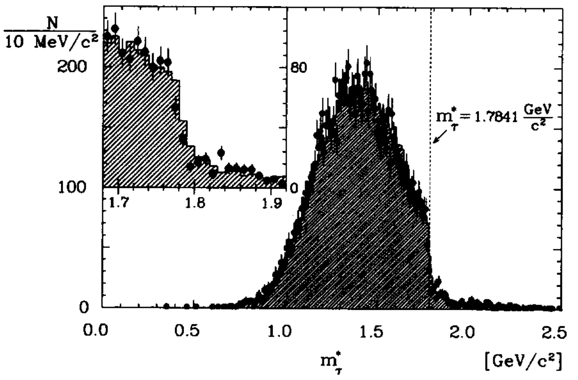


Fig. 3. Measured $3\pi$ pseudomass spectrum compared with the result from a Monte Carlo calculation (hatched histogram) of the $m^*_\tau$ spectrum for $\tau$ decays into $\pi^-\pi^-\pi^+\nu_\tau$ and for background, normalized to the data. The present nominal $\tau$ mass of $m^*_\tau = m_\tau = 1.7841\ \mathrm{GeV}/c^2$ [1] is indicated by the dotted line. The enlarged section in the upper left-hand corner provides a detailed view of the pseudomass region $1.68 \leqslant m^*_\tau \leqslant 1.92\ \mathrm{GeV}/c^2$.

estimated, leading to higher values of $m^*_\tau$. The position of the pseudomass threshold is directly related to the mass of the $\tau$ lepton. In fig. 3 the measured $m^*_\tau$ spectrum is compared to the Monte Carlo prediction including background. In the simulation of the $m^*_\tau$ spectrum from $\tau$ decays, the nominal $\tau$ mass of $m_\tau = 1784.1\ \mathrm{MeV}/c^2$ was used. The tail to pseudomasses above the nominal $\tau$ mass is well reproduced by the Monte Carlo calculation. However, the threshold for the data sample appears to lie below the Monte Carlo expectation for $m_\tau = 1.7841\ \mathrm{GeV}/c^2$ (enlarged section of fig. 3), indicating that the $\tau$ mass is smaller than previously measured.

The shape of the $m^*_\tau$ spectrum for background has been also determined from the data by an analysis of events which passed the same selection criteria with the exception that two photons were required on the 3-prong side. This two-photon system was required to have an invariant mass within $\pm 100\ \mathrm{MeV}/c^2$ of the nominal $\pi^0$ mass [1] and to yield a $\chi^2 < 9$ when kinematically constrained to the $\pi^0$ mass. The overall shape of the $m^*_\tau$ spectrum agrees well with the corresponding spectrum for simulated background events, but shows an even smoother slope in the region close to the nominal mass of the $\tau$ lepton.

The $\tau$ mass has been obtained by fitting the measured $m^*_\tau$ spectrum using a Monte Carlo calculation to determine the expected shape for arbitrary $\tau$ masses. Monte Carlo studies have shown that the $m^*_\tau$ spectrum for different $m_\tau$ masses can be obtained by a simple shift of the spectrum with respect to a simulated $m^*_\tau$ spectrum for a reference $\tau$ mass $m^0_\tau$ (here $m^0_\tau = 1.7841\ \mathrm{GeV}/c^2$), provided the $\tau$-mass difference $\delta m_\tau$ to $m^0_\tau$ is small:

$$f(m^*_\tau, m_\tau = m^0_\tau + \delta m_\tau)$$
$$= f(m^*_\tau - \delta m_\tau, m_\tau = m^0_\tau),$$

where $f(m^*_\tau, m^0_\tau)$ describes the expected shape of a $m^*_\tau$ spectrum for the reference $\tau$ mass. The simulated $m^*_\tau$ spectrum for $\tau$ decays into $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ is shown in fig. 4. Note that the influence of the beam energy spread of the DORIS II storage ring is included in the simulation. The shape of the spectrum has been modelled in the region $1.65 < m^*_\tau < 1.9\ \mathrm{GeV}/c^2$ with a heuristic function of the form

$$f(m^*_\tau, m^0_\tau) \sim a_1 \left( \frac{1}{\exp[(m^*_\tau - a_3)/a_4(1 - a_5 m^*_\tau)] + 1} \times (1 + a_2 m^*_\tau) \right),$$

where $a_i$ with $i = 1, \ldots, 5$ are free parameters.

In the fit to the data we used the same function with all parameters fixed to the values extracted

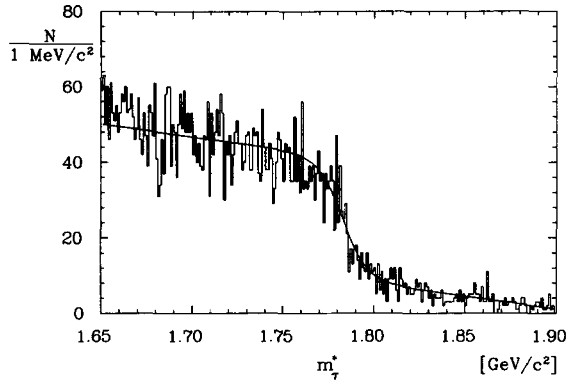


Fig. 4. Simulated pseudomass spectrum for $\tau$ decays of the type $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ ($m_\tau = 1784.1$ MeV/$c^2$). The curve shows the result of the fit described in the text.

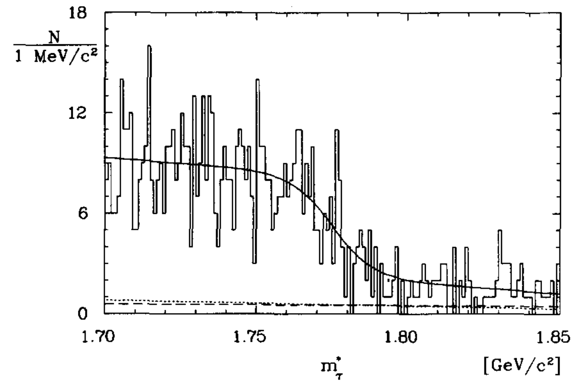


Fig. 5. Measured $m_\tau^*$ spectrum in the region of the threshold close to the $\tau$ mass. The curves show the results of the fit described in the text (broken line: fitted background) and the expected background level (dotted line).

from the simulation except the normalization $a_1$. The data have been fitted in the region $1.7 < m_\tau^* < 1.85$ GeV/$c^2$, limiting possible shifts in the $\tau$ mass to $\delta m_\tau < 50$ MeV/$c^2$. Although the background is small in this region and does not exhibit any threshold behaviour, we have included its contribution in the fit. The background $m_\tau^*$ spectra from $\tau$ decays and multihadron sources have been parametrized, leaving only the overall normalization as a free parameter. Hence, the fit to the observed $m_\tau^*$ spectrum has four free parameters: $m_\tau$ and the normalizations for the three contributing functions. By this procedure we obtain a $\tau$ mass of

$$m_\tau = 1776.3 \pm 2.4 \text{ MeV}/c^2,$$

where only the statistical error is given. The measured $m_\tau^*$ spectrum is shown in fig. 5 together with the fitted function. The threshold, visible in the data, and the expected background level, are well reproduced by the fit.

In order to determine the systematic error a variety of sources have been considered. A $\nu_\tau$ mass of $m_{\nu_\tau} = 20$ MeV/$c^2$ would cause a shift in $m_\tau$ of $\delta m_\tau \approx 0.3$ MeV/$c^2$. A systematic deviation of the beam energy from its nominal value by 3 MeV results in a change of $\delta m_\tau = 0.5$ MeV/$c^2$. Within statistical errors the obtained result did not change by analyzing the $m_\tau^*$ spectra for arbitrary subsets of the data sample, thereby accounting for different centre-of-mass energies at which the data have been taken. The absolute momentum scale of the experiment is known to $\pm 0.15\%$ [15], as determined from reconstructed $K_S^0$ mesons in various momentum and angular intervals, leading to $\delta m_\tau = 1.2$ MeV/$c^2$. The fit procedure has been checked by varying the fit region, allowing for different background contributions, using different parametrizations to model the simulated $m_\tau^*$ spectrum and accounting for possible deviations between the measured and simulated $3\pi$ mass spectra. The latter test has been performed since the shape of the threshold behaviour visible in the $m_\tau^*$ spectrum depends slightly on the $3\pi$ mass [#3]. The extracted $m_\tau$ values were stable at a level of $\delta m_\tau = 0.5$ MeV/$c^2$.

From these considerations, the systematic error on the fitted $\tau$ mass is determined to be $\sigma_{\text{sys}}(m_\tau) = 1.4$ MeV/$c^2$ by adding each individual error quadratically, leading to a final tau mass result of

$$m_\tau = 1776.3 \pm 2.4 \pm 1.4 \text{ MeV}/c^2.$$

Adding statistical and systematic errors in quadrature yields a total error of $\sigma_{\text{tot}}(m_\tau) = 2.8$ MeV/$c^2$, which is comparable to the error of the present world average $\sigma_{\text{PDG}}(m_\tau) = {}^{+2.7}_{-3.6}$ MeV/$c^2$ [1]. The central value of our measurement is smaller than the world average by 7.8 MeV/$c^2$, a discrepancy of about 1.7 standard deviations. No attempt has been made to calculate a new world average using our measurement since all previous measurements are based on a different

#3 The determination of $m_\tau$ does not rely on events where $m_{3\pi} \approx m_\tau$.

method, the determination of the cross section $\sigma_{\tau\tau} = \sigma(e^+e^- \to \tau^+\tau^-)$ close to the production threshold.

The measurement of the $\tau$ mass presented in this paper gives first evidence that the $\tau$ mass is significantly lower than has been previously inferred [#4]. Using our measured $\tau$ mass for the calculation of the theoretically expected branching ratio $(B_e)_{\text{theor}}$ for the decay $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ yields $(B_e)_{\text{theor}} = (18.5 \pm 0.4)\%$. Thus, evidence for a possible violation of the lepton universality becomes weaker and appears now to have a significance of 1.7 standard deviations.

The downward shift in the $\tau$ mass by $\delta m_\tau = 7.8$ MeV/$c^2$ also effects the upper limit on the mass of the $\tau$ neutrino. In 1987 we reported an improved upper limit on the $\nu_\tau$-mass of $m_{\nu_\tau} < 35$ MeV/$c^2$ at 95% confidence level [4]. The limit had been obtained from an analysis of the invariant $5\pi$ mass spectrum of the decay $\tau^- \to \pi^-\pi^-\pi^-\pi^+\pi^+\nu_\tau$. Since 1987 the available data sample has been enlarged, corresponding now to an integrated luminosity of 387 pb$^{-1}$ compared to 197 pb$^{-1}$ in 1987. In order to gain more information about the mass of the $\nu_\tau$, the analysis has been repeated. Including the old data, 20 (12) [#5] events are now selected, from which 19 (11) were used to determine the upper limit on the mass of the $\nu_\tau$. As discussed in our previous publication [4] the event with the highest $5\pi$ mass has been removed in order to account for possible uncertainties in the background determination.

The invariant mass spectrum of the 20 events is shown in fig. 6. Also shown in this figure is the expectation for a phase-space decay weighted by the weak matrix element, which is in reasonable agreement with the data. In addition, it can be seen that for the new data sample no event with a $5\pi$ mass close to the end point has been recorded. Therefore, the analysis of the $5\pi$ mass spectrum yields no change of the limit on the $\nu_\tau$ despite the increase of data sample's size; it remains at $m_{\nu_\tau} < 35$ MeV/$c^2$ (95% CL), assuming a $\tau$ mass of 1.7841 GeV/$c^2$. Using the $\tau$ mass obtained in this analysis as the end point of the $5\pi$ mass spectrum the revised upper limit on $m_{\nu_\tau}$ is determined to be

$$m_{\nu_\tau} < 31 \text{ MeV}/c^2,$$

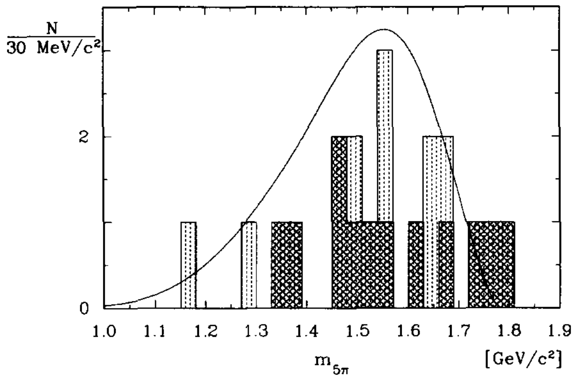


Fig. 6. Measured invariant $5\pi$ mass spectrum (histogram), where the hatched part displays the result of our previous analysis (see text). The curve corresponds to the expected shape of a phase-space decay weighted with the weak matrix element (assuming $m_{\nu_\tau} = 0$ MeV/$c^2$). Note that the curve has not been normalized to the data.

at the 95% confidence level.

In summary, the mass of the $\tau$ lepton has been measured, using a newly developed pseudomass method, to be $m_\tau = 1776.3 \pm 2.4 \pm 1.4$ MeV/$c^2$, representing a decrease in $m_\tau$ in comparison with the previous world average. Indications of a possible violation of lepton universality become less significant using this lower $\tau$ mass. Our measurement of $m_\tau$ also leads to a revised upper limit on the mass of the $\tau$ neutrino of $m_{\nu_\tau} < 31$ MeV/$c^2$ at the 95% confidence level.

It is a pleasure to thank U. Djuanda, E. Konrad, E. Michel, and W. Reinsch for their competent technical help in running the experiment and processing the data. We thank Dr. H. Nesemann, B. Sarau, and the DORIS group for the excellent operation of the storage ring. The visiting groups wish to thank the DESY directorate for the support and kind hospitality extended to them.

#4 The BES Collaboration reported [16] a $\tau$ mass measurement of $m_\tau = 1776.9 \pm 0.3 \pm 0.4$ MeV/$c^2$.

#5 The numbers in parantheses correspond to the analysis of 1987.

## References

[1] Particle Data Group, J.J. Hernández et al., Review of particle properties, Phys. Lett. B 239 (1990) 1.
[2] DELCO Collab., W. Bacino et al., Phys. Rev. Lett. 41 (1978) 13.
[3] A.A. Zholents et al., Phys. Lett. B 96 (1980) 214.
[4] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 202 (1988) 149.

[5] W.J. Marciano and A. Sirlin, Phys. Rev. Lett. 61 (1988) 1815.
[6] M.V. Danilov, plenary talk, in: Proc. LP–HEP91 Conf. (Geneva, Switzerland, July 1991), ITEP preprint ITEP-9-92 (1992), to appear.
[7] E. Ma, S. Pakvasa and S.F. Tuan, Particle World 3 (1992) 27.
[8] This ARGUS measurement has been first presented at the XXVIIth Rencontres de Moriond (Les Arcs, France, March 1992) and at the spring meeting of the German Physical Society DPG (Berlin, FRG, March–April 1992).
[9] ARGUS Collab., H. Albrecht et al., Nucl. Instrum. Methods A 275 (1989) 1.
[10] ARGUS Collab., H. Albrecht et al., Z. Phys. C 41 (1988) 405.
[11] S. Jadach and Z. Was, Comput. Phys. Commun. 36 (1985) 191; Acta Phys. Polon. B 16 (1985) 483 (E); CERN preprint CERN-TH-5855/90 (1990);
S. Jadach, J.H. Kühn and Z. Was, CERN preprint CERN-TH-5856/90 (1990).
[12] B. Andersson et al., Phys. Rep. 97 (1983) 31.
[13] ARGUS Collab., H. Albrecht et al., Z. Phys. C 33 (1986) 7.
[14] D.P. Barber et al., Phys. Lett. B 135 (1984) 498.
[15] ARGUS Collab., H. Albrecht et al., Phys. Lett. B 163 (1985) 404.
[16] BES Collab., at Spring Meeting APS (American Physical Society, Washington, DC, USA, April 1992).