Determination of the tau-neutrino helicity

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Using the ARGUS detector at the DORIS II e^+e^- storage ring we measured for the first time the τ neutrino helicity from a parity violating asymmetry in the τ decay into three charged pions. From the measured asymmetry we derived the normalized product of the axial and vector coupling constant $2g_A g_V/(g_A^2+g_V^2)=1.14\pm0.34\,^{+0.34}_{-0.17}$, which is in good agreement with the standard model prediction.

Since the discovery of the τ lepton [1] the properties of the τ and of its accompanying neutrino have been extensively investigated [2]. Except for some inconsistencies in the measured exclusive and inclusive one-prong branching ratios, all observations are in agreement with the assumption that the τ is a sequential lepton. A crucial test of the standard model is the experimental verification of the $V-A$ structure of the weak τ decays. The standard model puts the left-handed τ and ν_τ in a doublet and the right-handed τ in a singlet. Hence, if the τ neutrino is massless, it will only occur in a left-handed helicity state. The complete Lorentz structure of leptonic τ decays can be fixed by the measurement of six parameters [3]. Except for the sign of the τ neutrino's helicity all parameters can be measured in leptonic τ decays. Up to now only the Michel parameter ρ has been measured [4]. These measurements, though in agreement with the $V-A$ value $\rho=\frac{3}{4}$, do not uniquely determine the interaction since with a most general ansatz other combinations of scalar, tensor and vector couplings can yield the same value [3]. In this paper we report on the first determination of the τ neutrino helicity as analysed in the decay [#1]

$$\tau^- \to a_1^-(1270)\nu_\tau \to \pi^+\pi^-\pi^-\nu_\tau\,. \qquad (1)$$

As shown by Kühn and Wagner [5] the ν_τ helicity can be determined from a parity violating term in the decay (1) where the subsequent strong decay is used to analyse the helicity. In the following we summarize the formulae used in this analysis since ref. [5] contains some misprints. We derive the formulae for the τ^- decay but they hold also for the τ^+ decay except for a change of sign in the parity violating term.

The a_1^- (1270) is known to decay predominantly via an S-wave $\rho^0\pi^-$ intermediate state into three pions:

$$a_1^- \to \rho^0\pi^- \to \pi^+\pi_1^-\pi_2^-\,. \qquad (2)$$

There are two possibilities to form a ρ^0 candidate ($\pi^+\pi_1^-$ and $\pi^+\pi_2^-$) and the corresponding amplitudes have to be added coherently. The interference of these two amplitudes shows the parity violation which is sensitive to the helicity of the τ neutrino. Following refs. [5,6] we use the isobar model for the a_1 decay and require the

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

hadronic axial vector current to be conserved: $Q^\mu J_\mu = 0$. The lowest dimensional Born term for the three-pion current is then

$$J_\mu = G(Q^2)\left[\left(q_{1\mu} - q_{+\mu} - \frac{Q(q_1 - q_+)}{Q^2} Q_\mu\right) B(s_2) + (1 \leftrightarrow 2)\right], \tag{3}$$

where q_1, q_2, q_+ and $Q = q_1 + q_2 + q_+$ denote the four-momenta of the pions π_1^-, π_2^-, π^+ and of the three-pion system. From these vectors we construct the two-pion invariant masses $s_{1,2} = (q_{2,1} + q_+)^2$ and $s_3 = (q_1 + q_2)^2$. The Breit–Wigner amplitudes for the ρ resonances are defined as

$$B(s_i) = (s_i - m_\rho^2 - \mathrm{i} m_\rho \Gamma_\rho)^{-1} . \tag{4}$$

The function $G(Q^2)$ describes the mass distribution of the three-pion system, known to be dominated by the a_1^- resonance. In the three-pion rest frame the square of the decay matrix element is given by

$$\omega_- = (m_\tau^2 - Q^2)\,|G(Q^2)|^2$$
$$\times\left(\frac{m_\tau^2 - Q^2}{Q^2}\,|\hat{\boldsymbol{p}}\cdot\boldsymbol{J}|^2 + |\boldsymbol{J}|^2 - 3\gamma_{\mathrm{AV}}\,\hat{\boldsymbol{p}}\cdot\hat{\boldsymbol{n}}\,\mathrm{Im}[B(s_1)B^*(s_2)]\,\sqrt{\frac{s_1 s_2 s_3 - m_\pi^2(Q^2 - m_\pi^2)^2}{Q^2}}\right). \tag{5}$$

The unit vectors $\hat{\boldsymbol{p}}$ and $\hat{\boldsymbol{n}}$ are defined in the three-pion rest frame and denote the direction of the τ momentum and the normal to the three-pion plane, respectively. The last term is the crucial interference term which has to be measured. Note that in ref. [5] the quoted sign of this term is wrong [#2]. The interference term is proportional to the product of the axial and vector coupling constants of the charged weak current:

$$\gamma_{\mathrm{AV}} = 2 g_{\mathrm{A}} g_{\mathrm{V}} / (g_{\mathrm{A}}^2 + g_{\mathrm{V}}^2) , \tag{6}$$

with the sign convention $\gamma_{\mathrm{AV}} = +1$ $(g_{\mathrm{A}} = g_{\mathrm{V}} = +1)$ for the standard model left-handed leptons and $\gamma_{\mathrm{AV}} = -1$ $(g_{\mathrm{A}} = -g_{\mathrm{V}})$ for right-handed leptons. Since $\mathrm{Im}[B(s_1)B^*(s_2)] \sim s_1 - s_2$, the expression $\hat{\boldsymbol{p}}\cdot\hat{\boldsymbol{n}}\,\mathrm{Im}[B(s_1)B^*(s_2)]$ does not change sign by interchanging π_1^- and π_2^-. This defines, despite of the two identical pions, a unique orientation of the three-pion plane. Equivalently, the orientation of the plane can be defined by turning the slower of the two negative pions into the direction of the faster one: $\hat{\boldsymbol{n}}(s_1 - s_2) \sim \boldsymbol{q}_{\mathrm{slow}} \times \boldsymbol{q}_{\mathrm{fast}}$. The matrix element squared (5) yields an asymmetry of the orientation of the pion plane with respect to the τ direction which is proportional to γ_{AV}.

The experimental determination of the asymmetry is complicated by the fact that the τ direction $\hat{\boldsymbol{p}}$ is not observable. Instead one can refer to the boost direction of the three-pion system $-\hat{\boldsymbol{Q}}$. The τ momentum is known to lie on a cone around $-\hat{\boldsymbol{Q}}$ with opening angle 2ψ, where ψ can be calculated from measurable quantities:

$$\cos\psi = -\hat{\boldsymbol{Q}}\cdot\hat{\boldsymbol{p}} = \frac{x(m_\tau^2 + Q^2) - 2Q^2}{(m_\tau^2 - Q^2)\sqrt{x^2 - 4Q^2/s}}, \tag{7}$$

where $\sqrt{s}$ is the e^+e^- center of mass energy and x the normalized hadronic energy in the laboratory frame, $x = E_{3\pi}/E_{\mathrm{beam}}$.

An observable quantity is the expectation value of the orientation of the three-pion plane with respect to $-\hat{\boldsymbol{Q}}$ as a function of x and Q^2:

$$a(x, Q^2) \equiv \langle -\hat{\boldsymbol{Q}}\cdot\hat{\boldsymbol{n}}\,\mathrm{sgn}(s_1 - s_2)\rangle = \frac{\int \mathrm{d\,LIPS}(Q; q_1, q_2, q_+)\,\omega_\mp\,(-\hat{\boldsymbol{Q}}\cdot\hat{\boldsymbol{n}})\,\mathrm{sgn}(s_1 - s_2)}{\int \mathrm{d\,LIPS}(Q; q_1, q_2, q_+)\,\omega_\mp}$$
$$= \mp\gamma_{\mathrm{AV}}\cos\psi\,A(Q^2) . \tag{8}$$

[#2] The sign of the parity violating term in (5) has also been agreed on by Kühn [7].

The "−" sign applies for the τ^-, the "+" sign for τ^+. The x dependence is contained in $\cos\psi$; the asymmetry function $A(Q^2)$ is calculable:

$$A(Q^2)=\frac{3Q^2}{m_\tau^2+2Q^2}\,\frac{\int ds_1\,ds_2\,\mathrm{Im}[B(s_1)B(s_2)]\,\sqrt{[s_1s_2s_3-m_\pi^2(Q^2-m_\pi^2)^2]/Q^2}\,\mathrm{sgn}(s_1-s_2)}{\int ds_1\,ds_2\,(-J_\mu J^{*\mu})}. \tag{9}$$

Eqs. (8) and (9) indicate that the determination of γ_{AV} depends on assumptions about the hadronic current. Feindt [8] has shown that the amplitude (3) does not correspond to an S-wave transition but is a Q^2 dependent mixture of S- and D-waves. However, the asymmetry $A(Q^2)$ obtained for a pure S-wave matrix element does not differ severely from that predicted by Kühn and Wagner. For a pure D-wave matrix element, on the other hand, one finds an asymmetry with reversed sign. A D-wave admixture to the S-wave matrix element shows strong influence on the expected asymmetry. For the current value on the D/S amplitude ratio of -0.14 ± 0.03 (corresponding to a relative branching ratio of 2.2%) given by Isgur et al. [9] using our former analysis [10] Feindt estimated a change in the value of $A(Q^2)$ between −30% and +15% depending on Q^2.

In the following we describe the measurement of the expectation values (8) in the τ decay into three charged pions (1) and the determination of the vector–axial vector interference constant γ_{AV}.

The data were taken with the ARGUS detector at the e^+e^- storage ring DORIS II at DESY at center-of-mass energies between 9.4 and 10.6 GeV. The analysed sample corresponds to an integrated luminosity of 264 pb^{-1} which yields about 261 000 produced $\tau^+\tau^-$ pairs. The ARGUS detector is a 4π magnetic spectrometer described in detail elsewhere [11]. For this study photons were identified as neutral energy deposits in the electromagnetic calorimeter with energies larger than 80 MeV. Charged particle identification was made on the basis of specific ionisation in the drift chamber (dE/dx) and time-of-flight (TOF) measurements. This information was used to calculate, for all charged tracks, a likelihood ratio for each particle hypothesis (e, μ, π, K, p). All particle hypotheses with a likelihood ratio larger than 1% were accepted.

The event selection follows our previous analysis of the same final state [10]. Here we give only a summary of the cuts. We searched for τ^- decays into three charged pions according to reaction (1) in the 1–3-prong topology allowing the τ^+ to decay into $e^+\nu_e\bar\nu_\tau$, $\mu^+\nu_\mu\bar\nu_\tau$, $\pi^+\bar\nu_\tau$, $K^+\bar\nu_\tau$ or $\rho^+\bar\nu_\tau$. The selected events were required to have

- exactly four charged particles with total charge zero originating from the interaction region;
- a scalar momentum sum in the range $2.7\ \mathrm{GeV}/c\leqslant\sum_{i=1}^{4}|\boldsymbol{p}_i|\leqslant0.92\sqrt{s}$;
- one particle separated by an opening angle of more than 90° from each of the other three particles and by more than 120° from the momentum sum of the other three particles;
- the polar angle of the isolated particle satisfying the condition: $|\cos\theta_1|\leqslant0.75$;
- either no photon with $E_\gamma\geqslant80$ MeV or exactly one reconstructed π^0, which in combination with the isolated charged particle forms a ρ^+ candidate with mass between 0.54 and 1.0 GeV/c^2 and with an opening angle between the π^+ and π^0 of less than 53°;
- the opening angle between oppositely charged particles on the three-prong side larger than 7.25°;
- the shower counter energies deposited on the one-prong and on the three-prong side both smaller than $0.4\sqrt{s}$;
- all particles on the three-prong side in agreement with the pion hypothesis, the single-prong with either the electron, muon, pion or kaon hypothesis;
- $\cos\psi>0.2$.

The last cut reduces the background from $q\bar q$ and two-photon events. Although 35% of all a_1^- candidates are rejected by this cut, the result of the analysis is not affected since according to (8) events around $\cos\psi=0$ do not contribute to the asymmetry.

After these cuts a sample of 3899 $\tau^+\tau^-$ candidates remains which includes 18% background from the following sources:

– other τ decay modes, in particular $\tau^- \to \pi^+\pi^-\pi^-\pi^0\nu_\tau$: $(15.90 \pm 0.60 \pm 5.80)\%$,
– e^+e^- annihilation into hadrons: $(0.72 \pm 0.13)\%$,
– Bhabha scattering with converted photons: $(1.00 \pm 0.16)\%$,
– two-photon reactions: $(0.15 \pm 0.06)\%$.

The big systematic error on the background from other tau decay modes is due to the uncertainty of their branching ratios.

The methods to obtain these contributions and the influence of the background on the asymmetry measurement will be described below. Fig. 1a shows the three-pion mass distribution of the selected events where 3887 events are τ candidates with $m_{3\pi} < m_\tau$. The mass distribution of unlike-sign pion pair combinations (fig. 1b) shows a clear ρ peak with a combinatorial background which is approximately described by the like-sign combinations. As shown in our earlier analysis [10] both the three-pion and two-pion mass spectra are in good agreement with an a_1 dominance in the three-pion final state.

We now proceed to determine the parity violating asymmetry for the selected τ candidates. The expectation value (8) as a function of x and Q^2 is experimentally determined by

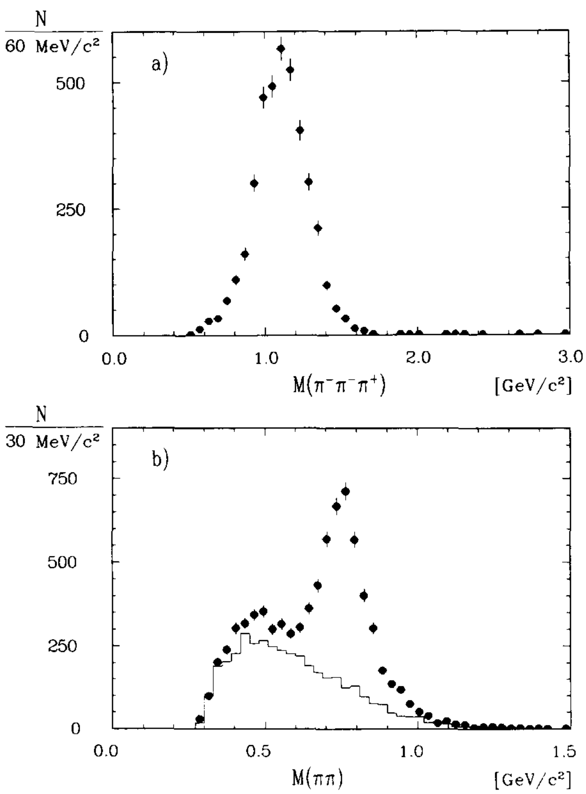

Fig. 1. (a) Three-pion mass distribution for the decay $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$. (b) Two-pion mass distribution: Full points: $\pi^+\pi^-$ (2 entries per event); histogram: $\pi^-\pi^-$ (1 entry per event).

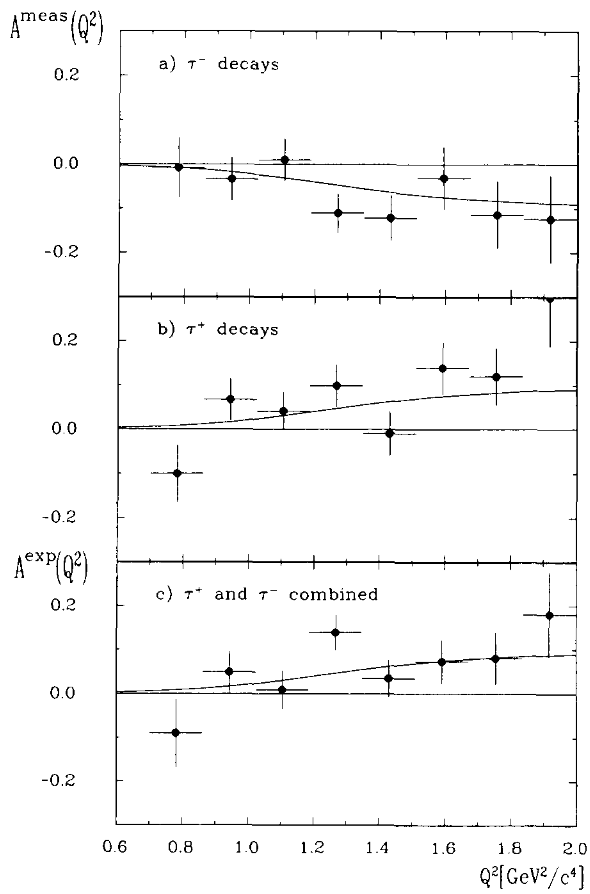

Fig. 2. (a) Measured $A(Q^2)$ for τ^- decays. (b) Measured $A(Q^2)$ for τ^+ decays. (c) Background corrected asymmetry $A^{\exp}(Q^2)$ for τ^- and τ^+ decays combined. The solid lines show the asymmetry function $A(Q^2)$ as predicted by Kühn and Wagner.

$$a^{\mathrm{meas}}(x, Q^2) = \frac{1}{n} \sum_{i=1}^{n} -\boldsymbol{Q}_i \cdot \hat{\boldsymbol{n}}_i \,\mathrm{sgn}(s_1 - s_2)_i \,, \tag{10}$$

where the sum runs over all events in an (x, Q^2) bin of size $\Delta x = 0.1$ and $\Delta Q^2 = 0.165\ \mathrm{GeV}^2/c^4$. The statistical errors of $a^{\mathrm{meas}}(x_j, Q^2)$ are determined as usual from the variance around the mean value. In each (x, Q^2) bin we determine $\langle \cos\psi \rangle$, the average of $\cos\psi$. By averaging over x, the Q^2 dependence of the asymmetry is

$$A^{\mathrm{meas}}(Q^2) = \sum_{j=1}^{n_x} \frac{1}{w_j^2} \frac{a^{\mathrm{meas}}(x_j, Q^2)}{\langle \cos\psi \rangle} \Big/ \sum_{j=1}^{n_x} \frac{1}{w_j^2} \,. \tag{11}$$

This expression is a weighted average over the x bins for a given Q^2 bin. The weights w_j are obtained from the variances of $a^{\mathrm{meas}}(x_j, Q^2)$ and $\cos\psi$ in each x bin. The measured asymmetries $A^{\mathrm{meas}}(Q^2)$ are plotted in figs. 2a and 2b for τ^- and τ^+ decays respectively. The average asymmetries in the interval $0.7 < Q^2 < 2.0\ \mathrm{GeV}^2/c^4$ are

$$\langle A^{\mathrm{meas}}(\tau^-) \rangle = -0.062 \pm 0.020, \quad \langle A^{\mathrm{meas}}(\tau^+) \rangle = 0.060 \pm 0.019 \,.$$

In both cases the experimentally determined asymmetries differ from zero by more than three standard deviations with signs as expected for standard left-handed ν_τ.

The measured asymmetries have to be corrected for the dilution due to the background. The corrections were determined for each background channel separately from appropriate data samples.

(1) Other τ decay modes, in particular $\tau^- \to \pi^+\pi^-\pi^-\pi^0\nu_\tau$: The absolute contribution was determined from Monte Carlo simulations taking the right composition of subresonances into account. To determine the asymmetry for this background channel we used a data sample of 1463 reconstructed τ^- decays into $\pi^+\pi^-\pi^-\pi^0\nu_\tau$ where the π^0 was seen in the detector. The averaged asymmetry determined from the three charged pions yielded 0.010 ± 0.006 whereby τ^+ (0.009 ± 0.0075) and τ^- (-0.012 ± 0.010) decays were combined with a reversed sign for the τ^- asymmetry.

(2) One-photon annihilation into hadrons: The absolute contribution was determined from Monte Carlo simulations normalized to the background above the τ mass $(1.8 < m_{3\pi} < 3.0\ \mathrm{GeV}/c^2)$. The final data sample contains 28 $q\bar{q}$ events which have an negligible effect on the asymmetry.

(3) Bhabha scattering with converted photons: This background contribution was studied from data itself using events with reconstructed converted photons. An average asymmetry of $(9 \pm 4) \times 10^{-5}$ was obtained.

(4) Two-photon reactions: The rejection of two-photon events was studied by Monte Carlo simulation. From the analysis of this background channel we find only six events, which do not contribute to the asymmetry.

Since the background contributions are found to have vanishing or very small asymmetries, the corrections tend to increase the measured asymmetry. Fig. 2c shows the combined background corrected asymmetry A^{exp} for τ^+ and τ^- as a function of Q^2. The τ^- asymmetry enters here with a reversed sign. The combined average asymmetry is $\langle A^{\mathrm{exp}} \rangle = 0.063 \pm 0.0155$. This measurement establishes parity violation (independent of any model) in the τ decay (1) with a significance of four standard deviations.

In order to determine γ_{AV} quantitatively we write according to (8)

$$A^{\mathrm{exp}}(Q^2) = \gamma_{\mathrm{AV}} A^{\mathrm{eff}}(Q^2) \,. \tag{12}$$

$A^{\mathrm{exp}}(Q^2)$ is the observed asymmetry corrected for background. $A^{\mathrm{eff}}(Q^2)$ is the acceptance corrected asymmetry function corresponding to $A(Q^2)$ in (9) and is obtained by evaluating the integrals in (9) over the acceptance volume. The integration is done by Monte Carlo methods including a full simulation of the detector and the selection efficiencies. The event generator treated the decays of the τ^+ and τ^- without correlations. For the three-prong decay the matrix element (5) was used, which also contains the asymmetry term. Fig. 3 shows that the Q^2 dependence of the asymmetry obtained at the generator level is within the statistical uncertainties the same as that obtained after including acceptance effects. The Monte Carlo procedure was extensively tested. In particular, it was made sure that the derived asymmetry function is proportional to the parameter γ_{AV} chosen

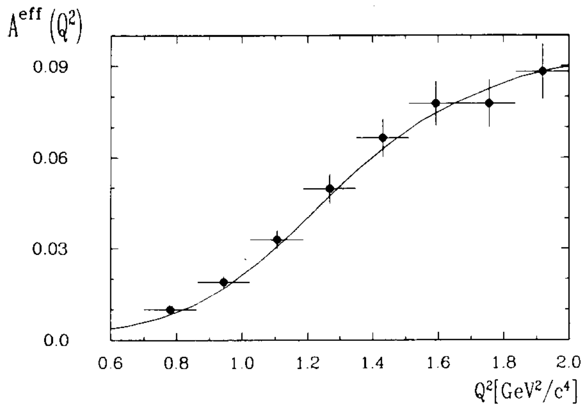

Fig. 3. Acceptance corrected asymmetry function $A^{eff}(Q^2)$ (crosses). The solid line shows the asymmetry function $A(Q^2)$ as predicted by Kühn and Wagner which was used as input for the detector simulation.

for the event generation. From these studies and from the experimental tests in connection with the background determination we conclude that detector effects cannot fake an asymmetry. A fit of (12) to the distribution in fig. 2c yields $\gamma_{AV}=1.14\pm0.34$. This is consistent with the value $\gamma_{AV}=+1$ expected for pure $V-A$ coupling at the leptonic τ^-–ν_τ vertex. In the Kühn–Wagner model with only g_A and g_V as coupling constants our result determines the ν_τ helicity to be, at least preferentially, negative. Note that even an assumed finite ν_τ mass of 35 MeV/c^2 which corresponds to the best experimental 95% CL upper limit [12] yields less than 0.75% admixture of right-handed ν_τ in the $V-A$ interaction.

The systematic error of γ_{AV} is completely dominated by the theoretical uncertainties arising from the not-well-known D-wave contribution to the $a_1^- \to \rho^0\pi^-$ decay. Following Feindt we estimate the theoretical uncertainty for γ_{AV} to be $^{+30\%}_{-15\%}$ depending on the relative sign between S- and D-wave. Our result on γ_{AV} is

$$\gamma_{AV}=\frac{2g_A g_V}{g_V^2+g_A^2}=1.14\pm0.34\,^{+0.34}_{-0.17}\,.$$

This uncertainty will be substantially decreased by a partial wave analysis of the three-pion final state.

In summary, we have for the first time measured parity violation in τ decays using the decay $\tau^-\to a_1^-(1270)\nu_\tau$. We found the ν_τ to be a left-handed particle and the $\bar{\nu}_\tau$ to be right-handed both with a significance of more than three standard deviations, the combined significance being four standard deviations. The measured value for the product of the axial and vector coupling constants, $\gamma_{AV}=1.14\pm0.34^{+0.34}_{-0.17}$, is in good agreement with the $V-A$ theory. This result supports e–μ–τ lepton universality.

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