

## Search for Lepton Flavor Violating Decays $\tau^\pm \rightarrow l^\pm \omega$

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A search for lepton flavor violating decays of a  $\tau$  to a lighter-mass charged lepton and an  $\omega$  vector meson is performed using  $384.1 \text{ fb}^{-1}$  of  $e^+e^-$  annihilation data collected with the *BABAR* detector at the Stanford Linear Accelerator Center PEP-II storage ring. No signal is found, and the upper limits on the branching ratios are determined to be  $\mathcal{B}(\tau^\pm \rightarrow e^\pm \omega) < 1.1 \times 10^{-7}$  and  $\mathcal{B}(\tau^\pm \rightarrow \mu^\pm \omega) < 1.0 \times 10^{-7}$  at 90% confidence level.

In the standard model (SM) with massless neutrinos, the lepton number is conserved separately for each generation. However, the discovery of large neutrino mixing [1] requires that lepton flavor violation (LFV) occur, although decays involving charged LFV have not yet been observed. In minimal extensions of the SM that account for neutrino oscillations by the seesaw mechanism of neutrino mass generation, the expected rates of LFV decays are no more than  $10^{-14}$  [2]. Thus the observation of neutrinoless decays like  $\tau^\pm \rightarrow \ell^\pm \omega$ , where  $\ell = e$  or  $\mu$ , would be an unambiguous signature of new physics, while limits on this process would provide constraints on theoretical models such as minimal supersymmetric SM [3], heavy singlet Dirac neutrino [4], and Majorana neutrino models [5].

The search for  $\tau^\pm \rightarrow \ell^\pm \omega$  decays presented here uses data recorded by the *BABAR* detector at the SLAC PEP-II asymmetric-energy  $e^+e^-$  storage ring. The data sample corresponds to an integrated luminosity  $\mathcal{L} = 347.5 \text{ fb}^{-1}$  recorded at an  $e^+e^-$  center-of-mass (c.m.) energy  $\sqrt{s} = 10.58 \text{ GeV}$ , and  $36.6 \text{ fb}^{-1}$  recorded at  $\sqrt{s} = 10.54 \text{ GeV}$ . With an average cross section of  $\sigma_{e^+e^- \rightarrow \tau^+\tau^-} = (0.919 \pm 0.003) \text{ nb}$  [6], this corresponds to a sample of  $3.53 \times 10^8$   $\tau$ -pair events.

The details of the *BABAR* detector are described elsewhere [7]. Charged particles are reconstructed as tracks with a five-layer silicon vertex tracker and a 40-layer drift chamber inside a 1.5 T solenoidal magnet. An electromagnetic calorimeter consisting of 6580 CsI(Tl) crystals is used to identify electrons and photons. A ring-imaging Cherenkov detector is used to identify charged pions and kaons. The flux return of the solenoid, instrumented with resistive plate chambers and limited streamer tubes, is used to identify muons.

The signature of the signal process is the presence of a  $\ell\omega$  pair having an invariant mass consistent with  $m_\tau = 1.777 \text{ GeV}/c^2$  [8] and a total energy equal to  $\sqrt{s}/2$  in the c.m. frame, along with other particles in the event whose properties are consistent with a  $\tau$  decay. Only the dominant decay mode of the  $\omega$  meson ( $\omega \rightarrow \pi^+\pi^-\pi^0$ ) is used in this analysis. The estimation of the background rate in the final sample comes from data only, while samples of Monte Carlo (MC) simulated events are used to obtain the signal reconstruction efficiency, the kinematic distributions of the signal and background events, to optimize the selection criteria and to study systematic uncertainties in the signal efficiency. Control samples with two identified electrons in the event are used to study background contamination from radiative Bhabha scattering, since the relevant cross section is large, making it impractical to generate a sufficient number of simulated events.

The signal events are simulated with KK2F [9], where one  $\tau$  decays to  $\ell^\pm\omega$  according to two-body phase space and the other  $\tau$  decays according to measured branching fractions [10] simulated with TAUOLA [11]. The  $\mu^+\mu^-$  and  $\tau^+\tau^-$  background processes are generated using KK2F and

TAUOLA, and  $q\bar{q}$  processes are generated using the EVTGEN [12] and JETSET [13] packages. The detector response for the MC events is simulated using the GEANT4 package [14]. Radiative corrections for signal and background processes are simulated using PHOTOS [15].

Events with four well-reconstructed tracks and zero total charge are selected, where no track pair is consistent with being a photon conversion in the detector material. Each event is divided into two hemispheres in the c.m. frame by a plane perpendicular to the thrust axis [16], calculated using all reconstructed charged and neutral particles. The events having 3-1 topology, where the signal-side hemisphere contains three tracks and the tag side contains one track, are selected.

Photon candidates are required to have the measured energy in the electromagnetic calorimeter greater than 0.1 GeV to reduce the background originating from the  $e^+e^-$  colliding beams in the accelerator beam pipe. Pairs of these photons are combined to form  $\pi^0$  candidates, with the invariant mass in the range  $m(\gamma\gamma) \in [0.115, 0.150] \text{ GeV}/c^2$ . The  $\omega$  mesons are reconstructed from two oppositely charged pion candidates combined with a  $\pi^0$ , with the invariant mass in the range  $m(\pi^+\pi^-\pi^0) \in [0.760, 0.805] \text{ GeV}/c^2$ . This corresponds to about  $\pm 3\sigma$  region around its nominal mass, where  $\sigma$  is the measured mass resolution of  $\omega$  candidates. In the  $\tau^\pm \rightarrow \ell^\pm \omega$  decay, two of the tracks in the signal-side hemisphere have the same charge. Each of these two same-sign tracks is combined independently with the opposite-sign track and the neutral pion to form two  $\omega$  candidates. The candidate with invariant mass nearest to the nominal  $\omega$  mass [10] is considered to be the signal  $\omega$ . The signal track that is not combined to form the  $\omega$  candidate is required to have a momentum in the laboratory frame greater than  $0.5 \text{ GeV}/c$  and to be identified as an electron or muon as appropriate, using *BABAR* particle identification techniques [17]. The three tracks in the signal-side hemisphere are fitted to a common vertex, and the photons from the  $\pi^0$  are assumed to originate from this vertex. The reconstructed  $\pi^0$  candidate from the signal  $\tau$  is constrained to the nominal  $\pi^0$  mass [10]. The  $\omega$  candidate is then combined with the lepton track to form the signal  $\tau$  candidate. The signal-side hemisphere may contain up to four photons so as to allow hadronic split-offs from the pion tracks in the EMC. Thus, there may be more than one  $\pi^0$  candidate, resulting in multiple  $\tau$  candidates. In this case, the  $\ell\omega$  combination with invariant mass closest to the nominal  $\tau$  mass is accepted as the signal  $\tau$  candidate. From a sample of  $1.6 \times 10^6$  generated signal MC events, all the reconstructed signal candidates are verified to have correct association with the true signal  $\tau$  decays.

Signal events are distinguished by two kinematic variables: the beam-energy constrained mass ( $m_{\text{EC}}$ ) and the energy difference  $\Delta E = E_\ell + E_\omega - \sqrt{s}/2$ , where  $E_\ell$  and  $E_\omega$  are energies of the lepton and the  $\omega$  in the c.m. frame.



TABLE I. The peak positions and standard deviations of the  $m_{\text{EC}}$  and  $\Delta E$  distributions, obtained from the fit to the signal MC events. Also shown are the reconstruction efficiencies ( $\varepsilon$ ), the number of expected background (exp.) events and the observed (obs.) events inside the signal box, and the resulting upper limits at 90% confidence level (C.L.) including the systematic uncertainties.

Decay modes	$\hat{m}_{\text{EC}}$	$\sigma(m_{\text{EC}})$	$\Delta\hat{E}$	$\sigma(\Delta E)$	$\varepsilon$ (%)	SB events		UL ( $\times 10^{-7}$ )	
	MeV/ $c^2$	MeV/ $c^2$	MeV	MeV		Exp.	Obs.	Exp.	Obs.
$\tau^\pm \rightarrow e^\pm \omega$	$1777.4 \pm 0.1$	$6.8 \pm 0.1$	$-14.4 \pm 0.3$	$32.2 \pm 0.3$	$2.96 \pm 0.13$	$0.35 \pm 0.06$	0	1.4	1.1
$\tau^\pm \rightarrow \mu^\pm \omega$	$1777.7 \pm 0.1$	$6.4 \pm 0.1$	$-11.2 \pm 0.2$	$30.9 \pm 0.3$	$2.56 \pm 0.16$	$0.73 \pm 0.03$	0	1.7	1.0

The  $m_{\text{EC}}$  is calculated from a fit to the reconstructed  $\tau$  candidate decay products with a constraint that the  $\tau$  energy is equal to  $\sqrt{s}/2$  in the c.m. frame. These two variables are weakly correlated and have non-Gaussian tails due to initial and final state radiation. For the signal MC events, the  $m_{\text{EC}}$  distribution peaks at  $m_\tau$ , while the  $\Delta E$  distribution peaks close to but below zero, primarily due to photon energy reconstruction effects producing a small negative offset in the reconstructed  $\tau$  energy. The peak positions ( $\hat{m}_{\text{EC}}$ ,  $\Delta\hat{E}$ ) and standard deviations [ $\sigma(m_{\text{EC}})$ ,  $\sigma(\Delta E)$ ] of the  $m_{\text{EC}}$  and  $\Delta E$  distributions for the reconstructed signal MC events are presented in Table I. To study signal-like events, a large box (LB) is defined in the  $m_{\text{EC}}$  vs  $\Delta E$  plane as:  $m_{\text{EC}} \in [1.6, 2.0]$  GeV/ $c^2$  and  $\Delta E \in [-0.8, 0.4]$  GeV. To avoid experimenter bias, the number and the properties of data events falling within the  $\pm 3\sigma$  rectangular region in the  $m_{\text{EC}} - \Delta E$  plane, defined as the signal box (SB), are neither used to optimize the selection criteria nor to study systematic effects. The region inside the LB but outside the SB is called grand side band (GSB) and is used for estimation of the background contribution in the SB. The selection requirements are optimized to yield the lowest expected upper limit (UL) [18] derived from the events inside the SB under a background-only hypothesis.

To suppress non- $\tau$  backgrounds with radiation along the beam direction, the polar angle of the missing momentum with respect to beam axis ( $\theta_{\text{miss}}$ ) is required to lie within the detector acceptance:  $\cos\theta_{\text{miss}} \in [-0.76, 0.92]$ . The total c.m. momentum of all tracks and photon candidates in the tag side must be less than 4.75 GeV/ $c$ .

The events are classified into four different categories depending on tag-side hemisphere properties: the particle identification for the track and the total neutral c.m. energy in the hemisphere ( $\Sigma E_{\text{neutral}}^{\text{CM}}$ ). If the tag-side track is identified as an electron or a muon it is categorized as an  $e$  tag or a  $\mu$  tag. Otherwise it is categorized as an  $h$  tag or a  $\rho$  tag, depending on whether  $\Sigma E_{\text{neutral}}^{\text{CM}}$  is less than or greater than 0.2 GeV. The  $e$ -tag events are not used in the final selection of  $\tau^\pm \rightarrow e^\pm \omega$  candidates, but are used as the control sample to estimate the Bhabha contribution to this decay mode.

The tag-side hemisphere is expected to contain a SM  $\tau$  decay characterized by the presence of one charged particle and one or two neutrinos. The missing mass due to the undetected neutrino(s) is reconstructed as  $m_\nu^2 =$

$(P_\tau^{\text{tag}} - P_{\text{obs}}^{\text{tag}})^2$ , where  $P_\tau^{\text{tag}}$  and  $P_{\text{obs}}^{\text{tag}}$  are four-momenta in the c.m. frame. The energy and momentum components of  $P_\tau^{\text{tag}}$  are  $[\sqrt{s}/2, \sqrt{(s/4 - m_\tau^2)} \cdot \hat{n}]$  where  $\hat{n}$  is the unit vector opposite in direction to the signal-side  $\tau$  momentum and  $P_{\text{obs}}^{\text{tag}}$  is the combined four-momentum in the c.m. frame of all the tracks and photon candidates observed in the tag-side hemisphere. To reduce non- $\tau$  backgrounds, tag-dependent requirements on  $m_\nu^2$  are applied for the  $\tau^\pm \rightarrow \mu^\pm \omega$  candidates. For  $e$  tags and  $\mu$  tags,  $m_\nu^2$  must be in the range  $\in [-2.0, 2.5]$  GeV $^2/c^4$ , whereas for  $h$  tags and  $\rho$  tags,  $m_\nu^2 \in [-1.2, 2.0]$  GeV $^2/c^4$  and  $m_\nu^2 \in [-2.0, 0.5]$  GeV $^2/c^4$ , respectively. As  $\tau^\pm \rightarrow e^\pm \omega$  candidates suffer small background contamination, no  $m_\nu^2$  requirement is applied on them. For the  $\tau^\pm \rightarrow \mu^\pm \omega$  candidates, the ratio  $p_{\text{miss}}^T/\sqrt{s}$  in the c.m. frame is required to be greater than 0.061, where  $p_{\text{miss}}^T$  is the component of the missing momentum of the event transverse to the beam direction. For  $\tau^\pm \rightarrow e^\pm \omega$  candidates,  $p_{\text{miss}}^T/\sqrt{s}$  is required to be greater than 0.034.

After applying all the selection criteria for  $\tau^\pm \rightarrow e^\pm \omega$  and  $\tau^\pm \rightarrow \mu^\pm \omega$  decays, the number of data events surviving inside the GSB are 39 and 502, respectively, as shown in Fig. 1. The number of background events in the MC and control samples, in the same region and passing the same set of requirements as data, is  $35 \pm 6$  for  $\tau^\pm \rightarrow e^\pm \omega$  and  $564 \pm 26$  for  $\tau^\pm \rightarrow \mu^\pm \omega$  decay. Out of these MC background events in the  $\tau^\pm \rightarrow e^\pm \omega$  decay, the dominant contributions are from  $q\bar{q}$  (54%) and  $\tau^+\tau^-$  (34%); the rest arise from radiative Bhabha scattering. About 92% of the

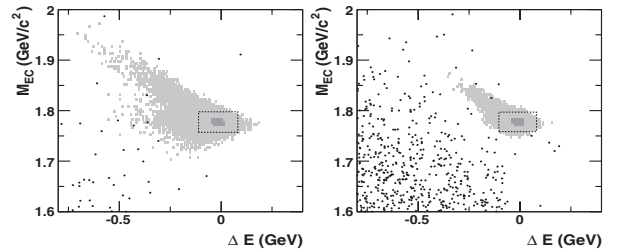


FIG. 1. The selected candidates (dots) inside the large box region of the  $m_{\text{EC}} - \Delta E$  plane for  $\tau^\pm \rightarrow e^\pm \omega$  (left plot) and  $\tau^\pm \rightarrow \mu^\pm \omega$  (right plot) decays. The  $\pm 3\sigma$  signal box is shown by a dashed rectangle. The dark and light shading indicates contours containing 50% and 90% of the selected MC signal events, respectively. The signal box contains 67% of the selected MC signal events for  $\tau^\pm \rightarrow e^\pm \omega$  and 77% for  $\tau^\pm \rightarrow \mu^\pm \omega$  decay.

TABLE II. The expected number of background events obtained from the fit to  $m_{\text{EC}} - \Delta E$  distributions within the  $\pm(3-5)\sigma$ ,  $\pm(5-7)\sigma$ ,  $\pm(7-9)\sigma$ ,  $\pm(9-11)\sigma$ , and the combined  $\pm(3-11)\sigma$  nested rectangular regions centered around the signal box. Also shown are the number of observed events inside the corresponding regions.

Decay modes	Number of events	$\pm(3-5)\sigma$	$\pm(5-7)\sigma$	$\pm(7-9)\sigma$	$\pm(9-11)\sigma$	$\pm(3-11)\sigma$
$\tau^\pm \rightarrow e^\pm \omega$	Expected	$0.6 \pm 0.1$	$1.0 \pm 0.2$	$1.4 \pm 0.2$	$1.9 \pm 0.3$	$4.9 \pm 0.8$
	Observed	0	0	1	2	3
$\tau^\pm \rightarrow \mu^\pm \omega$	Expected	$1.9 \pm 0.1$	$3.9 \pm 0.2$	$6.7 \pm 0.3$	$12.1 \pm 0.5$	$24.6 \pm 1.1$
	Observed	2	3	7	10	22

background in  $\tau^\pm \rightarrow \mu^\pm \omega$  decay is from  $\tau^+ \tau^-$  events; within this category, 94% are due to the decay  $\tau^- \rightarrow 2\pi^- \pi^+ \pi^0 \nu$ , where one of the charged pions is misidentified as a muon. The number of background events in the  $\tau^\pm \rightarrow \mu^\pm \omega$  sample is more than  $\tau^\pm \rightarrow e^\pm \omega$  because of the larger misidentification rate for a pion track to be identified as a muon than an electron. The background contamination from the two-photon events are estimated to be negligible.

The number of expected background events in the SB is extracted from an unbinned maximum likelihood fit to the  $m_{\text{EC}}$  and  $\Delta E$  distributions of data events inside the GSB, using a two-dimensional probability density function (PDF) made of a linear combination of PDFs representing each background component,  $e^+ e^-$ ,  $\mu^+ \mu^-$ ,  $\tau^+ \tau^-$ , and  $q\bar{q}$ . The MC event samples are used to determine each component PDF but the one describing radiative Bhabha events, for which a data control sample is used. Each PDF is obtained by interpolating the two-dimensional binned distribution of its respective sample using Gaussian weight terms that are fit with an adaptive kernel estimation procedure [19]. The expected background normalization is fixed to the amount of data events in the GSB, while the relative yields of the different background components are fitted to the background shape. The numbers of background events expected from this fit for various regions around the SB are compared with the numbers observed in Table II, and they confirm that the backgrounds in the data are adequately modeled.

Systematic uncertainties on the signal efficiency and the estimated background are considered in this measurement. The uncertainty due to knowledge of the efficiencies for trigger, for the tracking, and in the beam-energy scale and spread is 1.4% for both decay modes. An uncertainty of 2.0% originates from uncertainties on the lepton track momentum and on the photon energy scale and resolution, which affect the position and spread of the  $\Delta E$  and  $m_{\text{EC}}$  distributions. There is a 3.3% uncertainty in the  $\pi^0$  reconstruction efficiency, the uncertainty in lepton identification is 1.1% for electrons and 4.5% for muons. The uncertainty associated with the  $\tau$  pair production cross section is 0.3% [6] and the luminosity determination uncertainty is 0.9%. An uncertainty of 0.8% originates from the accuracy of the  $\omega \rightarrow \pi^+ \pi^- \pi^0$  branching fraction measurement. After combining these individual contributions in quadrature,

the total systematic uncertainty on efficiency is 4.4% for  $\tau^\pm \rightarrow e^\pm \omega$  and 6.2% for  $\tau^\pm \rightarrow \mu^\pm \omega$ . The uncertainties on background estimation are determined by the background fit errors. The uncertainty due to MC statistics is negligible.

The signal is simulated according to the two-body phase space, i.e., with a uniform distribution of the cosine of the helicity angle with respect to the  $\tau$  spin. Since  $\tau$  pairs are produced with spin correlation, the event selection efficiency may be sensitive to the helicity angle distribution of the  $\tau^\pm \rightarrow \ell^\pm \omega$  decay, which depends on the model of the LFV interaction [20]. This effect is simulated by weighting the generated events to match the helicity angle distributions of both  $V-A$  and  $V+A$  interactions and its consequences on the measured upper limit are found to be negligible.

The upper limits for  $\tau^\pm \rightarrow \ell^\pm \omega$  decays are calculated using  $\mathcal{B}_{\text{UL}}^{90} = N_{\text{UL}}^{90} / (2\mathcal{L}\sigma_{\tau\tau}\mathcal{B}\varepsilon)$ , where  $N_{\text{UL}}^{90}$  is the 90% C.L. upper limit on the number of signal events inside the SB,  $\mathcal{B}$  is the branching fraction [10] of the decay  $\omega \rightarrow \pi^+ \pi^- \pi^0$  ( $\pi^0 \rightarrow \gamma\gamma$ ), and  $\varepsilon$  is the reconstruction efficiency of the signal decay mode under consideration. The expected and observed upper limits, including all contributions from systematic uncertainties, are calculated using the technique of Cousins and Highland [21] with the implementation of Barlow [22]. No signal is found, and the upper limits on the branching ratios are determined to be  $\mathcal{B}(\tau^\pm \rightarrow e^\pm \omega) < 1.1 \times 10^{-7}$  and  $\mathcal{B}(\tau^\pm \rightarrow \mu^\pm \omega) < 1.0 \times 10^{-7}$  at 90% confidence level, as shown in Table I.

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