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Determination of the structure of τ decays in the reaction $e^+e^- \to \tau^+\tau^- \to \rho^+\bar{\nu}_\tau\, \rho^-\, \nu_\tau$ and a precision measurement of the τ-neutrino helicity

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Abstract

Using the ARGUS detector at the DORIS II storage ring we have investigated the Lorentz structure of the electroweak interaction in semi-hadronic τ decays. Spin correlations in the process $e^+e^- \to \tau^+\tau^- \to \bar{\nu}_\tau\pi^+\pi^0 \ \ \nu_\tau\pi^-\pi^0$ are exploited for a measurement of the normalized product of the vector (g_V) and axial vector (g_A) couplings of the τ lepton, $\gamma_{AV} = 2\,\mathrm{Re}\{g_A g_V^*\} / (|g_V|^2 + |g_A|^2)$. The correlations are sensitive to the product of the couplings in both τ decays: $\gamma_{AV}^2 = \gamma_{AV}(\tau^- \to \nu_\tau W^-)\,\gamma_{AV}(\tau^+ \to \bar{\nu}_\tau W^+)$, which can be interpreted as the product of the neutrino helicities: $\gamma_{AV}^2 = -h(\nu_\tau)h(\bar{\nu}_\tau)$. The measured value, $\gamma_{AV}^2 = 1.044 \pm 0.057 \pm 0.060$, determines the relative sign of the neutrino helicities. Assuming CP invariance, the absolute value $|\gamma_{AV}| = 1.022 \pm 0.028 \pm 0.030$ was found to be in excellent agreement with the Standard Model. The contribution of scalar (g_S) or pseudoscalar (g_P) couplings was also investigated. No evidence for a scalar-like coupling was found.

The investigation of the third lepton family, the τ lepton and the τ neutrino, remains a subject of major importance in particle physics [1]. Since the measured leptonic τ branching ratios are in good agreement with the predictions based on new measurements of the τ mass and lifetime [2], the tau sector is consistent with a universal electroweak interaction. Nevertheless, the expected incompleteness of the Standard Model due to the lack of an explanation for particle masses and coupling strengths motivates further searches for deviations from theory.

One of the most promising ways to look for physics beyond the Standard Model is through a detailed investigation of the Lorentz Structure of τ decays. The decay of this heavy lepton should be much more sensitive to new couplings having non V–A structure than those of the lighter leptons. Therefore several experimental tests of the Lorentz structure have previously been performed, e.g. the determination of the Michel parameters in purely leptonic τ decays [3] and the measurement of the ρ polarisation in the process $\tau^- \to \pi^-\pi^0\nu_\tau$ [4]. The observation of parity violation in the three-pion final state allowed the first measurement of the helicity of the τ neutrino [5]. A combined measurement of the τ polarisation and the τ neutrino helicity has been performed on $Z \to \tau^+\tau^-$ events [6].

In this paper a precise measurement of the value of $\gamma_{AV}^2 = \gamma_{AV}(\tau^- \to \nu_\tau W^-)\,\gamma_{AV}(\tau^+ \to \bar{\nu}_\tau W^+)$ is presented, where γ_{AV} is the normalized product of the vector (g_V) and axial vector (g_A) decay constants of the τ lepton:

$$\gamma_{AV} = \frac{2\,\mathrm{Re}\{g_A g_V^*\}}{|g_V|^2 + |g_A|^2}\,. \tag{1}$$

Since the parameter γ_{AV}^2 can be interpreted as the product of the neutrino helicities, $\gamma_{AV}^2 = -h(\nu_\tau)h(\bar{\nu}_\tau)$, the measurement determines the relative sign of the neutrino helicities, as well as the absolute value of γ_{AV}. The contribution from scalar (g_S) and pseudoscalar (g_P) couplings in τ decays has also been investigated. The applied method has been developed and extensively tested with simulated data, as described in re [8]. Therefore, only the basic ideas of the analysis method are described here.

Angular correlations between the final state hadrons of the reaction

$$e^+e^- \to \tau^+\tau^- \to \bar{\nu}_\tau\pi^+\pi^0 \quad \nu_\tau\pi^-\pi^0 \tag{2}$$

are analysed to determine the electroweak interaction in semi-hadronic τ decays. The electromagnetic production of the τ leptons of reaction (2) leads to correlated lepton spins because opposite spins are suppressed by a factor $2m_\tau^2c^4 / s \approx 1/16$ for center-of-

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mass energies $\sqrt{s}$ around 10 GeV. These correlations should be distinguished from polarized τ leptons generated via Z^0 exchange at much higher energies. Using the final state hadrons as spin analysers makes the structure of the coupling in τ decays observable.

The analysis of the Lorentz structure of semi-hadronic τ decays presented here comprises four parts: the selection of events of reaction (2), the investigation of signal and background contributions to the data, the measurement of the parameter γ_{AV} and the determination of scalar-like couplings.

The analysed data sample was collected with the ARGUS detector at the e^+e^- storage ring DORIS II at center-of-mass energies between 9.4 GeV and 10.6 GeV. The ARGUS detector is a 4π magnetic spectrometer described in [7]. The event sample corresponds to an integrated luminosity of 387 pb^{-1}, with about 373 000 produced τ pairs.

The τ pairs of reaction (2) were selected from a special two-prong data sample containing more than five million events preselected with moderate cuts, mainly to reject Bhabha events. Two charged tracks from a main vertex with minimum transverse momenta of $p_T > 60$ MeV/c and with zero net charge were required. Neutral energy deposits in the calorimeter with energies larger than 150 MeV and a minimum polar angle of $|\cos\theta| < 0.92$ were accepted as photon candidates. We further constrained the data by rejecting events with less than two photons. This resulted in a sample of about 260 900 events.

To ensure good trigger conditions, we restricted both charged tracks to the barrel region of the detector, $|\cos\theta| < 0.75$. Since the τ lepton pairs are produced back-to-back with large momenta their decay products typically point into opposite hemispheres. The characteristic 1-versus-1 topology of the charged particles was selected by requiring: $\cos(\boldsymbol{p}_1, \boldsymbol{p}_2) < -0.5$. The same angle was restricted to a maximum value of $\cos(\boldsymbol{p}_1, \boldsymbol{p}_2) > -0.9$ to reduce the background from the more collinear Bhabha and μ pair events. To take into account the possibility that a shower cluster produced by a charged track can fake a photon, we required photon candidates to satisfy a minimum opening angle $\cos(\boldsymbol{r}_i, \boldsymbol{p}_\gamma) < 0.990$, where $\boldsymbol{r}_i$ is defined as the direction between the main vertex and the impact point of a charged track at the calorimeter. A large suppression of two-photon reactions, hadronic processes and other QED processes was achieved with the following parabola cut on the relationship between the transverse momentum balance and the total visible momentum of charged and neutral particles:

$$|\sum_{i=1}^{n} \boldsymbol{p}_{Ti}| > (5 \cdot (\sum_{i=1}^{n} |\boldsymbol{p}_i| \cdot c/E_{\mathrm{cms}} - 0.5)^2 + 0.1) \ \mathrm{GeV/c}.$$

Each photon was assigned to the hemisphere of the charged track closest to it, and either one or two photons were permitted in each. The reconstruction of π^0s was performed in two different ways depending on the number of detected photons. If only one photon was found in a given hemisphere, a minimum energy of 1 GeV was required for it to be compatible with being a 'single-cluster π^0'. Photons from such high energy π^0s often merge into a single cluster in the electromagnetic calorimeter, the fraction of merged clusters rising from 5% for pion energies of 1 GeV to 60 % for 3 GeV [4]. If a two-photon system was found in one hemisphere, its invariant mass was restricted to a region within $\pm 100\,\mathrm{MeV/c^2}$ of the nominal π^0 mass and the system had to yield a $\chi^2 < 9$ when kinematically constrained to the π^0 mass.

Assuming the pion mass for both charged tracks without any attempt to use dE/dx or time-of-flight measurements for particle identification, exactly one $(\pi^\pm\pi^0)$ system was reconstructed in each hemisphere. To further reduce the background the invariant mass of each system was required to lie close to the nominal ρ mass because the decay $\tau^- \to \pi^-\pi^0\nu_\tau$ is known to be dominated by $\tau^- \to \rho^-\nu_\tau$:

$$0.5\ \mathrm{GeV/c^2} < m(\pi^\pm\pi^0) < 1.1\ \mathrm{GeV/c^2} .$$

Since the τ direction of flight has to be reconstructed (see likelihood analysis), the angle $\theta(\boldsymbol{p}_{\rho^+}, \boldsymbol{p}_{\rho^-})$ between the two ρ momenta and the two decay angles $\theta^\pm(\boldsymbol{p}_{\tau^\pm}, \boldsymbol{p}_{\rho^\pm})$ between the momenta of the τ leptons and the ρ mesons had to fulfill the condition:

$$\theta(\boldsymbol{p}_{\rho^+}, \boldsymbol{p}_{\rho^-}) + \theta^-(\boldsymbol{p}_{\tau^-}, \boldsymbol{p}_{\rho^-}) + \theta^+(\boldsymbol{p}_{\tau^+}, \boldsymbol{p}_{\rho^+}) > 180^\circ .$$

1707 events passed this last requirement. To proceed further requires a quantitative knowledge of the different background contributions to the data sample. We

discuss in detail the background from the following sources:
- e^+e^- annihilation into hadrons,
- two-photon reactions,
- radiative Bhabha events,
- τ pair events with one or both τ decays faking the decay mode $\tau^\pm \to \pi^\pm\pi^0\nu_\tau$.

The background contribution from non-τ pair events was found to be very small. These events were rejected effectively through application o the parabola cut and the restriction on the reconstructed ρ mass.

To determine the number of hadronic background events we used 624 867 $q\bar{q}$ events which were generated with the LUND Monte Carlo program (version 6.2 and 6.3) [9] including initial state radiation. Only 7 events satisfied all selection criteria. Scaling to the measured integrated luminosity yielded 13.9 ± 5.2 events expected in the data.

The strongest background contribution from two-photon reactions is the process $\gamma\gamma \to \pi^-\pi^0 \quad \pi^+\pi^0$. A major fraction of this final state is produced as a $\rho^+\rho^-$ system [10]. A data sample with simulated two-photon events of this type was investigated to determine the corresponding background fraction. The number of events which passed the selection was scaled to the data by studying a phase space region populated predominantly by two-photon events:
- $|\sum_{i=1}^{n} p_{Ti}| < (5 \cdot (\sum_{i=1}^{n} |p_i| \cdot c/E_{\rm cms} - 0.5)^2 + 0.1)$ GeV/c
- and $(\sum_{i=1}^{n} |p_i| \cdot c/E_{\rm cms}) < 0.5$.

After correcting for the expected number of τ events in this phase space region an estimate of 17.3 ± 10.7 two-photon events in the data was derived.

In consideration of the good particle identification properties of the ARGUS detector, we regarded all events with sufficiently high electron likelihoods for both charged tracks as radiative Bhabha events. A negligible number of 1.0 ± 1.0 events was found to remain in the selected data sample. Without the ρ mass restriction this number would increase to 19 events.

The study of background events from other τ decays was based on a simulated data sample of a few hundred thousand τ pair events generated with the KORALB event generator (version 2.2) [11] [11] After feeding this Monte Carlo sample through a simulation of the ARGUS detector [12] a detailed investigation of the different background channels and a determination of their selection efficiencies was made.

[11] A sign error in the matrix element programmed in KORALB affecting the spin correlations has been corrected.

Table 1
Branching ratios used in the Monte Carlo simulations. The expected background contributions from τ events where one $\tau^\pm \to \pi^\pm\pi^0\nu_\tau$ is faked by another mode are also indicated.

Decay channel	Branching ratio [2,13]	Expected events
$\tau^- \to e^-\bar{\nu}_e\nu_\tau$	$(17.9 \pm 0.1)\%$	13.2 ± 3.0
$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$	$(17.3 \pm 0.2)\%$	5.5 ± 1.9
$\tau^- \to \pi^-\nu_\tau$	$(11.1 \pm 0.2)\%$	4.7 ± 1.7
$\tau^- \to \pi^-2\pi^0\nu_\tau$	$(8.3 \pm 0.4)\%$	335.3 ± 27.8
$\tau^- \to \pi^-3\pi^0\nu_\tau$	$(1.1 \pm 0.2)\%$	22.1 ± 4.3
$\tau^- \to K^-\nu_\tau$	$(0.85 \pm 0.14)\%$	0.0 ± 1.2
$\tau^- \to K^*(892)^-\nu_\tau$	$(1.22 \pm 0.13)\%$	52.0 ± 8.4

A major part of the background (about 70%) is due to the decay $\tau^\pm \to \pi^\pm\pi^0\pi^0\nu_\tau$ of one or both τ leptons with one π^0 escaping detection. This hadronic final state originates from the decay $a_1^\pm \to \rho^\pm\pi^0$. Therefore, the loss of the π^0 from the direct $a_1^\pm$ decay results in background events which cannot be distinguished from signal events by the applied selection criteria. Two other important background sources are due to the decays $\tau^\pm \to \pi^\pm 3\pi^0\nu_\tau$ and $\tau^\pm \to K^*(892)^\pm\nu_\tau$.

The expected background from events where *one* $\tau^\pm \to \pi^\pm\pi^0\nu_\tau$ decay is faked by other decay modes is given in Table 1

together with the branching ratios used for the various decay channels. The errors include statistical and systematic uncertainties. Table 2 gives a compilation of the different signal and background classes and the corresponding contributions to the selected data.

The likelihood method described in detail in Ref. [8] was applied to determine the parameter γ_{AV}^2. This method exploits all the kinematical information of reaction (2) if the τ direction of flight is known. Although this vector cannot be measured directly with the ARGUS detector, it can be reconstructed within a twofold ambiguity using the kinematical information of the observed hadronic decay products of the τ pairs [8]. The squared matrix element entering the likelihood function has been derived in [8] and can be written as

$$|M(\boldsymbol{\alpha}|\gamma_{AV}^2)|^2 = C\left[A(\boldsymbol{\alpha}) + \gamma_{AV}^2 B(\boldsymbol{\alpha})\right] , \qquad (3)$$

with C a factor independent of γ_{AV}^2 and $\boldsymbol{\alpha}$ represents

Table 2
Number of selected events for the different data classes and background contributions.

	Data class	Expected events	Ratio
	selected events	1707	
	$\tau^+\tau^- \to \nu_\tau\bar{\nu}_\tau$ + ...		
1	... $\rho^+\rho^-$ (reaction 2)	1199.5 ± 111.3	70.3%
2	... $\rho^\pm K^*(892)^\mp$, $K^*(892)^+K^*(892)^-$	52.0 ± 8.4	3.0%
3	... $\rho^\pm a_1^\mp$, $K^*(892)^\pm a_1^\mp$, $a_1^\pm a_1^\mp$	361.6 ± 34.5	21.2%
4	other τ background	61.7 ± 8.4	3.6%
5	non-τ background	32.2 ± 12.0	1.9%

eleven measurable quantities (nine angles and two invariant masses). Since some of these quantities require the knowledge of the τ direction of flight, the likelihood function for one event is given by the sum of two probabilities $P^{1,2}(\boldsymbol{\alpha}|\gamma_{AV}^2)$ corresponding to the two possible τ directions. The product of the likelihoods for all events of a data sample yields the total likelihood function:

$$L(\gamma_{AV}^2) = \prod_i \{P^1(\boldsymbol{\alpha}|\gamma_{AV}^2) + P^2(\boldsymbol{\alpha}|\gamma_{AV}^2)\}$$
$$= \prod_i c_i \{|M_i^1(\boldsymbol{\alpha}|\gamma_{AV}^2)|^2 + |M_i^2(\boldsymbol{\alpha}|\gamma_{AV}^2)|^2\}, \quad (4)$$

where c_i is independent of γ_{AV}^2 and accounts for phase space and flux factors.

We have assumed that the data sample consists only of signal events and that these have been measured with an ideal detector. The effects of background contributions, radiative corrections and the acceptance of a real detector and of the applied data selection are not included. Therefore, Eq. (4) is not a proper likelihood function for the selected data sample. Nevertheless, it has properties similar to a true likelihood function. This has been determined through extensive Monte Carlo studies as described below.

For a determination of the parameter γ_{AV}^2 based on the Eq. (4) the following strategy has been used: The maximum value given by the pseudo-likelihood function $L(\gamma_{AV}^2)$ of the selected data sample yields an uncorrected value for γ_{AV}^2. This will differ from a best estimate for this parameter since $L(\gamma_{AV}^2)$ is not a proper likelihood function. Therefore, a determination of γ_{AV}^2 requires the relation between the uncorrected value γ_{AV}^2(uncorr) and the best estimate or corrected value γ_{AV}^2(corr). This relation has been derived from studies with large simulated data samples.

The required relation depends on a detailed knowledge of the pseudo-likelihood functions for simulated data samples containing mixtures of signal and background events comparable to the measured data. Since the pseudo-likelihood function can be factorized into contributions from the different event classes k, $L(\gamma_{AV}^2) = \prod_k L_k(\gamma_{AV}^2)$, the functions $L_k(\gamma_{AV}^2)$ have been investigated individually with simulated data which include the effects of radiation and acceptanc In the following the relevant characteristics of the functions for the data classes defined in Table 2 are discussed for the special case of events generated with $\gamma_{AV}^2(\text{corr}) = 1$.

The function $L_{\text{signal}}(\gamma_{AV}^2)$ for events from data classes 1 and 2 (in the proportions expected in the data) is shown as the full line in Fig. 1a. This function yields an expectation value for γ_{AV}^2 smaller than 1 due to acceptance effects. Events from data class 2 with τ leptons decaying via the channel $\tau^\pm \to K^*(892)^\pm\nu_\tau \to K^\pm\pi^0\nu_\tau$ are included in the signal data because this decay has the same spin information as the decay $\tau^\pm \to \rho^\pm\nu_\tau \to \pi^\pm\pi^0\nu_\tau$.

The primary background contribution is from data class 3 with τ leptons decaying through the channel $\tau \to a_1^\pm\nu_\tau \to \pi^\pm\pi^0\pi^0\nu_\tau$. This class results in a pseudo-likelihood function with a maximum value for γ_{AV}^2 around 0.6. The non-zero expectation value results from the fact that the $\rho^\pm$ meson produced in the $a_1^\pm$ decay can carry all the spin information of the $a_1^\pm$ meson for dominant S wave decay if the π^0 from the direct $a_1^\pm$ escapes detection. The amplitude ratio of the S wave to D wave is measured to be $S/D =$

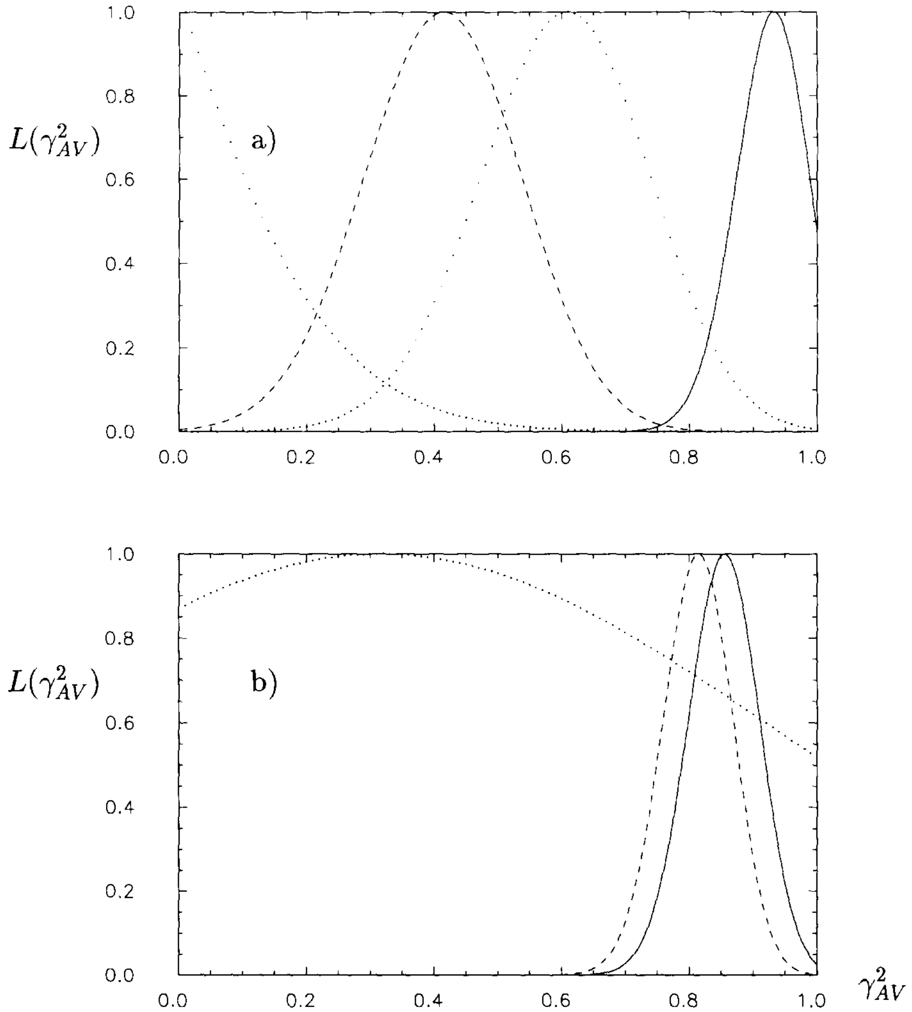

Fig. 1. a) Pseudo-likelihood function for simulated signal (full line) and background data (dashed line) as expected for the selected data sample. The right (left) dotted line corresponds to background from data classes 3 (4 and 5). b) Comparison of the pseudo-likelihood function for the selected data sample (full line) with the one for a simulated data sample containing a comparable mixture of signal and background events (dashed line). The dotted line represents a function using only the energy-energy correlation of the two ρ mesons.

-0.11 ± 0.02 [5]. Therefore, this background contribution has nearly the same angular momentum structure as the signal data. This is not the case if the π^0 produced by the $\rho^\pm$ is lost. Since this pseudo-likelihood function is important for the determination of γ_{AV}^2 we have compared the simulated background with measured background by requiring an additional π^0 in one hemisphere of the data selection described above. We then calculated the two corresponding pseudo-likelihood functions without using the additional π^0s of these events. Data and simulation were found to be in good agreement.

The backgrounds from other τ decays (data class 4) and from non-τ decays (data class 5) yield similar pseudo-likelihood functions with maxima at $\gamma_{AV}^2 = 0$. Fig. 1a shows the functions for the different background classes separately, as well as the pseudo-likelihood function of the total background. The product of the simulated signal and background functions yields a pseudo-likelihood function (dashed line in Fig. 1b) with a maximum at significantly lower values of γ_{AV}^2 than the pure signal function.

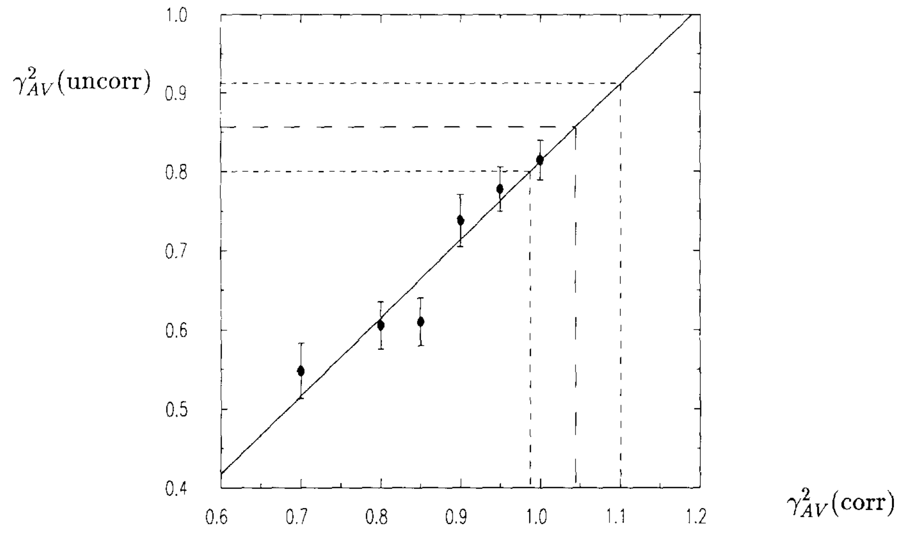

Fig. 2. Uncorrected values for γ^2_{AV} derived from simulated pseudo-likelihood functions versus the corrected values used in the event generation. The full line represents a linear fit to the data. The dashed lines illustrate the correction of γ^2_{AV}(uncorr) for the measured data.

The pseudo-likelihood function for the selected data sample (full line in Fig. 1b) yields an uncorrected γ^2_{AV} value of

$$\gamma^2_{AV}(\text{uncorr}) = 0.856 \pm 0.056 .$$

The statistical error was derived from the width of the function and has been checked using the distribution of uncorrected values γ^2_{AV}(uncorr) for simulated data samples containing the same number of signal and background events as expected in the measured data. Since the pseudo-likelihood function is in good agreement with the function for simulated data generated with $\gamma^2_{AV} = 1$ no significant deviation from the Standard Model value for γ^2_{AV} can be expected from the data. A comparison with a pseudo-likelihood function constructed using only the energy-energy correlation between the two ρ mesons is presented in Fig. 1b. Given that the same data sample has been analysed, the advantage of using the likelihood method, based on all available information, is obvious.

To derive the required relationship between the corrected and uncorrected values of γ^2_{AV} large data samples containing signal and background events in the same ratio as in the selected data sample were produced with different values of γ^2_{AV}(corr). The events were generated with radiative corrections and fed through a full detector simulation. The calculation of the corresponding pseudo-likelihood functions results in uncorrected values γ^2_{AV}(uncorr) for the simulated data samples. These are shown versus the corrected values γ^2_{AV}(corr) in Fig. 2. A straight line fit yields the following relation:

$$\gamma^2_{AV}(\text{uncorr}) = a_1 \left[\gamma^2_{AV}(\text{corr}) - 1\right] + a_0 , \qquad (5)$$

with: $a_1 = 0.988 \pm 0.125$, $a_0 = 0.812 \pm 0.019$, $\sigma^2_{a_0 a_1} = 0.002$ and $\chi^2_{\text{fit}} / \text{d.o.f.} = 5.0 / 4$. The errors are due to the statistical uncertainties caused by the limited Monte Carlo statistics of about 1.5 million generated events.

The pseudo-likelihood function for the selected data sample together with the derived linear relation between the corrected and uncorrected values results in a determination of the parameter γ^2_{AV} :

$$\gamma^2_{AV}(\text{corr}) = 1.044 \pm 0.057 \pm 0.060 ,$$

where the first error is due to the statistical uncertainty and the second is due to systematic uncertainties. The different contributions to the systematic uncertainty are summarized in Table 3. A variation in the admixture of the background classes to the data of 30 percent yields only a small contribution to the systematic error. In order to investigate systematic effects due to the event generation and detector simulation on the acceptance function we varied the criteria of the data selection. No significant influence on the measurement of γ_{AV}^2 could be observed. The systematic error given in Table 3 reflects the limited statistics of simulated and measured data available for these checks. The uncertainties in the parameters of the linear relation described above yield only a minor contribution to the systematic error.

Combining the measurement of the sign of γ_{AV} by the ARGUS collaboration in 1990 [5] with the result of this analysis, we arrive at a very precise determination of the parameter γ_{AV}:

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

The analysis of contributions from scalar-like couplings in τ decays is based on a matrix element for reaction (2) which includes scalar-like couplings. These couplings are defined in such a way [8] that $g_S = g_P$ corresponds to a pure left (right) handed coupling for the (anti) neutrino. For the vector-like couplings $g_V = g_A$ is assumed and all couplings g_i are assumed to be real. Terms proportional to $(g_S^2 + g_P^2)$ are neglected.

A scalar-like coupling in τ decays results in an asymmetry in the subprocess $h^\pm \to \pi^\pm\pi^0$ due to an interference between the decay of a $\rho^\pm$ meson and the decay of a scalar particle $h^\pm_{\text{scalar}}$. This asymmetry becomes observable in the distribution of $\cos\alpha^\pm = \hat{p}^{\pi^\pm}_{h^\pm\text{cm}} \cdot \hat{p}^{h^\pm}_{\tau^\pm\text{cm}}$, where $\hat{p}^{\pi^\pm}_{h^\pm\text{cm}}$ denotes the normalised pion momentum in the rest frame of the hadronic system $h^\pm$ and $\hat{p}^{h^\pm}_{\tau^\pm\text{cm}}$ is the normalised $h^\pm$ momentum in the $\tau^\pm$ rest frame:

$$\frac{1}{\Gamma_{\text{tot}}(Q^2)} \frac{d\Gamma_s(\tau^\pm \to \pi^\pm\pi^0\nu_\tau)}{d\cos\alpha^\pm} = \frac{3Q_\pm^2}{2m_\tau^2 + 4Q_\pm^2}\left[1 + \frac{m_\tau^2 - Q_\pm^2}{Q_\pm^2}\cos^2\alpha^\pm \mp \frac{g_S + g_P}{g_V}\,\text{Re}\left\{f_s(Q_\pm^2)\,X(Q_\pm^2)\right\}\cos\alpha^\pm\right] \quad (6)$$

with:

$$X(Q_\pm^2) = \frac{m_\tau}{\sqrt{Q_\pm^2\,(Q_\pm^2 - 4m_\pi^2)}} \cdot \frac{1}{F'_\pi(Q_\pm^2)} .$$

The vector or pion form factor $F'_\pi(Q_\pm^2)$ describes a $(\pi^\pm\pi^0)$ system in a vector state and the scalar form factor $f_s(Q_\pm^2)$ corresponds to a scalar hadronic system. Both functions depend on the invariant mass of the system ($Q_\pm^2 = m^2_{\pi^\pm\pi^0}$). Experimentally, one can only determine the global coefficient of the antisymmetric part of Eq. (6). Since this will be in general a quickly varying function of Q^2, we have analysed the data in intervals of Q^2. A decomposition of the different factors can only be carried out under the additional assumptions described below.

Table 3
Compilation of systematic errors for γ_{AV}^2.

Error sources	$\sigma_{\text{sys}}(\gamma_{AV}^2)$
background admixture	0.038
event generation and detector simulation	0.040
Monte Carlo statistics	0.024
total	0.060

Due to the reconstruction of the τ axis $\cos\alpha$ can only be measured within a twofold ambiguity. The influence of this uncertainty on a measurement of the antisymmetric term in Eq. (6) has been investigated with simulated data by comparing $\cos\alpha$ values calculated with the real and the reconstructed τ axes. In the latter case both possible $\cos\alpha$ values for each event were used and weighted by 0.5. The comparison yielded a reduction of the antisymmetric contribution by a factor 1.81 ± 0.04. This factor was found to be independent of the chosen Q^2 interval and of the asymmetry used for the simulated input function.

In Fig. 3, the $\cos\alpha^-$ distributions for background su d and acceptance corrected data are compared in four Q^2 intervals with the distributions for pure V–A simulated data (ideal detector, no background). The error bars account for the limited statistics of the data and the uncertainty in the background subtraction and the acceptance correction. A fit to the data with the function

$$N(\cos\alpha) = A\left[1 + B\cos^2\alpha + C\cos\alpha\right]$$

yields a value for the parameter C in each interval. These values are presented in Table 4 for the $\cos\alpha^-$ and $\cos\alpha^+$ distributions. Since all values for the parameter C are consistent with zero, no evidence for a scalar-like coupling can be found in the data.

A determination of the scalar-like coupling $(g_S + g_P) / g_V$ requires a parametrisation of the form factors. The pion form factor can be sufficiently well described

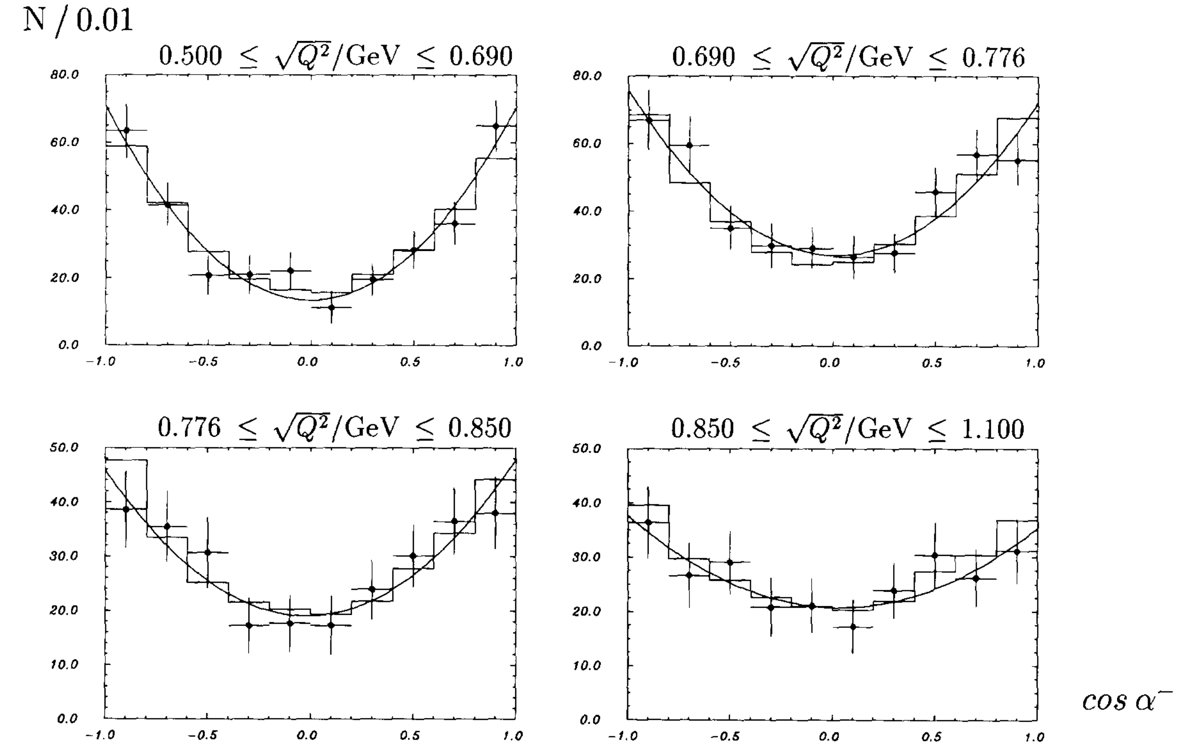

Fig. 3. Distribution of $\cos\alpha^-$ for background subtracted and acceptance corrected data (points with error bars) and for simulated data of reaction (2) with an ideal detector (histogram) in intervals of Q^2. The lines represent fits to the data.

Table 4
Fit parameters $C(Q^2)$, average values for $\mathrm{Re}\{X(Q^2_\pm)\} = \mathrm{Re}\{m_\tau/(F'_\pi(Q^2_\pm)\sqrt{Q^2_\pm\,(Q^2_\pm - 4m^2_\pi)}),\}$ and estimates for scalar-like couplings in intervals of Q^2.

Q^2 intervals		$C(Q^2)$ (χ^2/d.o.f.)	$\langle\mathrm{Re}\{X(Q^2)\}\rangle$	$f_s\,(g_S+g_P)\,/\,g_V$
$\cos\alpha^-$ data	$0.500 \le \sqrt{Q^2}/\mathrm{GeV} \le 0.690$	-0.174 ± 0.262 (4.5/7)	1.42 ± 0.76	-0.223 ± 0.356
	$0.690 \le \sqrt{Q^2}/\mathrm{GeV} \le 0.776$	-0.013 ± 0.185 (4.2/7)	0.28 ± 0.17	-0.084 ± 1.202
	$0.776 \le \sqrt{Q^2}/\mathrm{GeV} \le 0.850$	-0.099 ± 0.110 (2.7/7)	-0.18 ± 0.10	1.000 ± 1.242
	$0.850 \le \sqrt{Q^2}/\mathrm{GeV} \le 1.100$	-0.080 ± 0.124 (5.0/7)	-0.66 ± 0.21	0.220 ± 0.349
$\cos\alpha^+$ data	$0.500 \le \sqrt{Q^2}/\mathrm{GeV} \le 0.690$	0.004 ± 0.289 (1.9/7)	1.39 ± 0.72	0.005 ± 0.378
	$0.690 \le \sqrt{Q^2}/\mathrm{GeV} \le 0.776$	-0.064 ± 0.162 (5.1/7)	0.28 ± 0.18	-0.416 ± 1.085
	$0.776 \le \sqrt{Q^2}/\mathrm{GeV} \le 0.850$	0.056 ± 0.071 (3.1/7)	-0.18 ± 0.11	-0.566 ± 0.796
	$0.850 \le \sqrt{Q^2}/\mathrm{GeV} \le 1.100$	-0.052 ± 0.158 (2.8/7)	-0.69 ± 0.21	0.137 ± 0.418

by a Breit-Wigner:

$$F'_\pi(Q^2) = \sqrt{2}\cos\theta_c \frac{m_\rho^2}{m_\rho^2 - Q^2 - i\Gamma_\rho m_\rho}$$

with $m_\rho = 0.776$ GeV/c^2 and $\Gamma_\rho = 0.149$ GeV/c^2. The scalar form factor is, however, unknown. Therefore, we have assumed a simple constant behaviour for it: $f_s(Q^2) = f_s$, where f_s is real. This provides a plausible limit for the complete mass range. With this assumption we have averaged $\mathrm{Re}\{X(Q^2)\}$ over Q^2 separately in each Q^2 interval (Table 4). After correcting the fit parameters C for the ambiguity in the reconstruction of the τ axes, the ratios of the corrected parameters C with the average values $\langle \mathrm{Re}\{X(Q^2)\}\rangle$ become estimates for $(g_S+g_P)/g_V f_s$. The weighted mean of these estimates yields:

$$\frac{g_S + g_P}{g_V} f_s = 0.006 \pm 0.175\,.$$

Systematic uncertainties from sources other than the limited background statistics and the acceptance correction were found to be small and have been neglected. In particular the weighted mean is independent of a reasonable variation of the parameter m_ρ and of the chosen Q^2 intervals. The following upper limit for scalar-like couplings is derived:

$$\frac{g_S + g_P}{g_V} f_s \leq 0.29 \quad (90\%\,\mathrm{c.l.})\,.$$

An independent check using a likelihood method based on a matrix element extended to include scalar-like couplings has been performed in analogy to the determination of the parameter γ^2_{AV}. The results for this method, which exploits all available information of reaction (2), indicate that the $\cos\alpha^\pm$ asymetry analysis already has in fact a nearly optimal sensitivity. The likelihood method yields a comparable limit for scalar-like couplings.

In conclusion, we have used spin correlations in semi-hadronic τ decays to measure the value of the parameter $\gamma^2_{AV} = \gamma_{AV}(\tau^- \to \nu_\tau W^-)\,\gamma_{AV}(\tau^+ \to \bar{\nu}_\tau W^+)$ with high precision. The determined negative sign of the product of the neutrino helicities, $h(\nu_\tau)$ and $h(\bar{\nu}_\tau)$, and the absolute value, $\gamma_{AV} = 1.022 \pm 0.028 \pm 0.030$, are in excellent agreement with the Standard Model. An investigation into the asymmetry in the decay angular distribution of charged pions produced in the decay $\tau^\pm \to \pi^\pm\pi^0\nu_\tau$ allowed a determination of an upper limit for scalar-like couplings in τ decays. No evidence for deviations from a pure V–A coupling could be found.

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