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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, Hamburg, Germany
C. Hast, H. Kolanoski, A. Kosche, A. Lange, A. Lindner, R. Mankel, M. Schieber, T. Siegmund, B. Spaan, H. Thurn, D. Töpfer, D. Wegener
Institut für Physik[2], Universität Dortmund, Germany
M. Bittner, P. Eckstein
Institut für Kern- und Teilchenphysik[3], Technische Universität Dresden, Germany
M. Paulini, K. Reim, H. Wegener
Physikalisches Institut[4], Universität Erlangen-Nürnberg, Germany
R. Eckmann, R. Mundt, T. Oest, R. Reiner, W. Schmidt-Parzefall
II. Institut für Experimentalphysik, Universität Hamburg, Germany
W. Funk, J. Stiewe, S. Werner
Institut für Hochenergiephysik[5], Universität Heidelberg, Germany
K. Ehret, W. Hofmann, A. Hüpper, S. Khan, K. T. Knöpfle, M. Seeger, J. Spengler
Max-Planck-Institut für Kernphysik, Heidelberg, Germany
D. I. Britton[6], C. E. K. Charlesworth[7], K. W. Edwards[8], E. R. F. Hyatt[6], H. Kapitza[8], P. Krieger[7], D. B. MacFarlane[6], P. M. Patel[6], J. D. Prentice[7], P. R. B. Saull[6], K. Tzamariudaki[6], R. G. Van de Water[7], T.-S. Yoon[7]
Institute of Particle Physics[9], Canada
D. Reßing, M. Schmidtler, M. Schneider, K. R. Schubert, K. Strahl, R. Waldi, S. Weseler
Institut für Experimentelle Kernphysik[10], Universität Karlsruhe, Germany
G. Kernel, P. Križan, E. Križnič, T. Podobnik, T. Živko
Institut J. Stefan and Oddelek za fiziko[11], Univerza v Ljubljani, Ljubljana, Slovenia
V. Balagura, I. Belyaev, S. Chechelnitsky, M. Danilov, A. Droutskoy, Yu. Gershtein, A. Golutvin, G. Kostina, D. Litvintsev, V. Lubimov, P. Pakhlov, F. Ratnikov, S. Semenov, A. Snizhko, V. Soloshenko, I. Tichomirov, Yu. Zaitsev
Institute of Theoretical and Experimental Physics, Moscow, Russia

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

Using the ARGUS detector at the e^+e^- storage ring DORIS II, we have determined the Michel parameters ρ and ξ of $\tau \to \mu\nu\overline{\nu}$ and $\tau \to e\nu\overline{\nu}$ decays. From a data sample with 333 events/pb around $\sqrt{s} = 10$ GeV, we select 3230 events $e^+e^- \to \tau^+\tau^- \to (\mu^\pm\nu\overline{\nu})(e^\mp\nu\overline{\nu})$ and determine ρ from the e and μ momentum spectra and ξ from the correlations between e and μ momenta. For ρ we obtain $\rho_{\tau\to e} = 0.79 \pm 0.08 \pm 0.06$ and $\rho_{\tau\to\mu} = 0.76 \pm 0.07 \pm 0.08$ in accordance with the V−A structure of the decays. The momentum correlations are only sensitive to the product $\xi_{\tau\to e} \cdot \xi_{\tau\to\mu}$. Setting $\xi_{\tau\to e} = \xi_{\tau\to\mu}$, we obtain $|\xi_\tau| = 0.90 \pm 0.15 \pm 0.10$ also in accordance with V−A. The updated decay fractions are $B(\tau \to e\nu\overline{\nu}) = (17.5 \pm 0.3 \pm 0.5)\%$ and $B(\tau \to \mu\nu\overline{\nu}) = (17.4 \pm 0.3 \pm 0.5)\%$.

Muon decay has been investigated for determining the space-time structure of the weak interaction for more than 40 years. The muon lifetime τ_μ and the four Michel parameters [1-4] ρ_μ, η_μ, ξ_μ, δ_μ have been determined to ±18 ppm, ±0.35%, ±1.3%, ±0.8%, and ±0.5%, respectively. The value of τ_μ fixes one of the 18 parameters of the Standard Model, and the other four obtained values are in perfect agreement with standard W-boson exchange, i. e. with a V−A structure predicting 3/4, 0, 1, and 3/4 for the Michel parameters. In spite of the good experimental precisions reached, an overall analysis with all possible weak couplings [5] leaves much room for decay contributions in addition to those from the standard W-boson. The much higher mass of the τ-lepton is, therefore, a strong motivation to search for deviations of $\Gamma(\tau \to \ell\nu\overline{\nu})$, ρ_τ, η_τ, ξ_τ, and δ_τ from their V−A predictions in $\tau \to e\nu\overline{\nu}$ and $\tau \to \mu\nu\overline{\nu}$ decays. Hadronic τ decays allow also a direct determination of the τ-neutrino helicity h_{ν_τ} and a test of its V−A value $h_{\nu_\tau} = -1$.

After the recent improvement on the precision of the τ-lepton mass [6, 7, 8], the measured rate $\Gamma(\tau \to e\nu\overline{\nu})$ agrees with its V−A prediction $\Gamma(\mu \to e\nu\overline{\nu}) \cdot (m_\tau/m_\mu)^5$. The results on ρ_τ with an experimental mean of 0.727 ± 0.033 [9] also support V−A, and the first direct observation of parity violation in τ decays, $h_{\nu_\tau} = -1.25 \pm 0.23^{+0.08}_{-0.15}$ [10, 11], demonstrates that the τ-neutrino is indeed left-handed. In this paper, we report on a measurement of the parity-violating Michel parameter ξ_τ from 3230 $\tau^+\tau^- \to (\mu^\pm\nu\overline{\nu})(e^\mp\nu\overline{\nu})$ events and on simultaneously obtained results for ρ_τ and $\Gamma(\tau \to \ell\nu\overline{\nu})$.

In the τ rest frame, neglecting radiative corrections and terms proportional to m_ℓ^2/m_τ^2, the energy spectrum of the charged decay lepton ℓ is given by

$$\frac{d\Gamma_{\tau\to\ell\nu\overline{\nu}}}{d\Omega dx} \propto x^2 \cdot \left\{12(1-x) + \rho_\tau \cdot \left(\frac{32x}{3} - 8\right) + \eta_\tau \cdot \frac{m_\ell}{m_\tau} \cdot \frac{24(1-x)}{x} \right.$$
$$\left. - P_\tau \cdot \xi_\tau \cdot \cos\vartheta \cdot \left[4(1-x) + \delta_\tau \cdot \left(\frac{32x}{3} - 8\right)\right]\right\} ,$$

where $x = 2 \cdot E_\ell/m_\tau$ is the scaled lepton energy, P_τ the τ polarisation, and ϑ the angle between the τ spin and the lepton momentum. With unpolarised τ-leptons, or integrating over the full ϑ range, the spectrum depends only on ρ_τ and η_τ. Measurements of the other two Michel parameters require polarised taus. Electron-positron annihilation produces τ pairs with simple correlations between the two τ spins. At high energies, there are only events with both spins parallel, either $(P_{\tau^+} = +1,\ P_{\tau^-} = -1)$ or $(P_{\tau^+} = -1,\ P_{\tau^-} = +1)$. Their probabilities are equal as long as Z^0 contributions are negligible. This spin structure correlates the two charged lepton momenta in

$\tau^+\tau^- \to (\mu^\pm\nu\overline{\nu})(e^\mp\nu\overline{\nu})$ events if both $\xi_{\tau\to e}$ and $\xi_{\tau\to\mu}$ are non-zero. An observation of e and μ momentum correlations gives a measurement of the product $\xi_{\tau\to e}\cdot\xi_{\tau\to\mu}$.

The experiment has been performed in e^+e^- annihilation at centre-of-mass energies around 10 GeV with the ARGUS detector at the storage ring DORIS II. The storage ring is described in [12], ARGUS and its performance in [13]. The data sample used for this analysis has been collected between 1985 and 1989, and its integrated luminosity has been determined to be (333 ± 10)/pb. This is not the full data sample of ARGUS as used in most other analyses. Since the analysis of two-prong events requires careful attention of the trigger thresholds, we have restricted the data sample to those run periods where the trigger efficiency was well under control.

Events are selected with exactly two tracks of opposite charge. Each track must have a transverse momentum above 80 MeV/c, a polar angle with $|\cos\theta| < 0.7$, and must point to the primary interaction region defined by the cuts $r < 1.5$ cm and $|z| < 5$ cm. Electron and muon candidates are selected by requiring a muon likelihood $L_\mu > 0.8$ and an electron likelihood $L_e < 0.1$ for muons and $L_e > 0.8$, $L_\mu < 0.1$ for electrons. In order to keep high efficiency and small misidentification probabilities, we require electrons to have $p > 0.65$ GeV/c and muons $p > 1.30$ GeV/c. Events with neutrinos are enriched by the two event cuts $\cos\alpha_{\rm acol} > -0.9997$ and $m_{\rm miss} > 2$ GeV/c^2, where the acollinearity is defined as $\cos\alpha_{\rm acol} = \vec{p}_e \cdot \vec{p}_\mu/(|\vec{p}_e|\cdot|\vec{p}_\mu|)$ and $m_{\rm miss}$ is the missing mass in the event obtained from $m^2_{\rm miss} = (\sqrt{s} - E_e - E_\mu)^2 - (\vec{p}_e + \vec{p}_\mu)^2$. There remain 3336 events after these cuts.

Electron identification is studied in radiative Bhabha events and converted photons [14]. The efficiency of the likelihood cuts as used in this analysis is found to increase from 0.40 at 0.65 GeV/c to 0.90 at 2 GeV/c and is nearly constant above 2 GeV/c. Electron misidentification of muons and pions is obtained from samples of cosmic muons and reconstructed K^0_S decays in multihadronic events. In the p_e and $\cos\theta$ region of the present analysis, pions fake an electron with 0.6% probability and muons fake electrons with a probability rapidly decreasing from 2.0% at 0.6 GeV/c to zero at 1.0 GeV/c. Muon efficiencies are obtained from a Monte Carlo simulation which is cross-checked with cosmic ray measurements. The efficiency rises from 0.45 at 1.3 GeV/c to 0.78 above 2 GeV/c. Misidentification from electrons and pions is obtained from the Bhabha and K^0_S samples mentioned above. Pions fake muons with a probability of 2.0% and electrons fake a muon with a probability decreasing from 1.5% at 1.3 GeV/c to 0.3% at 5 GeV/c. Very detailed studies are also performed for all levels of the ARGUS trigger as functions of time and particle angle and momentum. Single track efficiencies in the second level trigger vary between 0.75 and 0.92 during the selected run periods.

The geometrical acceptance for $\tau^+\tau^- \to (e\nu\overline{\nu})(\mu\nu\overline{\nu})$ events is obtained by the ARGUS detector simulation using KORAL-B [15] for $\tau^+\tau^-$ pair generation with initial state radiation and TAUOLA [16] for τ decays including PHOTOS [17] for final state radiation. Assuming standard V$-$A decays, the overall efficiency for $(e\nu\overline{\nu})(\mu\nu\overline{\nu})$ events, including geometry, selection, and reconstruction, is found to be (17.3 ± 0.1)%. Since TAUOLA contains only combinations of V and A for the decay structure, the generator has been modified for this analysis in order to generate $\tau \to \ell\nu\,\overline{\nu}$ decays with arbitrary values of ρ, η, ξ, and δ [18]. Monte Carlo simulations are also used to estimate the non $(e\nu\overline{\nu})(\mu\nu\overline{\nu})$ background in the selected event sample, Table 1 summarizes the results. The total background amounts to 106, leaving 3230 signal events.

Table 1: Estimated number of background events in the selected sample of 3336 $(e\nu\overline{\nu})(\mu\nu\overline{\nu})$ events. The notation $\pi\nu$ includes the decay modes $\pi\nu$ and $\rho\nu$. The errors include misidentification uncertainties and are therefore correlated.

$e^+e^- \to e^+e^-(\gamma)$ and $\mu^+\mu^-(\gamma)$	10 ± 27
$e^+e^- \to e^+e^-\mu^+\mu^-(\gamma)$	13 ± 5
$\tau^+\tau^- \to (e\nu\overline{\nu})(e\nu\overline{\nu})$	16 ± 5
$\tau^+\tau^- \to (\mu\nu\overline{\nu})(\mu\nu\overline{\nu})$	6 ± 2
$\tau^+\tau^- \to (\pi\nu)(e\nu\overline{\nu})$	45 ± 10
$\tau^+\tau^- \to (\pi\nu)(\mu\nu\overline{\nu})$	15 ± 3
$\tau^+\tau^- \to (\pi\nu)(\pi\nu)$	< 1

From the number of selected events, the energy-weighted integrated luminosity, the overall event acceptance, and the backgrounds in Table 1, we obtain the product of decay fractions, $B(\tau \to e\nu\overline{\nu}) \cdot B(\tau \to \mu\nu\overline{\nu}) = 0.0313 \pm 0.0006 \pm 0.0016$, where the first error is statistical and the second systematic. The systematic error is the quadratic sum of 3% from luminosity, 4% from muon acceptance and identification, 1% from electron identification, and less than 1% from geometry, trigger, reconstruction, and background. The result is in good agreement with our previous result [19] and with the world average [9]. The data samples used in the previous analysis [19] of $\tau^\pm\tau^\mp \to (e^\pm\nu\overline{\nu})(\mu^\mp\nu\overline{\nu})$ events and in the present analysis overlap partiallly. The combined result of both analyses is

$$B(\tau \to e\nu\overline{\nu}) \cdot B(\tau \to \mu\nu\overline{\nu}) = 0.0306 \pm 0.0005 \pm 0.0013 \;;$$

it replaces our earlier value [19]. Using the measured ratio of muons to electrons in ref. [19], $B(\tau \to \mu\nu\overline{\nu})/B(\tau \to e\nu\overline{\nu}) = 0.997 \pm 0.035 \pm 0.040$, together with our combined result for the product, we obtain

$$B(\tau \to e\nu\overline{\nu}) = (17.5 \pm 0.3 \pm 0.5)\% \;,$$
$$B(\tau \to \mu\nu\overline{\nu}) = (17.4 \pm 0.3 \pm 0.5)\% \;.$$

Using recent τ mass [7] and lifetime [9] values, this leads to

$$\tau_\tau/B(\tau \to e\nu\overline{\nu}) = (1.067 \pm 0.041) \cdot \tau_\mu \cdot (m_\mu/m_\tau)^5,$$

which fulfills the lepton universality of the Standard Model within 1.6 standard deviations.

The Michel parameters $\rho_{\tau\to\mu}$ and $\rho_{\tau\to e}$ are obtained from the muon and electron momentum spectra, shown in Fig. 1. In contrast to earlier analyses, $\rho_{\tau\to\mu}$ is not obtained from a fit with fixed $\eta_{\tau\to\mu} = 0$; instead both ρ and η are allowed to vary within their physical boundaries. This variation does not require a large number of Monte Carlo generations. Because of the linear dependence on ρ and η, only three sets are required, and the most general form of the momentum spectrum is given by

$$\frac{dN}{dp}(\rho,\eta) = (1 - \frac{4\rho}{3}) \cdot \frac{dN}{dp}(0,0) + (\frac{4\rho}{3} - \eta) \cdot \frac{dN}{dp}(\frac{3}{4},0) + \eta \cdot \frac{dN}{dp}(\frac{3}{4},1) \;.$$

The result of a χ^2 fit to the muon spectrum in Fig. 1a is shown in Fig. 2. The sensitivity on η is very weak because its contribution to the spectrum is weighted with m_μ/m_τ. The χ^2 value at the minimum is 72.3 for 74 degrees of freedom. For fixed $\eta_{\tau\to\mu} = 0$, we obtain $\rho_{\tau\to\mu} = 0.76 \pm 0.06$. Taking the weak correlation with $\eta_{\tau\to\mu}$ into account, we obtain

$$\rho_{\tau\to\mu} = 0.76 \pm 0.07 \pm 0.08 ,$$

where the systematic error has its dominant contributions from background subtraction (± 0.07) and from the momentum dependence of the muon identification (± 0.03). As seen in Fig. 2, the fit to the muon spectrum does not constrain $\eta_{\tau\to\mu}$; any value in the allowed range is within the one sigma contour. A χ^2 fit to the electron spectrum gives

$$\rho_{\tau\to e} = 0.79 \pm 0.08 \pm 0.06 .$$

The correlation with $\eta_{\tau\to e}$ is negligible because of m_e/m_τ. The systematic error is dominated by the background subtraction. The two ρ results agree well with our earlier value [20]. This was obtained from $\tau^\pm\tau^\mp \to (\ell^\pm \nu\overline{\nu})(\pi^\mp\pi^+\pi^-\nu)$ events; i. e. our old and new values are statistically independent.

The p_e vs. p_μ biplot as shown in Fig. 3 exhibits a slight preference for low-low and high-high momentum pairs, demonstrated by the correlation coefficient which is found to be

$$k = \frac{\sum(p_e - \overline{p_e}) \cdot (p_\mu - \overline{p_\mu})}{\sqrt{\sum(p_e - \overline{p_e})^2 \cdot \sum(p_\mu - \overline{p_\mu})^2}} = +0.065 \pm 0.020 .$$

The positive correlation is in fact generated by initial state radiation and by the product $\xi_{\tau\to e} \cdot \xi_{\tau\to\mu}$. The Monte Carlo simulation gives $k = +0.018$ for zero ξ values and $k = +0.055$ for the V $-$ A values $\xi_{\tau\to e} = \xi_{\tau\to\mu} = 1$. Being sensitive to the product, the experimental value of k proves that $\xi_{\tau\to e}$ and $\xi_{\tau\to\mu}$ have the same sign and are both either close to $+1$ or close to -1. More information is obtained from a two-dimensional fit to the p_e vs. p_μ distribution. Because of a slight additional increase in information, we actually perform a χ^2 fit in three dimensions with ten bins of p_e, ten bins of p_μ, and two bins of α_{acol}, above and below $\cos\alpha = -0.92$. The bin widths have been chosen on the basis of equal bin contents. The fit is only sensitive to the product of both ξ values, we therefore use electron-muon universality $\xi_\tau = \xi_{\tau\to e} = \xi_{\tau\to\mu}$. Since ($\rho$, η) and (ξ, δ) are uncorrelated, we perform the ξ fits with fixed values $\rho = 3/4$ and $\eta = 0$.

The χ^2 distribution of the ξ fit with fixed value $\delta = 3/4$ is shown in Fig. 4. It is obtained by comparing the numbers of events in 200 bins with the expectations from a total of 72,000 Monte Carlo events. There is again a technique which avoids the generation of separate Monte Carlo sets for each value of ξ. The program KORAL-B [15] works with ξ-dependent weights which are used for event selection on a hit-or-miss basis. In the analysis here, each Monte Carlo event surviving the ρ and η hit-or-miss is retained, and its weights for 100 values of ξ are stored for the χ^2 tests which compare the distributions of the data and the weighted Monte Carlo events. The χ^2 distribution is symmetric around $\xi = 0$ and has its minima at $|\xi| = 0.90$. The χ^2_{min} value of 202.2 matches well with the 198 degrees of freedom. The difference $\chi^2(\xi = 0) - \chi^2_{min}$ is 14.9, i. e. our event distribution excludes parity conservation with 3.9 standard deviations. With one standard deviation we obtain $|\xi| = 0.90 \pm 0.13$, which agrees well with the V $-$ A prediction $\xi = 1$.

A two-dimensional fit to only p_e and p_μ gives $|\xi| = 0.95 \pm 0.20$. Fits of Monte Carlo to Monte Carlo distributions prove that our applied method is bias-free. Increasing the low-momentum

cuts to 0.8 and 1.5 GeV/c for e and μ, respectively, changes ξ only in the statistically expected range. The systematic error has contributions from background, momentum dependence of the muon efficiency, and initial and final state radiation. Final state radiation is negligible, background subtraction gives $\Delta\xi = \pm 0.08$, muon efficiency ± 0.02, and initial state radiation ± 0.06. The latter contribution may be overestimated; it is obtained by changing the electric coupling constant α in KORAL-B to $1.01 \cdot \alpha$. Adding the contributions quadratically, our result is

$$|\xi_\tau| = 0.90 \pm 0.13 \pm 0.10 ,$$

where the parameter δ_τ is fixed at its V $-$ A value $\delta_\tau = 3/4$. Varying δ_τ in its allowed range, the statistical error is estimated to increase to ± 0.15. Our final result with free δ_τ is

$$|\xi_\tau| = 0.90 \pm 0.15 \pm 0.10 .$$

The momentum-momentum correlation for determining ξ_τ is a scalar observable and can, therefore, not be parity-violating. This is reflected by the fact that our observation is in as good agreement with $(V + A) \cdot (V + A)$, $\xi_\tau = -1$, as with $(V - A) \cdot (V - A)$, $\xi_\tau = +1$. However, the source for $\xi_\tau \neq 0$ must be parity violation; the electron (or muon) momentum is correlated with the tau spin, and this pseudoscalar is non-zero. Measurements at LEP determine the sign of ξ_τ. Following a recent analysis of Privitera [21], the mean values of the four LEP experiments [22, 23, 24, 25] for $\xi_\tau \cdot P_\tau$ and $h_{\nu_\tau} \cdot P_\tau$ are -0.089 ± 0.054 and 0.143 ± 0.028, respectively, where P_τ is the tau polarisation in $Z^0 \to \tau^+\tau^-$, ξ_τ is the mean Michel parameter in $\tau \to e\nu\overline{\nu}$ and $\tau \to \mu\nu\overline{\nu}$ decays, and h_{ν_τ} the mean observed τ-neutrino helicity in $\tau \to \pi\nu$, $\tau \to \rho\nu$, and $\tau \to a_1\nu$. Combining this with the ARGUS measurement $h_{\nu_\tau} = -1.25 \pm 0.23^{+0.08}_{-0.15}$ [11] gives the model-independent result $\xi_\tau(\text{LEP}) = +0.78 \pm 0.52$ which is 3.4 standard deviations from -1.

To conclude, we have determined updated values for the purely leptonic decay fractions of the tau lepton, $B(\tau \to e\nu\overline{\nu}) = (17.5 \pm 0.3 \pm 0.5)\%$, $B(\tau \to \mu\nu\overline{\nu}) = (17.4 \pm 0.3 \pm 0.5)\%$, which replace our earlier results in ref. [19]. The new values are in agreement with the Standard Model expectation. Using recent τ mass [7] and lifetime [9] values, we obtain $\tau_\tau / B(\tau \to e\nu\overline{\nu}) = (1.067 \pm 0.041) \cdot \tau_\mu \cdot (m_\mu/m_\tau)^5$. Our Michel parameter results $\rho_{\tau\to e} = 0.79 \pm 0.08 \pm 0.06$ and $\rho_{\tau\to\mu} = 0.76 \pm 0.07 \pm 0.08$ are statistically independent from our earlier one in ref. [20] and agree well with the Standard Model value $\rho = 3/4$. The asymmetry parameter is found to be $|\xi_\tau| = 0.90 \pm 0.15 \pm 0.10$ in also good agreement with the Standard Model value $\xi = 1$.

Note added after completion: The analysis has been performed with the KORAL-B version of 1992. We have carefully controlled, not by repeating the full analysis but by comparing different Monte Carlo samples on the generator level, that the new KORAL-B version of May 1993 leads to only negligible shifts in the fit result for ξ_τ. The values of $B(\tau \to \ell\nu\overline{\nu})$ and ρ_τ are not affected by the change in KORAL-B.

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Figure Captions

Fig. 1: Observed momentum spectra of muons (a) and electrons (b) after background subtraction, without acceptance correction, in arbitrary units. The solid curves are the best fit results with free parameters $\rho_{\tau\to e}$, $\eta_{\tau\to e}$ and $\rho_{\tau\to\mu}$, $\eta_{\tau\to\mu}$, respectively. The dashed curves, in order to demonstrate the sensitivities on ρ, are drawn with $\rho = \eta = 0$.

Fig. 2: The dotted polygon shows the allowed range for ρ and η with arbitrary V, A, S, P, and T couplings. The solid point is the best fit for (ρ, η) from the muon momentum spectrum, and the two nearly parallel bands are the one and two sigma contours around this point. The bands show that any η value in the allowed range is compatible with our data set. Because of the weak ρ-η correlation, our quoted error on ρ with free η is slightly larger than the error on ρ with $\eta = 0$ as shown by the open point.

Fig. 3: Electron vs. muon momentum in the 3336 selected $(\mu\nu\overline{\nu})(e\nu\overline{\nu})$ events.

Fig. 4: Dependence of χ^2 on $\xi_\tau = \xi_{\tau\to e} = \xi_{\tau\to\mu}$ as result of a fit to the three-dimensional $p_e, p_\mu, \alpha_{acol}$ distribution.

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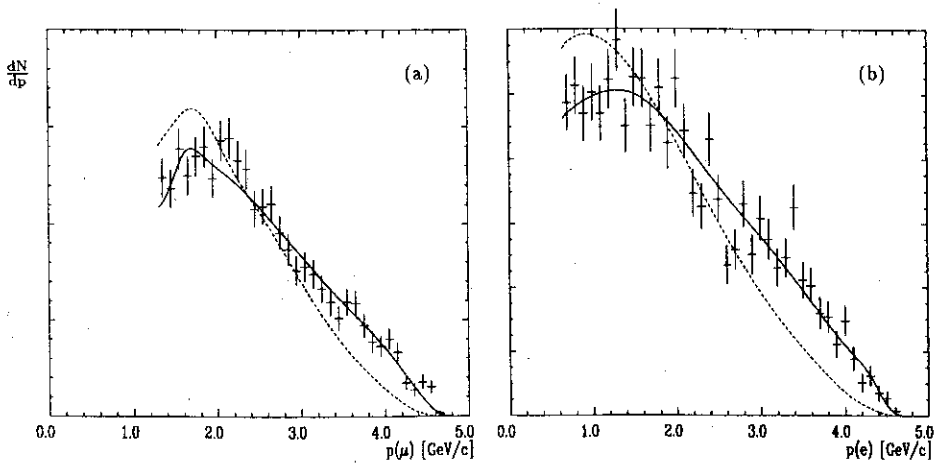


Fig. 1

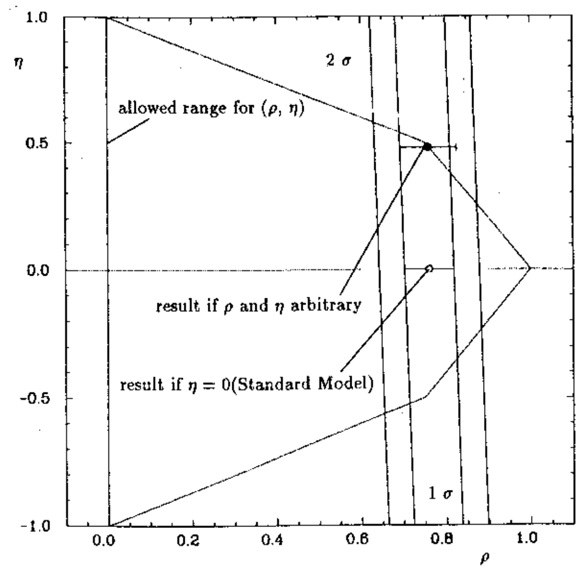
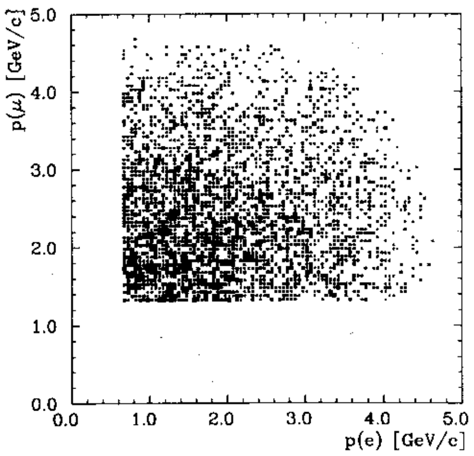
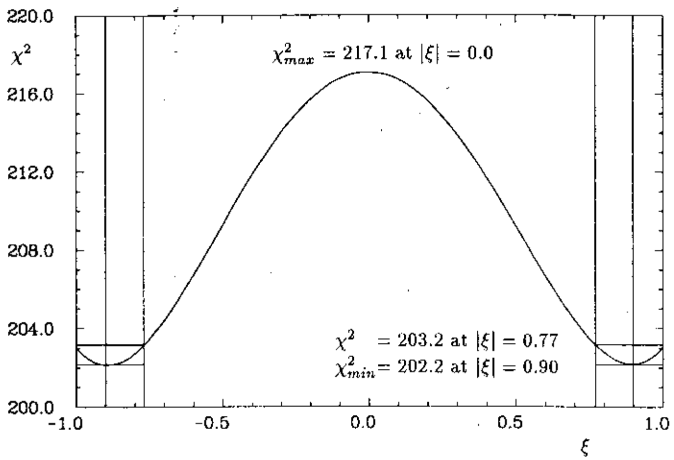


Fig. 2



p(μ) [GeV/c]
5.0
4.0
3.0
2.0
1.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
p(e) [GeV/c]

Fig. 3



220.0
χ^2
216.0
212.0
208.0
204.0
200.0
-1.0
-0.5
0.0
0.5
1.0
ξ
$\chi^2_{max} = 217.1$ at $|\xi| = 0.0$
$\chi^2 \quad = 203.2$ at $|\xi| = 0.77$
$\chi^2_{min} = 202.2$ at $|\xi| = 0.90$

Fig. 4