DESY 96-015

determined b and has compared the value to the prediction of the KORALB Monte Carlo for a $V-A$ interaction of the $\tau-\nu_\tau$ vertex [224]:

$$\begin{aligned} b_{meas} &= 0.57 \pm 0.12 \\ b_{MC} &= 0.57 \pm 0.01 \end{aligned}$$

This result confirms that the interaction is vector-like (V or A or both) and excludes that the ν_τ spin could be 3/2.

Since the sign of the ρ spin cannot be measured the analysis of the ρ channel is not sensitive to the V, A composition of the interaction. The V, A interference and hence parity violation has been observed by the ARGUS Collaboration in τ decays into three pions and in correlations between hadronically decaying τ pairs.

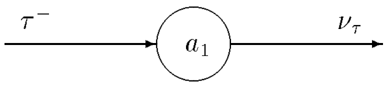
Parity Violation in Hadronic Tau Decays and the Tau Neutrino Helicity

To resolve the sign ambiguity which usually occurs in analyses of the Lorentz structure of τ decays when the τ's are produced by unpolarised beams, one has to determine the sign of particle polarisations in the final state. This is very difficult. However, following an idea of Kühn and Wagner [250] this is in principle possible using those hadronic final states which allow one to construct pseudo-scalar observables from the measured kinematics. Such a pseudo-scalar observable can be employed as an analyser of the ν_τ spin.

Kühn and Wagner suggested as an analyser of the ν_τ spin the three-pion final state in the τ decay channel [250]:

$$\tau^- \to a_1^- \nu_\tau \to \rho^0 \pi^- \nu_\tau \to \pi^+ \pi^- \pi^- \nu_\tau \tag{4.28}$$

It is known that the three charged pion final state is dominated by the axial vector meson resonance $a_1(1270)$ which decays dominantly into an S-wave $\rho\pi$ intermediate state.



$J_z(\tau^-)$	$J_z(a_1)$	$J_z(\nu_\tau)$
$-\frac{1}{2}$	0	$-\frac{1}{2}$
$+\frac{1}{2}$	$+1$	$-\frac{1}{2}$

Figure 4.11: *Possible spin configurations in the decay (4.28) if the ν_τ is left-handed (a_1^- rest system).*

From Figure 4.11 we see that in the a_1 rest system the spin component of the a_1 in ν_τ direction can only be $J_z(a_1) = 0$ and $+1$ and not -1 if the ν_τ is left-handed and vice versa for a right-handed ν_τ. Note that because of its large mass the τ^- couples with both helicities even for pure V-A. The task is therefore to distinguish $J_z(a_1) = +1$ from $J_z(a_1) = -1$. Preference of either $J_z = +1$ or -1 implies that parity is not conserved.

A parity violating observable is the expectation value of the pseudoscalar

$$\hat{p}_\tau\, \hat{n}_{3\pi} \cdot sign(s_1 - s_2). \tag{4.29}$$

The vector $\hat{p}_\tau$ denotes the direction of the τ and the axial vector $\hat{n}_{3\pi}$ the orientation of the three-pion plane, both taken in the three-pion CM system. The four-vectors of the two like-sign pions are q_1 and q_2, of the third pion q_+, and of the three-pion system Q. The sign term with $s_1 = (q_2+q_+)^2$ and $s_2 = (q_1+q_+)^2$ in (4.29) establishes Bose symmetry of the expression (4.29) with respect to the interchange of π_1^- and π_2^- ($\hat{n}_{3\pi} \sim \vec{q}_1 \times \vec{q}_2$) and results at the same time in a unique orientation of the three-pion plane defined by $\hat{n}_{3\pi} \cdot sign(s_1 - s_2)$.

The analysis of the parity violation is complicated by the fact that the τ direction is not observable. However $\hat{p}_\tau$ is known to lie on a cone around the measurable three-pion direction (in the three-pion

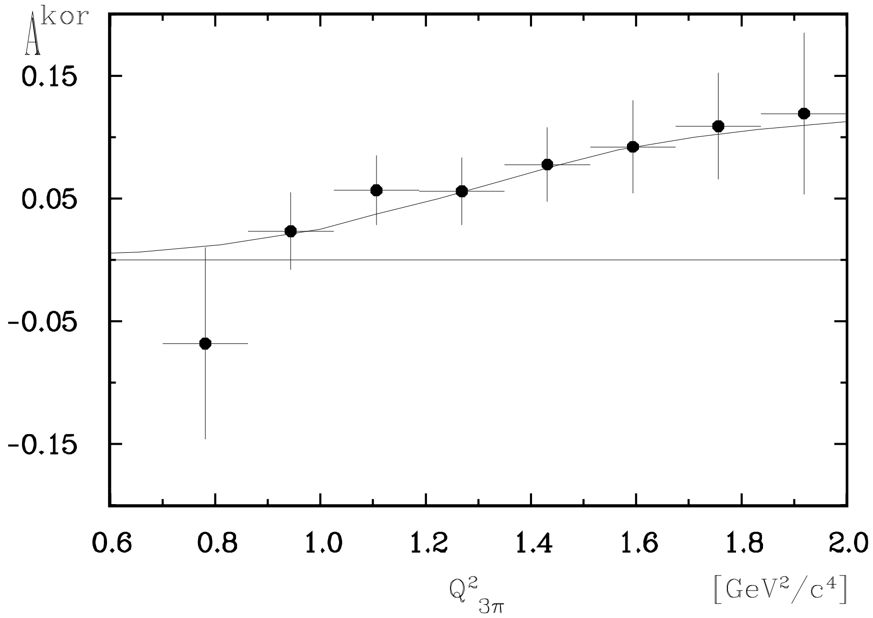


Figure 4.12: *The parity violating asymmetry measured as a function of the square of the three-pion invariant mass combined for τ^- and τ^+ decays [226].*

c.m. system this direction corresponds to the direction of the boost from the laboratory system to the c.m. system) with a half opening angle ψ. This angle is calculable from the three-pion mass Q^2 and the three-pion laboratory energy, $E_{3\pi} = x \cdot E_{beam}$. The parity violating asymmetry corresponding to (4.29) can now be obtained in $Q^2 - x$ bins:

$$A(Q^2, x) = \frac{\langle \hat{Q}\, \hat{n}_{3\pi}\, sign(s_1 - s_2) \rangle}{\langle \cos\psi \rangle} \tag{4.30}$$

where the nominator and the denominator are both average values in a $Q^2 - x$ bin.

The ARGUS group has measured the asymmetry (4.30) as a function of Q^2 and x. The data sample used in this analysis corresponds to about 260 pb^{-1}. Reaction (4.28) was selected from τ pairs decaying into four charged particles with no additional observed photons (1-3 topology). After cuts a sample of 3899 τ pair candidates remained including about 18% background. The by far largest background (about 16%) stems from τ decays of the type $\tau^- \to \pi^+\pi^-\pi^-\pi^0\nu_\tau$.

As expected the parity violating asymmetry was found to have a different sign for particles and anti-particles. In Figure 4.12 the combined asymmetry for τ^+ and τ^- decays is shown as a function of Q^2 averaged over x. Averaging also over Q^2 yields

$$\overline{A}(\tau^- + \tau^+) = 0.063 \pm 0.0155.$$

With a four standard deviation offset from zero this result established for the first time parity violation in τ decays.

The measured asymmetry can be used to determine the electro-weak coupling constants and the helicity of the τ neutrino. To do this one has to evaluate the τ decay matrix element

$$T(\tau^- \to 3\pi\nu_\tau) = L^\mu J_\mu. \tag{4.31}$$

with the leptonic current

$$L^\mu \;=\; \frac{G_F}{\sqrt{2}}\, \overline{u}_{\nu_\tau}\, (g_V + g_A\gamma_5)\, \gamma^\mu\, u_\tau \tag{4.32}$$

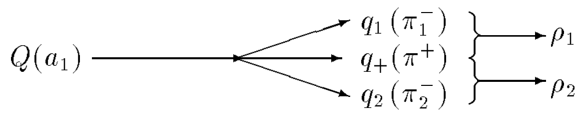
and a model dependent hadronic current J^μ. The squared matrix element contains a parity violating asymmetry

For the first analysis of the ν_τ helicity [220] we have used the Born term ansatz of [250], which represents an almost pure S-wave decay in the considered Q^2 range [251]:

$$J_\mu = G(Q^2) \left[\left(q_{1\mu} - q_{+\mu} - \frac{Q(q_1 - q_+)}{Q^2} Q_\mu \right) B(s_2) \; + \; (1 \; \leftrightarrow \; 2) \right] \tag{4.33}$$

with $G(Q^2)$ and $B(s_i)$ being the Breit-Wigner functions for the a_1 and the ρ's, respectively.

The sign of J_z can be determined from the interference between the two possible amplitudes for the $\rho\pi$ final state [250]. Denoting the two π^- mesons in (4.28) by π_1^- and π_2^- we have the two combinations $\pi^+\pi_1^-$ and $\pi^+\pi_2^-$ which can form a ρ^0:



The interference of both amplitudes leads to a parity violating asymmetry in the decay probability:

$$A^{theo} = \mp \frac{2 g_A g_V}{g_A^2 + g_V^2} \, A_{RL}(Q^2) \tag{4.34}$$

with A_{RL} being, for a given hadronic current, a calculable function of Q^2. The signs correspond to τ^- and τ^+ decays, respectively. Fitting this function to the data we obtained for the normalized product of the vector and axial vector coupling constants [226]:

$$\gamma_{AV} = \frac{2 g_A g_V}{g_A^2 + g_V^2} = 1.25 \pm 0.23 \; {}^{+0.15}_{-0.18}$$

This is an updated result which was derived with an experimentally determined S- and D-wave composition of the $\rho\pi$ final state (see sect. 4.3.2). The originally published result [220] had a larger systematic error due to the uncertain D-wave amplitude which could contribute even with different sign to the asymmetry [251].

The coupling constants are defined such that the standard model predicts $\gamma_{AV} = +1$. Therefore the observed consistency of the measured γ_{AV} with $+1$ means that the τ neutrino is dominantly left-handed. A right-handed τ neutrino would result in $\gamma_{AV} = -1$.

Tau Neutrino Helicity from Angular Correlations in Hadronic Tau Decays

In the electro-weak production process

$$e^-e^+ \;\rightarrow\; \gamma,\, Z^0 \;\rightarrow\; \tau^-\tau^+$$

the τ pairs have correlated spins, preferring opposite helicities. This leads in general to correlations between the decay products of both τ's.

The ARGUS group has exploited the angular correlations in the final state of the reaction:

$$e^-e^+ \;\rightarrow\; \tau^-\tau^+ \;\rightarrow\; \nu_\tau\rho^-\overline{\nu}_\tau\rho^+ \;\rightarrow\; \nu_\tau\pi^-\pi^0\overline{\nu}_\tau\pi^+\pi^0$$

to determine with high precision $|\gamma_{AV}|$ [229]. The matrix element of this reaction depends on 11 variables $\vec{\eta} = (\eta_1, ..., \eta_{11})$. The variables are the two $\pi\pi$ masses, the τ production and decay angles and the ρ decay angles. The matrix element can be expressed as [252]:

$$|\mathcal{M}(\vec{\eta})|^2 \;=\; A(\vec{\eta}) \;+\; \gamma_{AV}^2 \cdot B(\vec{\eta}). \tag{4.35}$$

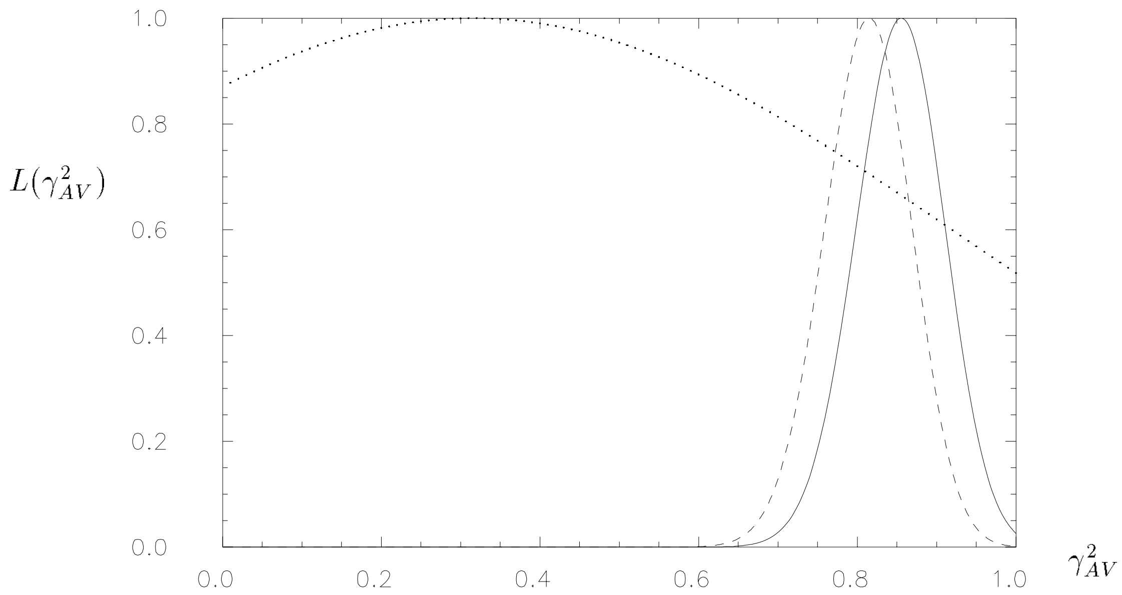


Figure 4.13: *Pseudo-likelihood as a function of* γ^2_{AV} *(uncorrected) for the selected* $\rho^-\rho^+$ *events (full line) and for a simulated data sample containing a comparable mixture of signal and background events (dashed line) [229]. The dotted line represents a function using only the energy-energy correlation of the two* ρ *mesons.*

The explicit expressions A and B can be found in [252]. Since γ^2_{AV} can be interpreted as the product of the neutrino helicities,

$$\gamma^2_{AV} = -h_{\nu_\tau} h_{\overline{\nu}_\tau}, \tag{4.36}$$

the measurement determines the relative sign of the neutrino helicities as well as the absolute value of γ_{AV}.

Experimentally, however, the kinematics can only be reconstructed up to a two-fold ambiguity because of the undetected neutrinos. The ARGUS group defined a likelihood function using the average matrix element for these two solutions. To derive the likelihood function for real data the matrix elements have to be corrected for detector effects and radiative corrections. Lacking an analytic expression for these corrections we used the above defined likelihood function (without corrections) as a 'pseudo-likelihood function' to determine γ^2_{AV} by a maximum likelihood fit. This fitted γ^2_{AV} value was then related to the true γ^2_{AV} by Monte Carlo methods.

Figure 4.13 shows the pseudo-likelihood function of the data compared to the same function for data simulated with $\gamma^2_{AV} = 1$. The data sample comprised ≈ 1700 events from an integrated luminosity of $387\,pb^{-1}$. The simulation also included the expected background, mainly from the $\pi^-\pi^0\pi^0$ final state where one π^0 was lost. The background has a non-negligible asymmetry since about 50% of the $\pi^-\pi^0$ from the a_1 decay form a ρ resonance with the same spin polarisation as in the direct ρ channel (because of the dominant S-wave decay of the a_1).

The sign of the fitted γ^2_{AV} confirms opposite helicities for neutrinos and anti-neutrinos. Together with the sign of γ_{AV} from the three-pion analysis the final result is [229]:

$$\gamma_{AV} = 1.022 \pm 0.028 \pm 0.030.$$

This is at present the most precise determination of the handedness of the τ neutrino ($\gamma_{AV} = -h_{\nu\tau}$). The results sets a lower limit on the mass of a hypothetical right-handed W boson. Assuming that the right-handed couplings have the same strength as the left-handed, i. e. that they are only suppressed by the W_R propagator, one finds:

$$M_{W_R} \; > \; 227\, GeV/c^2 \qquad (90\% \text{ c.l.}).$$

A possible scalar and pseudo-scalar coupling to the two-pion final state would result in an asymmetry in the decay angular distribution of the two-pion system. No such asymmetry was observed. Quantitative limits on scalar couplings are however quite model dependent and a detailed discussion can be found in [229, 253].

4.5.2 Leptonic Decays and the Michel Parameters

For a four-fermion pointlike interaction the most general matrix element for the leptonic τ decay is given by [249]:

$$\mathcal{M} \; = \; 4\frac{G_0}{\sqrt{2}} \sum_{\substack{\gamma = S,V,T \\ \epsilon,\mu = R,L}} g^{\gamma}_{\epsilon\mu} \left\langle \bar{l}_\epsilon \left| \Gamma^\gamma \right| \nu_l \right\rangle \left\langle \overline{\nu}_\tau \left| \Gamma_\gamma \right| \tau_\mu \right\rangle \; . \tag{4.37}$$

This is a sum over products of two currents which behave like scalars (S), vectors (V) and tensors (T) under Lorentz transformations and which connect right- and left-handed (R, L) τ leptons to right- and left-handed electrons and muons (l). There are 10 independent complex coupling constants $g^{\gamma}_{\epsilon\mu}$ yielding 19 independent real parameters. In the Standard Model we have $g^V_{LL} = 1$, all other $g^{\gamma}_{\epsilon\mu} = 0$, and G_0 the Fermi coupling constant.

The decay matrix element (4.37) can be written in terms of the coupling constants, the lepton momenta and the polarisation vector of the τ lepton yielding the differential decay width in the τ rest frame:

$$\begin{aligned} \frac{d\Gamma(\tau^\mp \to l^\mp \nu\overline{\nu})}{d\Omega dx} \; &= \; \frac{G_F^2 m_\tau^5}{192\pi^4} x^2 \left[3(1-x) + \frac{2}{3}\rho(4x-3) + 6\eta\frac{m_l}{m_\tau}\frac{1-x}{x} \right. \\ & \left. \mp\xi P_\tau \cos\theta \left((1-x) + \frac{2}{3}\delta(4x-3) \right) \right] \end{aligned} \tag{4.38}$$

Radiative corrections and terms of order $(m_l/m_\tau)^2$ have been neglected. In the formula $x = 2E_l/m_\tau$ is the normalised lepton energy, P_τ the τ polarisation and θ the angle between the τ spin and the lepton momentum. The Michel parameters ρ, η, ξ and δ depend on the coupling constants $g^{\gamma}_{\epsilon\mu}$ (see e. g. [249]). A deviation from the Standard Model prediction,

$$\rho = 3/4, \;\; \eta = 0, \;\; \xi = 1, \;\; \delta = 3/4, \tag{4.39}$$

would indicate new physics.

Determination of the ρ and η parameters

The ARGUS Collaboration started the investigation of the Michel parameters in τ decays with the analysis of single electron and muon spectra in τ events [219]. For this analysis 1 - 3 topologies were selected, i. e. the leptonic decay was required to be accompanied by a three-prong decay of the other τ. With additional cuts 5106 events containing electrons and 3041 containing muons with background contaminations of less than 0.8% and 2.0%, respectively, were found from a data sample corresponding to an integrated luminosity of 455 pb^{-1} (about 450 000 produced τ pairs). The laboratory energy spectra of the electrons and muons are shown in Figure 4.14.

With unpolarised beams these spectra depend only on the parameters ρ and η (the first three terms in (4.38)). The η dependence is proportional to the ratio of the light lepton mass to the τ mass, m_l/m_τ, and is only measurable for the decay into a muon and for not too high τ energies. In