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The first measurement of the Michel parameter η in τ decays

ARGUS Collaboration

H. Albrecht [a], T. Hamacher [a], R.P. Hofmann [a], T. Kirchhoff [a], R. Mankel [a,1], A. Nau [a], S. Nowak [a,1], H. Schröder [a], H.D. Schulz [a], M. Walter [a,1], R. Wurth [a], C. Hast [b], H. Kapitza [b], H. Kolanoski [b], A. Kosche [b], A. Lange [b], A. Lindner [b], M. Schieber [b], T. Siegmund [b], B. Spaan [b], H. Thurn [b], D. Töpfer [b], D. Wegener [b], P. Eckstein [c], K.R. Schubert [c], R. Schwierz [c], R. Waldi [c], K. Reim [d], H. Wegener [d], R. Eckmann [e], H. Kuipers [e], O. Mai [e], R. Mundt [e], T. Oest [e], R. Reiner [e], W. Schmidt-Parzefall [e], J. Stiewe [f], S. Werner [f], K. Ehret [g], W. Hofmann [g], A. Hüpper [g], K.T. Knöpfle [g], J. Spengler [g], P. Krieger [h,6], D.B. MacFarlane [h,7], J.D. Prentice [h,6], P.R.B. Saull [h,7], K. Tzamariudaki [h,7], R.G. Van de Water [h,6], T.-S. Yoon [h,6], C. Frankl [i], D. Reßing [i], M. Schmidtler [i], M. Schneider [i], S. Weseler [i], G. Kernel [j], P. Križan [j], E. Križnič [j], T. Podobnik [j], T. Živko [j], V. Balagura [k], I. Belyaev [k], S. Chechelnitsky [k], M. Danilov [k], A. Droutskoy [k], Yu. Gershtein [k], A. Golutvin [k], I. Korolko [k], G. Kostina [k], D. Litvintsev [k], V. Lubimov [k], P. Pakhlov [k], S. Semenov [k], A. Snizhko [k], I. Tichomirov [k], Yu. Zaitsev [k]

[a] *DESY, Hamburg, Germany*
[b] *Institut für Physik, Universität Dortmund, Germany* [2]
[c] *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Germany* [3]
[d] *Physikalisches Institut, Universität Erlangen-Nürnberg, Germany* [4]
[e] *II. Institut für Experimentalphysik, Universität Hamburg, Germany*
[f] *Institut für Hochenergiephysik, Universität Heidelberg, Germany* [5]
[g] *Max-Planck-Institut für Kernphysik, Heidelberg, Germany*
[h] *Institute of Particle Physics, Canada* [8]
[i] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, Germany* [9]
[j] *Institut J. Stefan and Oddelek za fiziko, Univerza v Ljubljani, Ljubljana, Slovenia* [10]
[k] *Institute of Theoretical and Experimental Physics, Moscow, Russia*

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Abstract

Using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY, we have studied lepton energy spectra in τ decays. We present a "pseudo-rest-frame" technique in which the second τ in the event, decaying into a heavy hadronic system, is used as reference. This method allows for the first measurement of the Michel Parameter η in τ decays. We also determine the Michel Parameter ρ in $\tau \to e\bar{\nu}\nu$ decays with a precision comparable to the present world average. The measured values of the parameters $\rho = 0.735 \pm 0.036 \pm 0.020$ and $\eta = 0.03 \pm 0.18 \pm 0.12$ are in good agreement with standard V-A coupling at the τ-ν-W vertex.

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Michel parameters [1–3] describing the space-time structure of the weak leptonic decays have been determined with high accuracy [4]. All values are in perfect agreement with the Standard Model predictions. The τ lepton discovered in 1975 [5], with its two leptonic decays $\tau \to e\bar{\nu}\nu$ and $\tau \to \mu\bar{\nu}\nu$, offers a unique opportunity to study the universality of the charged weak interaction.

Describing the leptonic τ decay by the most general four-fermion Hamiltonian we get the following matrix element [6]:

$$M = 4\frac{\sqrt{G_l}\sqrt{G_\tau}}{\sqrt{2}} \times \sum_{\substack{\gamma=S,V,T \\ \epsilon,\mu=R,L}} g^{\gamma}_{\epsilon\mu} \langle \bar{l}_\epsilon | \Gamma^\gamma | (\nu_l)_n \rangle \langle (\bar{\nu}_\tau)_m | \Gamma_\gamma | \tau_\mu \rangle$$

where γ labels the type of interaction: Scalar, Vector and Tensor. The indices ϵ and μ indicate the chiral projections of the lepton from the τ decay and the τ lepton, respectively. The helicities n and m for the ν_l and the ν_τ, respectively, are uniquely determined for given γ, ϵ, and μ. Neglecting radiative corrections and finite mass effects one can write the lepton momentum spectrum in the decay $\tau \to l\bar{\nu}\nu$ as:

$$\frac{d\Gamma_{\tau\to l\nu\bar{\nu}}}{d\Omega dx} \propto x^2 G_l G_\tau \Big\{ 12(1-x) + \rho\left(\frac{32x}{3} - 8\right) + \eta\,\frac{m_l}{m_\tau}\,\frac{24(1-x)}{x} - P_\tau\,\xi\,\cos\vartheta \left[4(1-x) + \delta\left(\frac{32x}{3} - 8\right)\right]\Big\} \qquad (1)$$

where $x = 2 \cdot E_l/m_\tau$ is the scaled lepton energy, ϑ the angle between the τ spin and the lepton momentum, and P_τ the τ polarization which vanishes in our case. The Michel parameters ρ, η, ξ, and δ are combinations of the ten complex coupling constants $g^{\gamma}_{\epsilon\mu}$ [6]. In the framework of the Standard Model, pure V-A interaction is expected with $\rho = 0.75, \eta = 0, \xi = 1$, and $\delta = 0.75$.

The experimental results of the last few years on $\rho = 0.727 \pm 0.033$ [7], on the τ neutrino helicity $h_{\nu_\tau} = -1.014 \pm 0.036$ [8–11], and on $|\xi| = 0.90 \pm 0.15 \pm 0.10$ [12] agree well with the Standard Model predictions.

We report here on a new precise measurement of the Michel Parameter ρ in $\tau \to e\bar{\nu}\nu$ decays together with the first measurement of the Michel Parameter η in $\tau \to \mu\bar{\nu}\nu$ decays. The analysis was performed with the ARGUS detector operating at the e^+e^- storage ring DORIS II. The data sample, corresponding to 455 pb^{-1} and containing about 450000 produced $\tau^+\tau^-$ events, was collected at center-of-mass energies between 9.5 and 10.6 GeV. The ARGUS detector and its trigger requirements have been described in detail elsewhere [14]. Particles were identified by coherently combining the available information from drift chamber, time-of-flight counters, electromagnetic calorimeter, and muon chambers into global likelihood ratios. Particles with a pion likelihood ratio larger than 5% were considered to be pions. For electrons, the corresponding ratio was required to exceed 80%. Muon identification was performed by selecting tracks with associated hits in one of the outer layers of the μ-chambers and an energy deposition in the shower counters less than 0.5 GeV.

While the shapes of both electron and muon momentum spectra in τ decays are sensitive to the Michel parameter ρ, the η parameter affects only the shape of the muon spectrum. The value of η has no effect upon the electron momentum spectrum because the term in expression (1) depending on η contains the very small factor m_e/m_τ. The dependence of electron and muon spectra on the Michel parameters in the τ rest frame is illustrated in Fig. 1 where we present two theoretical spectra calculated for different values of the parameter ρ (0.75 and 0) with a fixed value of $\eta = 0$ (Fig. 1A) and the same spectra representing different

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[2] Supported by the German Bundesministerium für Forschung und Technologie, under contract number 054DO51P.
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[4] Supported by the German Bundesministerium für Forschung und Technologie, under contract number 054ER12P.
[5] Supported by the German Bundesministerium für Forschung und Technologie, under contract number 055HD21P.
[6] University of Toronto, Toronto, Ontario, Canada.
[7] McGill University, Montreal, Quebec, Canada.
[8] Supported by the Natural Sciences and Engineering Research Council, Canada.
[9] Supported by the German Bundesministerium für Forschung und Technologie, under contract number 055KA11P.
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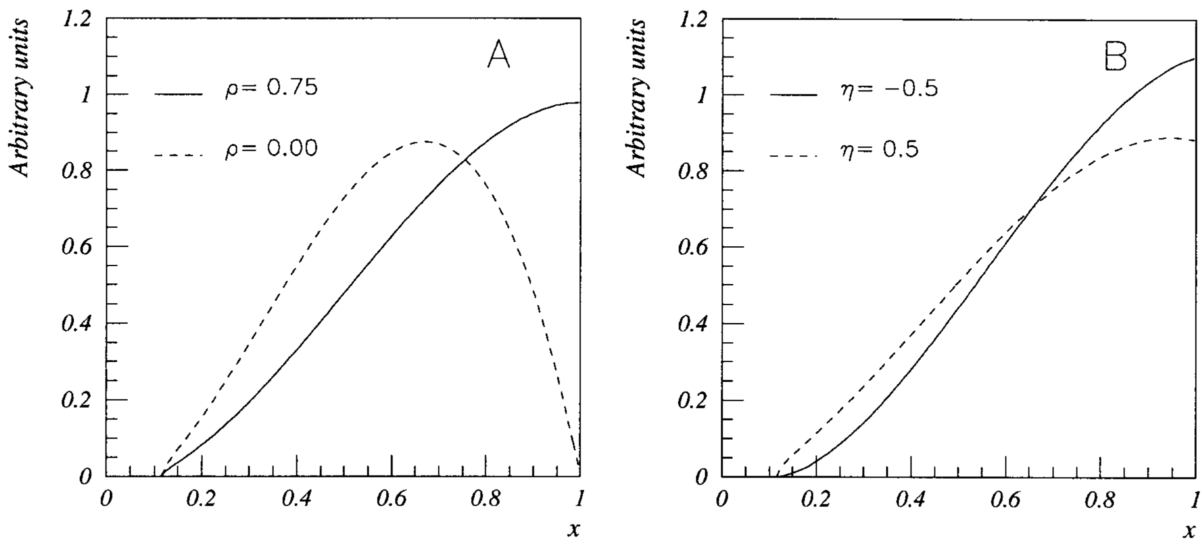

Fig. 1. Theoretical predictions for the electron spectrum with $\rho = 0.75$ and $\rho = 0$ (A) and of the muon spectrum with $\eta = -0.5$ and $\eta = 0.5$ (B)

values of the parameter η (-0.5 and 0.5) [11] with a fixed value of $\rho = 0.75$ (Fig. 1B). For all values of the Michel parameters the spectra are normalizied to equal number of events.

In the laboratory frame at $\sqrt{s}$ around 10 GeV the dependence of the lepton momentum spectra on the Michel parameters is substantially diluted by the Lorentz transformation. The maximum sensitivity to the Michel parameters ρ and η is achieved in the τ rest frame. In order to perform the Lorentz boost into the τ rest frame, the τ four-momentum has to be known. The τ energy is determined by the beam energy of the storage ring up to initial state radiative corrections. The direction of the τ cannot be exactly reconstructed since the neutrinos escape detection. It can, however, be inferred from the direction of the system of charged hadrons originating from the decay of the other τ lepton in the event which is required to decay into $(3h)^{\pm}$ or $(3h)^{\pm}\pi^0$. Due to its relatively high mass this system gives a good approximation to the flight direction of its parent τ [15] and, consequently, of the τ under study since both τ leptons are flying back-to-back. The rest system determined with this approximation is called "pseudo rest frame". Monte Carlo calculations show that this approximation works well both for $\tau \to (3h)^{\pm}\nu$ and $\tau \to (3h)^{\pm}\pi^0\nu$ decays. Both 3-prong modes were used for this analysis.

The expected momentum spectrum of electrons from $\tau \to e\bar{\nu}\nu$ decays in the τ pseudo rest frame is shown in Fig. 2A for two values of the parameter ρ. The statistical accuracy of the ρ parameter measurement which corresponds to the size of the ARGUS data sample has been estimated with Monte Carlo calculations. A series of statistically equivalent samples was generated with $\rho = 0.75$ and then fitted to theoretical models with arbitrary values of ρ. Performing this procedure both in the laboratory system and in the τ pseudo rest frame we have found that the accuracy of the ρ measurement is higher in the τ pseudo rest frame by a factor of 1.5. A similar investigation for the η parameter leads to a gain in precision by a factor of 2. The spectrum of muons from $\tau \to \mu\bar{\nu}\nu$ decays calculated in the pseudo rest frame for $\eta = -0.5$ and $\eta = 0.5$ with a fixed value of $\rho = 0.75$ is shown in Fig. 2B.

The selection criteria used for this analysis are similar to those applied in other investigations of τ decays

[11] In the most general case the parameter η can vary from -0.5 to 0.5 if the parameter ρ is fixed to 0.75

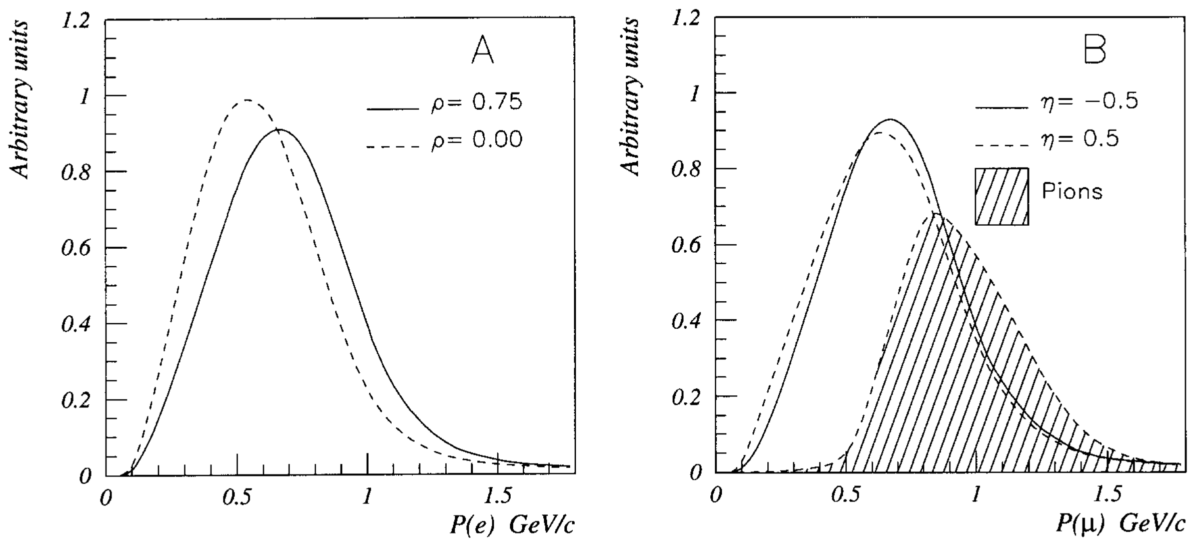

Fig. 2. Prediction for the spectrum of electrons with $\rho = 0.75$ and $\rho = 0$ (A) and for muons with $\eta = -0.5$ and $\eta = 0.5$ together with the pion spectrum of the decay $\tau \to \pi\nu$ (B)

[8,9,13]. Firstly, we have applied cuts common to $\tau \to e\bar{\nu}\nu$ and $\tau \to \mu\bar{\nu}\nu$ decays. Events were selected by requiring exactly four charged tracks originating from the interaction vertex with a charge sum of zero. Each track has to have a transverse momentum $p_t > 0.06$ GeV/c. Tau leptons are produced back-to-back with large momenta, so their decay products point into opposite hemispheres. To exploit this feature we require that the opening angle between the single-prong and each particle on the three-prong side should be larger than 90°. The opening angles between each pair of particles on the three-prong side are required to be less than 90°. To ensure good trigger conditions we require the one-prong track to point into the barrel region of the detector by restricting the polar angle to the region $|\cos\theta| < 0.75$.

Along with the decays of τ pairs there exist several physical processes which can satisfy the topological requirements described above:

(1) Radiative Bhabha- and $\mu\mu$-events with one photon converted into an e^+e^- pair close to the interaction vertex. These events are characterized by a small value of the summed transverse momentum ($P_t = |\sum p_t|$) and high energy deposited in the calorimeter E_{tot}.

(2) Two-photon interactions. Their products have small E_{tot} and P_t values since both initial electron and positron escape down the beam pipe.

(3) Exclusive resonance decays: $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-, \Upsilon(1S) \to l^+l^-$.

(4) Multihadron events.

To reduce these backgrounds to a negligible level the following cuts are used. The scalar momentum sum $\sum_{i=1}^{4} |\boldsymbol{p}_i|$ for all charged particles is required to be larger than 2.7 GeV/c and less than $0.92 \cdot \sqrt{s}$. Furthermore we apply a heuristic cut on the relationship between the transverse momentum balance and the total visible momentum of charged particles [9]. The energy deposited in the shower counters on the 3-prong side has to be smaller than 3.5 GeV/c. The angle $\theta^\pm$ between oppositely charged particles on the 3-prong side is required to satisfy the condition $\cos\theta^\pm < 0.992$. Photons are identified as energy deposits in the shower counters not associated with a charged track. Their energy has to exceed 80 MeV. In order to suppress multihadron background, at most two photons are allowed on the three-prong side of the event. These selection criteria reduce the backgrounds (1), (2), and (3) to the level of 5 events which are neglected in the further analysis.

Secondly, we have applied cuts specific to the decay channels $\tau \to e\bar{\nu}\nu$ and $\tau \to \mu\bar{\nu}\nu$, respectively. Electrons are required to have momenta above 0.4 GeV/c where the identification efficiency is around 90% or higher and the pion fake rate is 0.5% [14]. We restricted the number of photons on the one-prong side to be at most one with an energy not larger than 300 MeV. This leaves $\tau \to e\bar{\nu}\nu$ decays with final-state radiation unaffected while removing background from other single-prong τ-decays with neutral pions. Finally we have obtained 4725 electron candidates from our data sample. The remaining background was estimated to be 14 events coming from $\tau \to \pi\nu$ decays and 10 events from multihadron interactions.

For muons, conceivable background sources to $\tau \to \mu\bar{\nu}\nu$ from other τ decays consist of the following channels:

- The decay $\tau \to e\bar{\nu}\nu$ was suppressed by requiring the electron likelihood ratio of the charged track to be below 0.5.
- The decays $\tau^- \to \rho^-\nu, \rho^- \to \pi^-\pi^0$ and $\tau^- \to a_1^-\nu, a_1^- \to \pi^-\pi^0\pi^0$ were reduced by not allowing any photon on the one-prong side. The contribution from events with overlapping charged pions and photons was decreased by requiring the energy deposited in the calorimeter by the one-prong particle to be less than 0.5 GeV.
- At momenta in the pseudo rest frame, p_{ps}, below 0.6 GeV/c, the background contribution from $\tau \to \pi\nu$ events is very small for kinematical reasons (see Fig. 2B), and no muon identification is necessary. Pion-muon separation is essential for $p_{ps} > 0.6$ GeV/c. This region is mainly populated by muons with high momenta in the laboratory frame, p_{lab}. Thus, muons were accepted if they were positively identified and if p_{lab} exceeded 1.5 GeV/c where the identification efficiency is constant at a level of 80% and the pion fake rate is 2.5% [14]. Muon candidates with $p_{ps} > 0.6$ GeV/c and $p_{lab} < 1.5$ GeV/c are ignored, and the corresponding efficiency loss has been taken into account.

The number of events for the two parts of the muon spectrum (below and above 0.6 GeV/c in the pseudo rest frame) is presented in Table 1 along with the remaining backgrounds.

These backgrounds and the acceptance for the investigated τ decays were determined by a Monte Carlo simulation of the detector [16] using KORALB [17] for $\tau^+\tau^-$ pair generation with initial state radiation and TAUOLA [18] for τ decays including PHOTOS [19] for final state radiation. The generator has been modified for this analysis in order to generate $\tau \to l\bar{\nu}\nu$ decays with arbitrary values of Michel parameters ρ, η, ξ, and δ [20]. The trigger efficiency has been determined to be about 96% from the analysis of coincidences of different trigger types.

The efficiency corrected and background subtracted spectra of electrons and muons in the pseudo rest frame are shown in Figs. 3 and 4. The analysis of these spectra allows to deduce the Michel parameters. The electron spectrum which is not sensitive to η has been

Table 1
Backgrounds and number of events for the soft and hard part of the muon spectrum

	Reaction	Number of events
$p_{ps} < 0.6$ GeV/c	$\tau \to \rho\nu$	119 ± 12
	$\tau \to \pi\nu$	61 ± 8
	$e^+e^- \to q\bar{q}$	39 ± 7
	$\tau \to K^*\nu$	30 ± 10
	$\tau \to e\bar{\nu}\nu$	15 ± 5
	$\tau \to K\nu$	15 ± 6
	other τ decays	13 ± 7
	$\tau \to \mu\bar{\nu}\nu$	1741 ± 51
$p_{ps} > 0.6$ GeV/c	$\tau \to \pi\nu$	51 ± 11
	$\tau \to \rho\nu$	5 ± 3
	$e^+e^- \to q\bar{q}$	7 ± 3
	$\tau \to \mu\bar{\nu}\nu$	1774 ± 44

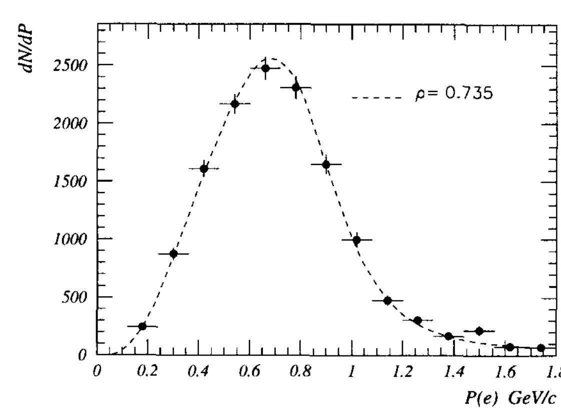

Fig. 3. Efficiency corrected electron spectrum in the τ pseudo rest frame (full points) and the result of the fit with the parameter $\rho = 0.735$ (dashed line)

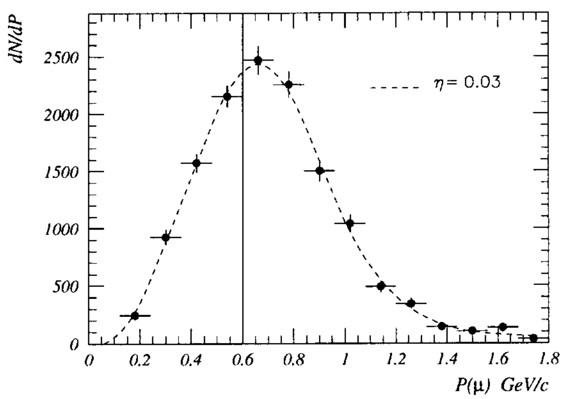

Fig. 4. Efficiency corrected muon spectrum in the τ pseudo rest frame (full points) and the result of the fit with the parameter $\eta = 0.03$ (dashed line)

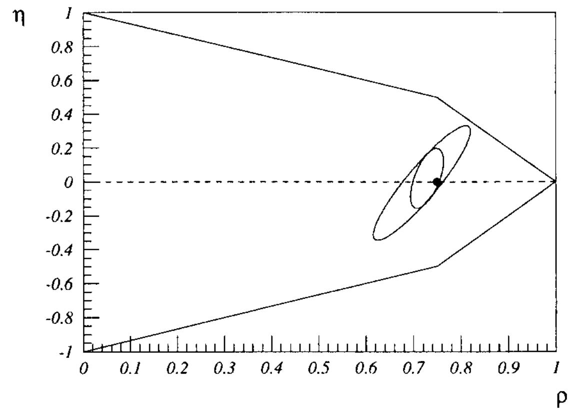

Fig. 5. Theoretical limits for the Michel parameters ρ and η for all possible couplings. The full point denotes the Standard Model prediction. The large ellipse represents the one sigma contour obtained for the parameters ρ and η from the muon spectrum only. The small ellipse represents the same contour obtained from the combined fit of electron and muon spectra.

used to determine the value of ρ.

Using the fact that the momentum spectrum depends linearly on the parameter ρ we fitted the data with a combination of the spectrum expected for $\rho = 0$ and the spectrum expected for $\rho = 0.75$, expressing the relative weights of both contributions in terms of the parameter ρ. The fit gives $\rho_e = 0.735 \pm 0.036$ in perfect agreement with the world average value and the V-A theory prediction. The accuracy of the new ARGUS measurement is comparable with that of the world average. A considerable improvement of the accuracy has been achieved by performing the analysis in the τ pseudo rest frame. The different sources of systematic errors on the ρ measurement are listed in Table 2 which includes the uncertainty from differently modelling the $\tau \to (3h)^{\pm}\nu$ and $\tau \to (3h)^{\pm}\pi^0\nu$ channels, in particular the error on their relative branching ratios. Adding them quadratically we obtained the final result $\rho_e = 0.735 \pm 0.036 \pm 0.020$.

To extract the second Michel Parameter η we have studied the pseudo rest frame momentum spectrum of muons from the decay $\tau \to \mu\bar{\nu}\nu$ (Fig. 4). In the most general case the muonic decay of τ lepton can differ by its space time structure from the electronic one. So one should try to determine the Michel parameters separately for these two decays. We have performed a three parameter fit of the muon spectrum with ρ, η and a normalization parameter. The fit results in $\rho_\mu = 0.712 \pm 0.103$ and $\eta_\mu = 0.01 \pm 0.34$ The one sigma contour of the error ellipse in the ρ-η plane is shown in Fig. 5 (the large ellipse) together with the theoretically allowed region for the fitted parameters. The fit of the muon spectrum itself does not allow to make restrictive constraints on the values of Michel parameters due to the high correlation between the fitted parameters. With the additional assumption about the equality of the parameter ρ in $\tau \to e\bar{\nu}\nu$ and $\tau \to \mu\bar{\nu}\nu$ decays, we have performed a combined fit of electron and muon spectra. The fit gives $\rho_{e\mu} = 0.732 \pm 0.034$ and $\eta_{e\mu} = 0.03 \pm 0.18$. The one sigma contour of the error ellipse is also shown in Fig. 5 (the small ellipse). The different sources of systematic errors are listed in Table 3. Summing the systematic uncertainties quadratically, we have obtained the Michel parameters $\rho_{e\mu} = 0.732 \pm 0.034 \pm 0.020$ and $\eta_{e\mu} = 0.03 \pm 0.18 \pm 0.12$.

Changing the value of the minimal energy deposition which is identified as photon within a 60–100 MeV range and the allowed value for

Table 2
Contributions to the systematic error on the ρ measurement from the decay $\tau \to e\bar{\nu}\nu$

Uncertainty	Systematic error
Electron identification efficiency	0.012
Trigger efficiency	0.010
$BR(\tau \to (3h)^{\pm}\nu)/BR(\tau \to (3h)^{\pm}\pi^0\nu)$	0.010
Backgrounds	0.004

Table 3
Contributions to the systematic error on the measurement of η from the decay $\tau \to \mu\bar{\nu}\nu$

Uncertainty	Systematic error
Muon identification efficiency	0.08
Backgrounds	0.08
Trigger efficiency	0.03
$\mathrm{BR}(\tau \to (3h)^{\pm}\nu)/\mathrm{BR}(\tau \to (3h)^{\pm}\pi^0\nu)$	0.03

the energy deposition of 1-prong tracks within a 400–800 MeV range (the last for selected muons), we have found that our results remain the same within the statistical errors.

To conclude, we have presented a "pseudo rest frame" method for measuring the energetic Michel parameters in leptonic τ decays. Analyzing the spectrum of electrons from $\tau \to e\bar{\nu}\nu$ decays, we have obtained the so far most precise value of the parameter $\rho_e = 0.735 \pm 0.036 \pm 0.020$ which replaces our earlier result in Ref. [13]. Using the additional assumption about the universality of τ decays, we have determined the second Michel Parameter $\eta_{e\mu} = 0.03 \pm 0.18 \pm 0.12$ from the combined fit of muon and electron spectra. Our results agree well with the Standard Model predictions of $\rho = 0.75$ and $\eta = 0$.

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