SLAC-PUB-7333
hep-ex/9701020
January 1997

Measurement of the τ Neutrino Helicity and Michel Parameters in Polarized e^+e^- Collisions [1]

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Abstract

We present a new measurement of the τ neutrino helicity h_{ν_τ} and the τ Michel parameters ρ, η, ξ and the product $\delta\xi$. The analysis exploits the highly polarized SLC electron beam to extract these quantities directly from a measurement of the τ decay spectra, using the 1993-1995 SLD data sample of 4328 $e^+e^- \to Z^0 \to \tau^+\tau^-$ events. From the decays $\tau \to \pi\nu_\tau$ and $\tau \to \rho\nu_\tau$ we obtain a combined value $h_{\nu_\tau} = -0.93 \pm 0.10 \pm 0.04$. The leptonic decay channels yield combined values of $\rho = 0.69 \pm 0.13 \pm 0.05$, $\eta = -0.13 \pm 0.47 \pm 0.15$, $\xi = 1.02 \pm 0.36 \pm 0.05$ and $\delta\xi = 0.87 \pm 0.27 \pm 0.04$.

submitted to Physical Review Letters

[1] This work was supported by Department of Energy contracts and grants: DE-FG02-91ER40676 (BU), DE-FG03-92ER40701 (CIT), DE-FG03-91ER40618 (UCSB), DE-FG03-92ER40689 (UCSC), DE-FG03-93ER40788 (CSU), DE-FG02-91ER40672 (Colorado), DE-FG02-91ER40677 (Illinois), DE-AC03-76SF00098 (LBL), DE-FG02-92ER40715 (Massachusetts), DE-AC02-76ER03069 (MIT), DE-FG06-85ER40224 (Oregon), DE-AC03-76SF00515 (SLAC), DE-FG05-91ER40627 (Tennessee), DE-FG02-95ER40896 (Wisconsin), DE-FG02-92ER40704 (Yale); National Science Foundation grants: PHY-91-13428 (UCSC), PHY-89-21320 (Columbia), PHY-92-04239 (Cincinnati), PHY-88-17930 (Rutgers), PHY-88-19316 (Vanderbilt), PHY-92-03212 (Washington); the UK Particle Physics and Astronomy Research Council (Brunel and RAL); the Istituto Nazionale di Fisica Nucleare of Italy (Bologna, Ferrara, Frascati, Pisa, Padova, Perugia); and the Japan-US Cooperative Research Project on High Energy Physics (Nagoya, Tohoku).

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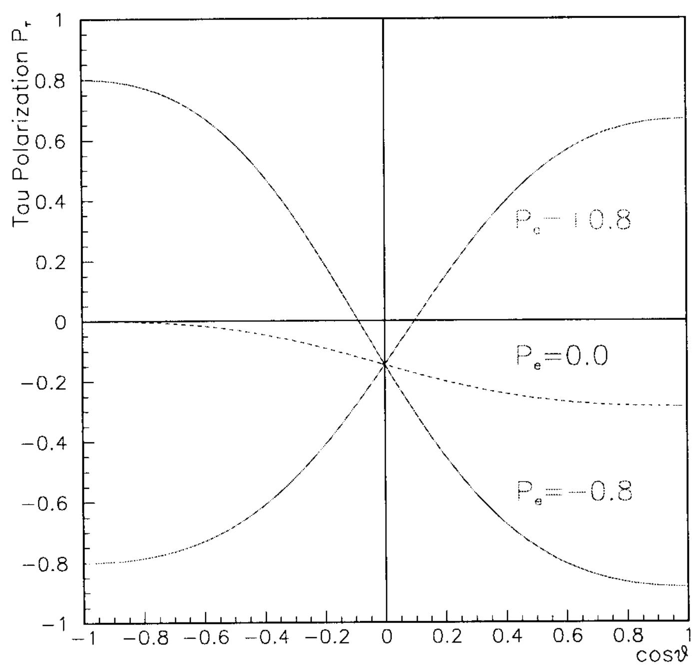
We present a study of the fundamental structure of the charged weak current by investigating the energy spectra of decay products of polarized τ leptons. We measure the τ neutrino helicity and decay Michel parameters, which are related [1, 2] to the couplings in $W \rightarrow \tau\nu_\tau$. The τ decay spectra are determined by the nature of the decay [3] and the spin polarization of the taus. Tau pairs are produced with high longitudinal polarization in collisions of highly polarized electrons with positrons at the SLC.

In $e^+e^- \rightarrow \tau^+\tau^-$, final state τ polarization results both from incident beam polarization and from parity violation of the Z^0 couplings. Neglecting γ exchange and $\gamma - Z^0$ interference we can write the τ polarization as:

$$P_\tau(\cos\theta, P_e) \equiv \frac{\frac{d\sigma_R}{d\cos\theta} - \frac{d\sigma_L}{d\cos\theta}}{\frac{d\sigma_R}{d\cos\theta} + \frac{d\sigma_L}{d\cos\theta}} = -\frac{A_\tau + 2\frac{A_e - P_e}{1-AP_e}\frac{\cos\theta}{1+\cos^2\theta}}{1 + 2A_\tau\frac{A_e - P_e}{1-AP_e}\frac{\cos\theta}{1+\cos^2\theta}}, \qquad (1)$$

where θ is the polar angle of the τ^- (τ^+) with respect to the incident e^- (e^+) direction, P_e is the e^- beam polarization, and A_e and A_τ [4] are the e^- and τ parity-violation asymmetry parameters. This expression is plotted in Fig. 1 for $P_e = 0$ and ± 0.8. Experiments without beam polarization have relied on spin correlations between the final state taus [4-7] for measuring the parameters described above.

Figure 1: τ polarization vs production angle with and without beam polarization.



At the SLC, P_τ is largely determined by the beam polarization and the production angle, as seen in Fig. 1. Therefore, this allows a direct measurement using all individual identified τ decays and, unlike the correlation methods, provides the sign as well as the magnitude of the polarization-dependent parameters. This is the first such measurement to be performed with polarized beams.

identification is provided by the Čerenkov Ring-Imaging Detector (CRID), and muons are identified in the Warm Iron Calorimeter (WIC).

The initial selection of τ-pair candidates is based on the multiplicity, momentum and direction of tracks in the CDC, and on properties of EM showers in the calorimeter, resulting in a sample of 4328 events with a purity of 98% and an efficiency of 80% in the fiducial region. The background contamination and efficiency of event selection and decay identification (described below) were estimated and parametrized using a Monte Carlo (MC) simulation. Details on the event selection and simulation are in Ref. [13]. These events are divided into hemispheres by the plane normal to the event thrust axis, and the hemispheres are treated independently. Any pair of oppositely charged tracks which is consistent with originating from a γ conversion is removed. Hemispheres are then required to contain exactly one track, and the track is required to have at least one hit in the VXD to improve momentum resolution.

The selection of $\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$ in the region $|\cos\theta| < 0.62$ is performed by associating WIC hits with CDC tracks. In the $0.62 < |\cos\theta| < 0.75$ region, shower information from the LAC is used instead. A minimum track momentum of 1.6 GeV/c is required. This results in a sample of 1143 tracks identified as muons, with an estimated selection efficiency of 72% within the acceptance, and an estimated purity of 94%. The background comes from μ-pairs (2%), 2γ events (0.8%) and mis-identified τ decays (3.2%).

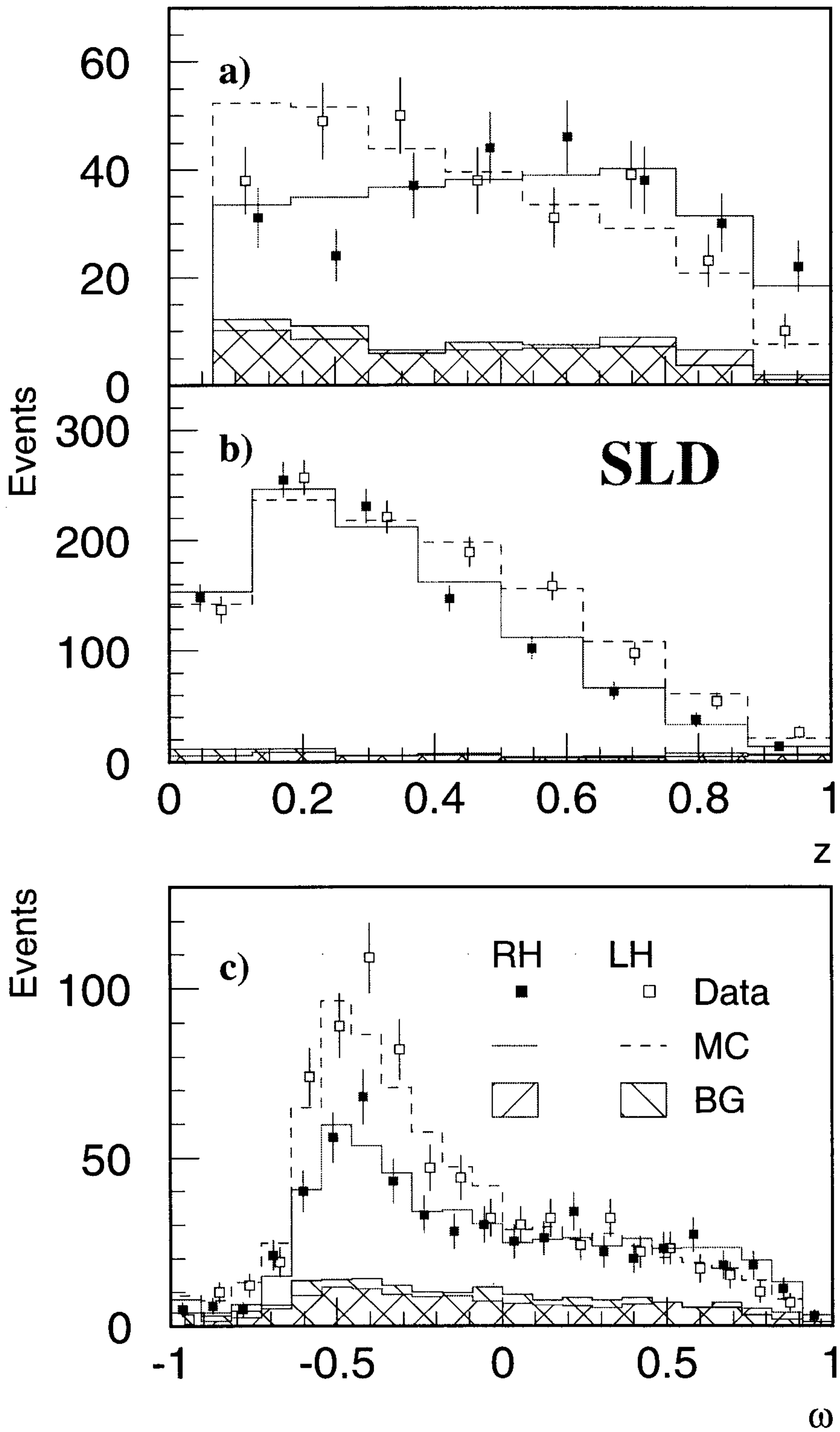
For selection of $\tau \rightarrow e\bar{\nu}_e\nu_\tau$ the LAC energy deposition must be consistent with that of an electron, or the electron must be identified by the CRID. The momentum of the track must be greater than 1.6 GeV/c, and a quasi-invariant mass calculated using track momentum and LAC energy clusters is required to be less than 0.5 GeV/c^2. This results in a sample of 948 identified electron tracks with an estimated efficiency of 63% within the acceptance and an estimated purity of 96.4%. The background to this mode is composed of Bhabha and 2γ events and mis-identified τ decays at the levels of 0.8%, 0.8% and 2% respectively.

For the $\tau \rightarrow \pi\nu_\tau$ selection, we first reject electron and μ candidates. Then a candidate is required to have track momentum greater than 3 GeV/c, and no EM clusters within 10° of the thrust axis that are not associated with a CDC track. Here the calculated quasi-invariant mass is required to be less than 0.3 GeV/c^2, and additional criteria are imposed based on the ratio of LAC energy to track momentum. No attempt is made to separate kaons from pions, and a small correction is made in the analysis for the effect of the larger kaon mass. This selection provides a sample of 558 tracks identified as $\tau \rightarrow \pi\nu_\tau$, with an efficiency of 58% within the angular acceptance. The purity of the sample is approximately 79% where the main contamination sources are ρ-meson, e, and μ decay channels at the rates of 13%, 5% and 1.4% respectively. The non-tau background is estimated to be less than 0.5%.

Events not selected as leptons or pions are candidates for $\tau \rightarrow \rho\nu_\tau$ decays. Hemispheres are then categorized according to the number of EM clusters found within 20° of the event thrust axis, and according to whether such clusters are associated or unassociated with the charged track in the corresponding hemisphere. The charged track momentum and the EM cluster energies are used to calculate a ρ-meson energy and its invariant mass, and the mass is required to fall in the range between 0.44 and 1.2 GeV/c^2. This selection results in a sample of 1295 identified ρ-meson decays, with an efficiency of 60% within $|\cos\theta| < 0.74$. The purity of the sample is approximately 76%, where background is dominated by decays to $\pi 2\pi^0$ (14.7%), K^* (2.4%), and single π or K (2.4%). The non-tau background is estimated to be less than 0.3%.

In Fig. 2(a), the energy spectrum of $\tau \rightarrow \pi\nu_\tau$ decays is plotted separately for different com-

Figure 2: (a) $\tau \to \pi \nu_\tau$, (b) $\tau \to \ell \bar{\nu}_\ell \nu_\tau$ and (c) $\tau \to \rho \nu_\tau$ decay spectra. The solid squares (line) represent the sum of the measured (MC) spectra for τ decays in the forward direction with $P_e < 0$ and in the backward direction with $P_e > 0$, and the open squares (dashed line) are the measured (MC) sum of the spectra for τ decays in the backward direction with $P_e < 0$ and in the forward direction with $P_e > 0$. The hatched regions represent the estimated backgrounds in the two combinations.



binations of the production angle and the sign of P_e. For left-handed incident e^- and τ^- emitted at forward polar angles, or for right-handed beam and τ^- in the backward region, the τ^- are predominantly left-handed and the π energy spectrum is expected to be relatively soft. For the two opposite combinations of P_e and $\cos\theta$, the spectrum should be harder since the decaying τ^- are predominantly right-handed. Fig. 2(c) shows the same comparison for the $\tau\to\rho\nu_\tau$ decays. The difference is expected to be less obvious for the three-body decays $\tau\to\ell\bar{\nu}_\ell\nu_\tau$, but is still quite visible in Fig. 2(b).

The ν_τ helicity and the Michel parameters ρ, η, ξ and $\delta\xi$ are determined using a maximum likelihood fit to the τ production angle and the energy spectra of the decay channels $\tau\to\pi\nu_\tau$ and $\tau\to\ell\bar{\nu}_\ell\nu_\tau$ (ω spectrum for $\tau\to\rho\nu_\tau$). The following expression is minimized:

$$\mathcal{L} = -2 \sum_{decays} \ln \left\{ \frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta \, dz} \right\}. \tag{5}$$

The sum in Eq. 5 runs over all $\tau\to e\bar{\nu}_e\nu_\tau$, $\tau\to\mu\bar{\nu}_\mu\nu_\tau$, $\tau\to\rho\nu_\tau$ or $\tau\to\pi\nu_\tau$ candidates. The fit function includes effects of γ exchange and $\gamma - Z^0$ interference, radiation, detector resolution, efficiency and backgrounds. The dependence of MC efficiencies and backgrounds on z (ω) and $\cos\theta$ is parametrized using low order polynomials. The effect of initial and final state radiation is determined from the ratio of the spectrum for MC events generated using KORALZ 4.0 [14] (including radiation) to the spectrum for the Born level cross-sections. Effects of detector resolution are studied using MC for each input variable (i.e. track momentum or ω, and τ direction). Fits to multiple Gaussians are performed to model both the core and tails of the resolution distributions, and these functions are convoluted with the theoretical expression. Since the spectra are different for decays of left- and right-handed taus, all the correction functions are divided into four categories corresponding to combinations of positive or negative e^- beam polarization and the forward or backward half of the detector.

TABLE I. Systematic uncertainties ($\times 10^{-2}$).

	h_ν^π	h_ν^ρ	ρ^e	ρ^μ	η^μ	η	ξ^e	ξ^μ	$\delta\xi^e$	$\delta\xi^\mu$
Selection	0.7	2.7	2.7	4.5	13.8	6.6	2.6	4.3	4.4	2.0
Background	1.1	1.3	1.2	13.3	41.7	10.5	1.1	13.1	0.7	6.3
K fraction	0.8									
Rad. corr.	0.5	0.4	0.4	0.4	0.8	0.9	0.2	0.1	0.2	0.1
Resolution	1.3	1.5	3.8	2.6	5.1	9.2	4.9	2.2	5.9	2.9
Beam P_e	0.9	0.6	1.6	0.4	4.5	0.4	0.9	2.1	0.7	0.4
A_e, A_τ [4]	0.7	0.8	0.3	0.2	1.4	0.3	1.6	2.4	1.6	0.8
TOTAL	2.4	3.5	5.1	14.3	44.5	15.5	5.9	14.4	7.6	7.2

These measurements are dominated by statistical errors. Table I summarizes the systematic errors. To investigate these, each parameter used in the fitting program is modified by its uncertainty, the fit is redone to obtain new values of h_{ν_τ}, ρ, η, ξ and $\delta\xi$, and changes in the fitted values are taken as the systematic errors. The validity of these errors has been checked by comparing data and MC distributions, for example, of cluster energies, number of associated and unassociated clusters, and π^0 and ρ-meson reconstructed masses. The effect of increasing the detector resolution in the data was studied and found to be small. The observed number of events and the calculated efficiencies and backgrounds are consistent with measured branching ratios [2]. The uncertainty in the fraction of kaons in the $\tau\to\pi\nu_\tau$ sample affects the correction for the kaon mass. The errors on radiative corrections are dominated by MC statistics. The beam polarization uncertainties are as

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These parameters were originally conceived to describe μ decay. They describe the energy and angular spectra of the resultant electron with respect to the initial μ spin direction. Lepton universality implies that the τ Michel parameters should be identical to the well-measured μ Michel parameters [1, 2].

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