Search for Lepton Flavor Violating Decays $\tau^{\pm} \to \ell^{\pm}\pi^{0}, \ell^{\pm}\eta, \ell^{\pm}\eta'$

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(Received 23 October 2006; published 8 February 2007)

A search for lepton flavor violating decays of the τ lepton to a lighter mass lepton and a pseudoscalar meson has been performed using 339 fb^{-1} of e^+e^- annihilation data collected at a center-of-mass energy near 10.58 GeV by the *BABAR* detector at the SLAC PEP-II storage ring. No evidence of a signal has been found, and upper limits on the branching fractions are set at the 10^{-7} level.

DOI: 10.1103/PhysRevLett.98.061803 PACS numbers: 13.35.Dx, 14.60.Fg, 11.30.Hv

The recent discovery of large neutrino mixing [1] suggests that lepton flavor violation (LFV) occurs. Charged LFV decays have not yet been observed, although they have long been identified as an unambiguous signature of new physics. Neutrinoless decays like $\tau^\pm \to \ell^\pm P^0$, where $\ell = e$, μ and $P^0 = \pi^0$, η, η', are likely candidates for LFV [2,3], which could be induced by potentially large mixing between the supersymmetric partners of the leptons and is further enhanced by color factors associated with these semileptonic decays. Some models with heavy Dirac neutrinos [4,5], two Higgs doublet models, R-parity violating supersymmetric models, and flavor changing Z' models with nonuniversal couplings [6] allow for observable parameter space of new physics [7], while respecting the existing experimental bounds [8].

The results presented here use an integrated luminosity $\mathcal{L} = 339\ \text{fb}^{-1}$ collected at a center-of-mass (c.m.) energy, $\sqrt{s}$, near 10.58 GeV by the detector at the SLAC PEP-II e^+e^- asymmetric-energy storage ring. Details of the *BABAR* detector are described elsewhere [9].

The signature of the signal process is the presence of an ℓP^0 pair having an invariant mass consistent with $m_\tau = 1.777\ \text{GeV}/c^2$ [10] and a total energy equal to $\sqrt{s}/2$ in the c.m. frame, along with other particles in $e^+e^- \to \tau^+\tau^-$ events having properties consistent with a τ lepton decay. Two neutral decay modes ($\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$) and three charged decay modes [$\eta \to \pi^+\pi^-\pi^0$ ($\pi^0 \to \gamma\gamma$), $\eta' \to \pi^+\pi^-\eta$ ($\eta \to \gamma\gamma$), and $\eta' \to \rho^0\gamma$] are reconstructed. Signal events are simulated with the KK2F [11] Monte Carlo (MC) program, where the $\tau^\pm \to \ell^\pm P^0$ decays according to two body phase space, while the other τ decays according to measured branching fractions [12] simulated with TAUOLA [13]. $\mu^+\mu^-$ and $\tau^+\tau^-$ background processes are generated using KK2F and TAUOLA, and $q\bar{q}$ processes are generated using EVTGEN [14] and JETSET [15]. Radiative corrections are simulated using PHOTOS [16]. The detector response is simulated with GEANT4 [17]. The MC events are used for the optimization and systematic studies of the signal efficiencies, and for determination of the background shapes. Estimates of the rates for the backgrounds are derived directly from the data.

Events with two or four well-reconstructed tracks and zero total charge are selected. Tracks are rejected if they are consistent with coming from photon conversions. An event is divided into two hemispheres ("signal"- and "tag"- sides) in the c.m. frame by a plane perpendicular to the thrust axis [18], calculated using all observed particles.

The signalside hemisphere is required to contain one or three tracks and two photon candidates with energy $E_\gamma > 50$ MeV for the $\pi^0 \to \gamma\gamma$, $\eta \to \pi^+\pi^-\pi^0$ ($\pi^0 \to \gamma\gamma$) and $\eta' \to \pi^+\pi^-\eta$ ($\eta \to \gamma\gamma$) channels, and $E_\gamma > 100$ MeV for the $\eta \to \gamma\gamma$ channel. For the $\eta' \to \rho^0\gamma$ channel, the single photon candidate is required to have $E_\gamma > 100$ MeV. Events with additional photon candidates in the signal hemisphere with $E_\gamma > 100$ MeV are rejected.

The P^0 candidates are reconstructed in the following mass windows: $m(\pi^0 \to \gamma\gamma) \in [0.115, 0.150]\ \text{GeV}/c^2$, $m(\eta \to \gamma\gamma) \in [0.515, 0.565]\ \text{GeV}/c^2$, $m(\eta \to \pi^+\pi^-\pi^0) \in [0.537, 0.558]\ \text{GeV}/c^2$, $m(\eta' \to \pi^+\pi^-\eta) \in [0.950, 0.965]\ \text{GeV}/c^2$, $m(\eta' \to \rho^0\gamma) \in [0.940, 0.970]\ \text{GeV}/c^2$, and $m(\rho^0 \to \pi^+\pi^-) \in [0.600, 0.900]\ \text{GeV}/c^2$. To reduce combinatorial backgrounds, the momentum of P^0 is required to satisfy: $p_{\pi^0} > 0.5\ \text{GeV}/c$ for $\tau^\pm \to e^\pm\pi^0$, $p_{\pi^0} > 1.5\ \text{GeV}/c$ for $\tau^\pm \to \mu^\pm\pi^0$, $p_\eta > 1.0\ \text{GeV}/c$ for $\tau^\pm \to e^\pm\eta$ ($\eta \to \gamma\gamma$), $p_\eta > 1.4\ \text{GeV}/c$ for $\tau^\pm \to \mu^\pm\eta$ ($\eta \to \gamma\gamma$), $p_\eta > 1.2\ \text{GeV}/c$ for $\tau^\pm \to \mu^\pm\eta$ ($\eta \to \pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$) and $p_{\eta'} > 1.3\ \text{GeV}/c$ for $\tau^\pm \to \mu^\pm\eta'$ ($\eta' \to \rho^0\gamma$) decays.

The track unassociated with any of the P^0 daughters is required to have a momentum $>0.5\ \text{GeV}/c$ and is identified as an electron or muon, but not as a kaon, using standard *BABAR* particle-identification techniques [19]. In the case of a charged P^0 decay, this criteria is applied on the track that combines with the one having opposite-sign charge and the photon candidate(s) to give an invariant mass farthest from the nominal P^0 mass [12]. This provides the correct pairing for $>99.7\%$ of selected signal MC events after particle-identification requirements.

The origin of the photon(s) is assigned to the point of closest approach of the lepton track to the e^+e^- collision axis for neutral P^0 decays, or to the common vertex in the signalside hemisphere for the charged P^0 decays. The P^0 momentum is kinematically fitted with its respective mass constraints, and combined with the lepton track to form the signal τ candidate. An event is accepted based upon the closeness of the signal τ candidate to m_τ.

Signal decays are identified by two kinematic variables: the beam-energy constrained τ mass m_{EC} and $\Delta E \equiv E_\ell + E_{P^0} - \sqrt{s}/2$, where E_ℓ and E_{P^0} are the respective energies in the c.m. frame. These two variables are independent apart from small correlations arising from initial and final state radiation. For signal events, the reconstructed peak positions of the m_{EC} distribution agree very well with m_τ, while those of ΔE vary between -5 to -23 MeV. The shift from zero in the ΔE peak comes from miscalibration

TABLE I. The $m_{\rm EC}$ and ΔE resolutions for the signal MC events, the number of observed (obs.) and expected (exp.) events inside $\pm 3\sigma$ to $\pm 11\sigma$ boxes and $\pm 2\sigma$ box, the branching fractions ($\mathcal{B}$), the efficiencies (ε), and the 90% C.L. upper limits (UL).

Decay modes	$\sigma(m_{\rm EC})$ MeV/c^2	$\sigma(\Delta E)$ MeV	$\pm 3\sigma$ to $\pm 11\sigma$ box obs.	exp.	$\pm 2\sigma$ box obs.	exp.	$\mathcal{B}$ (%)	ε (%)	UL ($\times 10^{-7}$) obs.	exp.
$\tau^\pm \to e^\pm \pi^0$ ($\pi^0 \to \gamma\gamma$)	9.1	46.4	4	5.37 ± 1.14	0	0.17 ± 0.04	98.80 ± 0.03	2.83 ± 0.25	1.3	1.4
$\tau^\pm \to \mu^\pm \pi^0$ ($\pi^0 \to \gamma\gamma$)	9.0	46.4	43	40.68 ± 4.32	1	1.33 ± 0.15	98.80 ± 0.03	4.75 ± 0.37	1.1	1.1
$\tau^\pm \to e^\pm \eta$ ($\eta \to \gamma\gamma$)	8.5	42.6	4	4.99 ± 1.18	0	0.20 ± 0.05	39.38 ± 0.26	3.59 ± 0.24	2.5	2.8
$\tau^\pm \to e^\pm \eta$ ($\eta \to \pi^+\pi^-\pi^0$)	5.9	31.4	0	0.64 ± 0.32	0	0.02 ± 0.01	22.43 ± 0.40	3.17 ± 0.32	5.4	5.5
$\tau^\pm \to e^\pm \eta$					0	0.22 ± 0.05	$\mathcal{B}\varepsilon = 2.12 \pm 0.20$ (%)		1.6	1.9
$\tau^\pm \to \mu^\pm \eta$ ($\eta \to \gamma\gamma$)	8.3	40.8	20	17.36 ± 2.12	1	0.67 ± 0.08	39.38 ± 0.26	7.03 ± 0.53	1.9	1.6
$\tau^\pm \to \mu^\pm \eta$ ($\eta \to \pi^+\pi^-\pi^0$)	5.6	31.0	3	2.01 ± 0.41	0	0.08 ± 0.02	22.43 ± 0.40	3.67 ± 0.32	4.5	4.8
$\tau^\pm \to \mu^\pm \eta$					1	0.75 ± 0.08	$\mathcal{B}\varepsilon = 3.59 \pm 0.41$ (%)		1.5	1.3
$\tau^\pm \to e^\pm \eta'$ ($\eta' \to \pi^+\pi^-\eta$)	5.9	31.0	0	0.14 ± 0.14	0	0.01 ± 0.01	17.52 ± 0.56	3.75 ± 0.27	5.8	5.9
$\tau^\pm \to e^\pm \eta'$ ($\eta' \to \rho^0\gamma$)	4.4	24.3	2	2.97 ± 0.54	0	0.11 ± 0.03	29.40 ± 0.90	2.98 ± 0.28	4.2	4.5
$\tau^\pm \to e^\pm \eta'$					0	0.12 ± 0.03	$\mathcal{B}\varepsilon = 1.53 \pm 0.16$ (%)		2.4	2.6
$\tau^\pm \to \mu^\pm \eta'$ ($\eta' \to \pi^+\pi^-\eta$)	5.6	29.1	1	2.42 ± 0.47	0	0.07 ± 0.02	17.52 ± 0.56	5.87 ± 0.46	3.6	3.8
$\tau^\pm \to \mu^\pm \eta'$ ($\eta' \to \rho^0\gamma$)	4.1	23.1	13	11.06 ± 0.65	0	0.42 ± 0.03	29.40 ± 0.90	3.90 ± 0.46	2.7	3.7
$\tau^\pm \to \mu^\pm \eta'$					0	0.49 ± 0.04	$\mathcal{B}\varepsilon = 2.18 \pm 0.26$ (%)		1.4	2.0

of the measured photon energy. The resolutions of the $m_{\rm EC}$ and ΔE distributions for the signal events are presented in Table I. Events in the data within a $\pm 3\sigma$ rectangular box centered around the signal MC peak positions are excluded until all optimization and systematic studies of the selection criteria have been completed. The selection is optimized to yield the smallest expected upper limit [20] in a background-only hypothesis for observing events inside the $\pm 2\sigma$ rectangular signal box around the signal MC peak positions shown in Fig. 1.

The dominant backgrounds are from $\tau \to e\nu\bar{\nu}\gamma$ or $\tau \to \rho\nu$ decays in $\tau^+\tau^-$ events, with additional contributions from Bhabha, di-muon, and $q\bar{q}$ processes. The backgrounds are higher for searches with muons, due to misidentification of a π track as a μ candidate. Another source of background is the misreconstruction of η and π^0 candidates.

Non-τ backgrounds with radiation along the beam directions are suppressed by requiring the polar angle of the missing momentum to lie between -0.76 and 0.92. The total c.m. momentum of all tracks and photon candidates on the tagside is required to be less than 4.75 GeV/c.

A tagside hemisphere containing a single track is classified as e-tag, μ-tag, or h-tag if the track is exclusively identified as an electron, muon, or neither, respectively. For these tags, the total neutral c.m. energy in the hemisphere $\Sigma E_\gamma^{\rm c.m.}$ is required to be less than 0.2 GeV, and the invariant mass $m_{\rm tag}$, calculated using all observed charged and neutral particles, to be less than 0.4 GeV/c^2. For $\tau^\pm \to e^\pm P^0$ channels, the data events in e-tag are used as a control sample to estimate the Bhabha background, and are not included in the final selection. If the track is neither an electron nor a muon, $\Sigma E_\gamma^{\rm c.m.} > 0.2$ GeV and $m_{\rm tag} \in [0.6, 1.3]$ GeV/c^2, the event is classified as a ρ-tag. For searches of neutral P^0 decay modes, events with three tracks in the tagside with $m_{\rm tag} \in [0.9, 1.6]$ GeV/c^2 are also allowed.

Taking the direction of the tagside τ to be opposite the signal candidate, all tracks and photon candidates in the tagside hemisphere are used to calculate the invariant mass

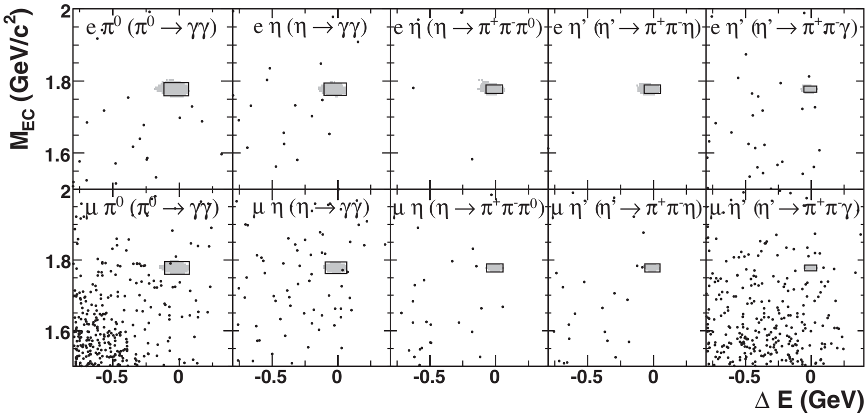

FIG. 1. Selected data (dots) and 68% of signal MC events (shaded region) inside the GSB region, and the $\pm 2\sigma$ signal box.

squared of the tagside missing momentum (m_ν^2). To reduce non-τ backgrounds for $\tau^\pm \to e^\pm \pi^0$, $\tau^\pm \to e^\pm \eta$ ($\eta \to \gamma\gamma$) searches, $(m_\nu^2/1.8\ \mathrm{GeV}^2/c^4) - \ln(2 \times p^T_{\mathrm{miss}}/\sqrt{s})/2.0$ is required to be less than unity [21], where p^T_{miss} is the component of the missing momentum transverse to the collision axis. For the other searches, $-\ln(2 \times p^T_{\mathrm{miss}}/\sqrt{s})$ is required to be less than 2.5, except for $\tau^\pm \to e^\pm \eta$ ($\eta \to \pi^+\pi^-\pi^0$) and $\tau^\pm \to \mu^\pm \eta'$ ($\eta' \to \pi^+\pi^-\eta$) searches, where very few events are expected.

To focus on selected signal-like events, a grand sideband (GSB) is defined in the m_{EC} vs ΔE plane as: $m_{\mathrm{EC}} \in [1.5, 2.0]\ \mathrm{GeV}/c^2$ and $\Delta E \in [-0.8, 0.4]$ GeV. With electrons as the lepton track, 22, 18, 4, 1 and 30 events survive in the GSB for $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, $\eta \to \pi^+\pi^-\pi^0$, $\eta' \to \pi^+\pi^-\eta$ and $\eta' \to \rho^0\gamma$ channels, and 311, 69, 24, 24, and 285 events survive for the corresponding channels with muons as the lepton track, as shown by dots in Fig. 1. Also shown are the shaded regions containing 68% of the selected signal MC events inside the GSB.

The number of expected background events in the signal box is extracted from an unbinned maximum likelihood fit to the distributions of m_{EC} and ΔE in data inside the nonblinded parts of the GSB, using two-dimensional probability density functions (PDF) for e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$ and $q\bar{q}$ backgrounds. The kernel of the PDFs are estimated [22] from the data control samples for e^+e^-, and respective MC events for the others.

The dominant contribution to the uncertainty in background estimation arises from the statistical precision on the selected data sample inside the nonblinded parts of the GSB, or from the variation of background components within $\pm 1\sigma$ from their fitted values. The observed and expected events from the fit to the data inside the $\pm 3\sigma$ to $\pm 11\sigma$ annular boxes and the signal boxes are shown in Table I, which confirm good modeling of the backgrounds in data and show no evidence of signal.

The largest systematic uncertainties in the signal reconstruction efficiency are due to the signal track momentum and the photon energy scale and resolution, estimated by varying the peak position and resolution of the m_{EC} and ΔE distributions. The errors associated with the modeling of each selection variable are estimated from the relative change in signal efficiency when varying the selection criteria by the difference between the data and MC events in the mean of that variable. Other sources of systematic uncertainties include those arising from trigger inefficiencies, tracking and neutral energy reconstruction efficiencies, the signal lepton identification, beam-energy scale and spread, luminosity estimation and $e^+e^- \to \tau^+\tau^-$ cross-section ($\sigma_{\tau\tau} = 0.89 \pm 0.02$ nb) [23]. About 2.4×10^6 MC events are used per channel, resulting in a negligible systematic uncertainty due to MC statistics. Although the signal MC events have been modeled using a two body phase space model, the results obtained in this analysis are insensitive to this assumption as demonstrated by considering the two extreme cases of a $V - A$ and a $V + A$ form of interaction.

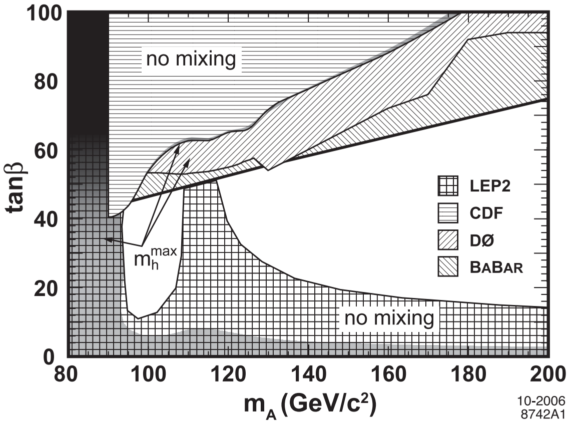

FIG. 2. Excluded regions in $\tan\beta$ vs m_A plane (see text).

The upper limits for $\tau^\pm \to \ell^\pm P^0$ decays are calculated using $\mathcal{B}^{90}_{\mathrm{UL}} = N^{90}_{\mathrm{UL}}/(2\mathcal{L}\sigma_{\tau\tau}\mathcal{B}\varepsilon)$, where N^{90}_{UL} is the 90% confidence level (C.L.) upper limit on the number of signal events inside the signal box, $\mathcal{B}$ and ε are the branching fraction [12] and reconstruction efficiency of the signal decay mode under consideration. To obtain a combined upper limit with η and η' decays, the observed and expected background events and the signal efficiencies are added using $\mathcal{B}\varepsilon = (\mathcal{B}_1 \times \varepsilon_1 + \mathcal{B}_2 \times \varepsilon_2)$, where $\mathcal{B}_1$, $\mathcal{B}_2$ are the respective branching fractions and ε_1 and ε_2 are the corresponding efficiencies. This combination takes into account correlated uncertainties from the track and neutral cluster reconstruction efficiency and the signal lepton identification. The observed and the expected upper limits at 90% C.L. are presented in Table I including all contributions from systematic uncertainties [24,25]. These limits present up to a factor of 4 improvement over the previously published results [8], except for $\tau^\pm \to \mu^\pm \eta$ search, where the limit is similar.

Mixing between left-handed smuons and staus allows one to translate the $\tau^\pm \to \mu^\pm \eta$ limit to an exclusion plot in the $\tan\beta$ vs m_A plane [3], where $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets and m_A is the mass of the pseudoscalar Higgs boson. The excluded regions at 95% C.L. from this $\tau^\pm \to \mu^\pm \eta$ search ($< 1.9 \times 10^{-7}$) with right-handed neutrino mass $= 10^{14}\ \mathrm{GeV}/c^2$ introduced via the seesaw mechanism are shown in Fig. 2. This result is competitive with those obtained from the direct searches for the Higgs boson $\to b\bar{b}$, $\tau^+\tau^-$ decays by CDF [26] and D0 [27], and complementary to the region excluded by the LEP experiments with a top quark mass of 174.3 GeV/c^2 [28], for two common scenarios of stop-mixing benchmark models [29]: $m_h^{\max}$ and no-mixing models obtained with the Higgs mass parameter $\mu = -200\ \mathrm{GeV}/c^2$ shown by darker and lighter shaded regions, respectively.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), MEC (Spain), and PPARC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

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