Search for Lepton-Flavor Violation in the Decay $\tau^- \to \ell^- \ell^+ \ell^-$

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A search for the lepton-flavor-violating decay of the tau into three charged leptons has been performed using 91.5 fb$^{-1}$ of data collected at an $e^+e^-$ center-of-mass energy of 10.58 GeV with the BABAR detector at the PEP-II storage ring. In all six decay modes considered, the numbers...
Lepton-flavor violation (LFV) involving charged leptons has never been observed, and stringent experimental limits exist from muon branching fractions: $\mathcal{B}(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}$ [1] and $\mathcal{B}(\mu \rightarrow ee\mu) < 1.0 \times 10^{-12}$ [2] at 90% confidence level (CL). Recent results from neutrino oscillation experiments [2] show that LFV does indeed occur, although the branching fractions expected in charged lepton decays over muon decays with branching fractions from $10^{-10}$ up to the current experimental limits [3]. Observation of LFV in tau decays would be a clear signature of non-SM physics, while improved limits will provide further constraints on theoretical models.

This analysis is based on data recorded by the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ storage ring operated at the Stanford Linear Accelerator Center. The data sample consists of 81.9 fb$^{-1}$ recorded at $\sqrt{s} = 10.58$ GeV and 9.6 fb$^{-1}$ recorded at $\sqrt{s} = 10.54$ GeV. With an expected cross section for tau pairs at the $\tau^-\tau^-$ mass and energy equal to that of the parent tau lepton, the energy difference is defined as $\Delta E \approx E_{\text{beam}} - \gamma_{\text{rec}}$, where $E_{\text{beam}}$ is the total energy of the decay yields one charged particle (1-prong). Four well reconstructed tracks are required with zero net charge, pointing towards a common region consistent with $\tau^-\tau^-$ production and decay. One of these tracks must be separated from the other three by at least 90° in the CM frame. The plane perpendicular to this isolated track divides the event into two hemispheres and defines the 1-3 topology. Pairs of oppositely charged tracks identified as photon conversions in the detector material with an $e^+e^-$ invariant mass below 30 MeV/c$^2$ are ignored.

Each of the charged particles found in the 3-prong hemisphere must be identified as either an electron or muon candidate. Electrons are identified using the ratio of calorimeter energy to track momentum ($E/p$), the ionization loss in the tracking system ($dE/dx$), and the shape of the shower in the calorimeter. Muons are identified by hits in the IFR and small energy deposits in the calorimeter.

This paper presents a search for LFV in the neutrino-antineutrino mode of events found in data are compatible with the background expectations. Upper limits on the branching fractions are set in the range $(1 - 3) \times 10^{-7}$ at 90% confidence level.
tracks observed in the 3-prong hemisphere and \( E_{\text{beam}} \) is the beam energy, both in the CM frame. The mass difference is defined as \( \Delta M \equiv M_{\text{rec}} - m_\tau \) where \( M_{\text{rec}} \) is the reconstructed invariant mass of the three tracks and \( m_\tau = 1.777 \text{GeV}/c^2 \) is the tau mass \( [10] \).

The signal distributions in the \((\Delta M, \Delta E)\) plane are broadened by detector resolution and radiative effects. The radiation of photons from the incoming \( e^+e^- \) particles before annihilation affects all decay modes, leading to a tail at low values of \( \Delta E \). Radiation from the final-state leptons is more likely for electrons than muons, and produces a tail at low values of \( \Delta M \) as well. Rectangular signal regions are defined separately for each decay mode as follows. For all six decay modes, the upper right corner of the signal region is fixed at \((30 \text{ MeV}/c^2, 50 \text{ MeV})\), while the lower left corner is at \((-70, -120)\) for the \( e^-e^+e^- \) and \( \mu^-e^+e^- \) decay modes, \((-100, -200)\) for \( \mu^+e^-e^- \), \((-50, -200)\) for \( e^+\mu^-\mu^- \), \((-50, -150)\) for \( e^+\mu^+\mu^- \), and \((-30, -150)\) for \( \mu^+\mu^-\mu^- \). All values are given in units of \((\text{MeV}/c^2, \text{MeV})\). These signal region boundaries are chosen to provide the smallest expected upper limits on the branching fractions in the background-only hypothesis. These expected upper limits are estimated using only Monte Carlo (MC) simulations and data control samples, not candidate signal events. Figure 1 shows the observed data in the \((\Delta M, \Delta E)\) plane, along with the signal region boundaries and the expected signal distributions. To avoid bias, a blinded analysis procedure was adopted with the number of data events in the signal region remaining unknown until the selection criteria were finalized and all cross checks were performed.

The efficiency of the selection for signal events is estimated with a MC simulation of LFV tau decays. Simulated tau-pair events including higher-order radiative corrections are generated using KK2f \( [3] \) with one tau decaying to three leptons with a 3-body phase space distribution, while the other tau decays according to measured rates \( [11] \) simulated with Tauola \( [12] \). Final state radiation effects are simulated for all decays using Photos \( [13] \). The detector response is simulated with GEANT4 \( [14] \), and the simulated events are then reconstructed in the same manner as data.

About 50% of the MC signal events pass the 1-3 topology requirement. The lepton identification efficiencies and misidentification probabilities are measured using tracks in kinematically-selected data samples (radiative Bhabha, radiative \( \mu^+\mu^- \), two-photon \( e^+e^-\ell^+\ell^- \), and \( J/\psi \to \ell^+\ell^- \)) and parameterized as a function of particle momentum, polar angle, and azimuthal angle in the laboratory frame. These data-derived efficiencies are then used to give the probability that a simulated MC particle will be identified (or misidentified) as an electron or a muon. For the lepton momentum spectrum predicted by the signal MC, the electron and muon identification requirements are found to have an average efficiency per lepton of 91% and 63%, respectively. The probability for a hadron to be misidentified as an electron in SM 3-prong tau decays is 2.2%, while the probability to be misidentified as a muon is 4.8% \( [15] \). The final efficiency for signal events to be found in the signal region is shown in Table II for each decay mode and ranges from 7% to 12%. This efficiency includes the 85% branching fraction for 1-prong tau decays.

There are three main classes of background remaining after the selection criteria are applied: low multiplicity \( qg \) events (mainly continuum light-quark production), QED events (Bhabha and \( \mu^+\mu^- \)), and SM \( \tau^+\tau^- \) events. These three background classes have distinctive distributions in the \((\Delta M, \Delta E)\) plane: \( qg \) events tend to populate the plane uniformly, while QED backgrounds are restricted to a narrow band at positive values of \( \Delta E \), and \( \tau^+\tau^- \) backgrounds are restricted to negative values of both \( \Delta E \) and \( \Delta M \). A negligible two-photon background remains.

The expected background rates for each decay mode are determined by fitting a set of probability density functions (PDFs) to the observed data in the \((\Delta M, \Delta E)\) plane in a grand sideband (GS) region. The GS region, shown in Fig. 1, is defined as the rectangle bounded by the points \((-600 \text{ MeV}/c^2, -700 \text{ MeV})\) and \((400 \text{ MeV}/c^2, 400 \text{ MeV})\), excluding the signal region. For both the \( qg \) and \( \tau^+\tau^- \) backgrounds, an analytic PDF is constructed from the product of two PDFs \( P_M \) and \( P_E \),
that the particle in the 1-prong hemisphere is identified obtained by fitting control samples with a 1-3 topology. The PDF shape determinations and background fits are constructed from the product of a Crystal Ball function \[17\] in \(\Delta M\) and a linear function in \(\Delta E\) across the Dalitz plane, provided the invariant mass for any pair of leptons is less than 1 GeV. The selection efficiency is found to be uniform within 10% across the Dalitz plane, provided the invariant mass for any pair of leptons is less than 1.4 GeV.

Since the background levels are extracted directly from the data, systematic uncertainties on the background estimation are directly related to the background parameterization and the fit technique used. The finite data available in the GS region to determine the background rates is the largest uncertainty and varies from 10% to 25% depending upon the decay mode. Additional uncertainties are estimated by varying the fit procedure and changing the functional form of the background PDFs. Cross checks of the background estimation were performed by considering the number of events expected and observed in sideband regions immediately neighboring the signal region for each decay mode.

The numbers of events observed \((N_{\text{obs}})\) and the background expectations \((N_{\text{bkgd}})\) are shown in Table 1 with no significant excess found in any decay mode. Upper limits on the branching fractions are calculated according to \(N_{\text{UL}} = N_{\text{UL}}^{bkgd}/(2\varepsilon L\sigma_{\tau\tau})\), where \(N_{\text{UL}}^{bkgd}\) is the 90% CL upper limit for the number of signal events when \(N_{\text{obs}}\) events are observed with \(N_{\text{bkgd}}\) background events expected. The values \(\varepsilon, L,\) and \(\sigma_{\tau\tau}\) are the selection efficiency, luminosity, and \(\tau^+\tau^-\) cross section, respectively. The estimates of \(L = 91.5\,\text{fb}^{-1}\) and \(\sigma_{\tau\tau} = 0.89\,\text{nb}\) are correlated \[19\], and the uncertainty on the product \(L\sigma_{\tau\tau}\) is 2.3%. The branching fraction upper limits have been calculated including all uncertainties using the technique of Cousins and Highland \[20\] following the implementation of Bar-

| Decay mode     | \(e^-e^+e^-\) | \(\mu^-e^-e^-\) | \(\mu^+\mu^-\) | \(\mu^-e^-e^-\) |
|---------------|---------------|---------------|---------------|---------------|
| Efficiency [%] | 7.3 ± 0.2     | 11.6 ± 0.4    | 7.7 ± 0.3     | 7.3 ± 0.2     |
| \(q\bar{q}\)  | 0.67          | 0.17          | 0.39          | 0.67          |
| QED bgd.      | 0.84          | 0.20          | 0.23          | 0.84          |
| \(\tau^+\tau^-\) | 0.00        | 0.01          | 0.00          | 0.00          |
| \(N_{\text{bkgd}}\) | 1.56 ± 0.11   | 0.37 ± 0.08   | 0.62 ± 0.10   | 1.56 ± 0.11   |
| \(N_{\text{obs}}\) | 1            | 0             | 1             | 1             |
| \(E_{\text{UL}}\) | 2.0 \times 10^{-2} | 1.1 \times 10^{-2} | 2.7 \times 10^{-2} | 2.0 \times 10^{-2} |
| Efficiency [%] | 9.8 ± 0.5     | 6.8 ± 0.4     | 6.7 ± 0.5     | 9.8 ± 0.5     |
| \(q\bar{q}\)  | 0.20          | 0.19          | 0.29          | 0.20          |
| QED bgd.      | 0.00          | 0.19          | 0.01          | 0.00          |
| \(\tau^+\tau^-\) | 0.01        | 0.01          | 0.01          | 0.01          |
| \(N_{\text{bkgd}}\) | 0.21 ± 0.07   | 0.39 ± 0.08   | 0.31 ± 0.09   | 0.21 ± 0.07   |
| \(N_{\text{obs}}\) | 0             | 1             | 0             | 0             |
| \(E_{\text{UL}}\) | 1.3 \times 10^{-2} | 3.3 \times 10^{-2} | 1.9 \times 10^{-2} | 1.3 \times 10^{-2} |

where \(P_M(\Delta M)\) is the sum of two Gaussians with a common mean and \(P_E(\Delta E) = (1-x/\sqrt{1+x^2})(1+ax+bx^2+cx^3)\) with \(x = (\Delta E-d)/e\) [14]. The shapes of these PDFs are described by a total of nine free parameters, which are determined by fits to MC \(q\bar{q}\) and \(\tau^+\tau^-\) background samples for each decay mode.

For the QED backgrounds, an analytic PDF is constructed from the product of a Crystal Ball function [17] in \(\Delta E\) and a linear function in \(\Delta M\), where the \((\Delta M, \Delta E)\) axes have been rotated slightly from \((\Delta M, \Delta E)\) to fit the observed distribution. The six parameters of this PDF, including the rotation angle, are obtained by fitting control samples with a 1-3 topology that are enhanced in Bhabha or \(\mu^+\mu^-\) events by requiring that the particle in the 1-prong hemisphere is identified as an electron or muon. Any value for \(\cos\theta_{13}\) is allowed, but the control sample events otherwise pass the selection criteria.

With the shapes of the three background PDFs determined, an unbinned maximum likelihood fit to the data in the GS region is used to find the expected rate of each background type in the signal region, as shown in Table 1. The PDF shape determinations and background fits are performed separately for each of the six decay modes. Figure 2 shows the data and the background PDFs for values of \(\Delta E\) in the signal range.

The largest systematic uncertainty in the signal efficiency is due to the uncertainty in measuring the PID efficiencies. This uncertainty is determined from the statistical precision of the PID control samples, and ranges from 0.7% for \(e^-e^+e^-\) to 6.2% for \(\mu^-e^-e^-\) relative to the efficiency [18]. The modeling of the tracking efficiency contributes an additional 2% uncertainty, as does the statistical limitation of the MC signal sample. All other sources of uncertainty are found to be small, including the modeling in the generator of radiative effects, track momentum resolution, trigger performance, observables used in the selection criteria, and knowledge of the tau 1-prong branching fractions. The efficiency has been estimated using a 3-body phase space model and no uncertainty is assigned for possible model dependence. The selection efficiency is found to be uniform within 10% across the Dalitz plane, provided the invariant mass for any pair of leptons is less than 1.4 GeV/c^2.

Since the background levels are extracted directly from the data, systematic uncertainties on the background estimation are directly related to the background parameterization and the fit technique used. The finite data available in the GS region to determine the background rates is the largest uncertainty and varies from 10% to 25% depending upon the decay mode. Additional uncertainties are estimated by varying the fit procedure and changing the functional form of the background PDFs. Cross checks of the background estimation were performed by considering the number of events expected and observed in sideband regions immediately neighboring the signal region for each decay mode.

The numbers of events observed \((N_{\text{obs}})\) and the background expectations \((N_{\text{bkgd}})\) are shown in Table 1 with no significant excess found in any decay mode. Upper limits on the branching fractions are calculated according to \(N_{\text{UL}} = N_{\text{UL}}^{bkgd}/(2\varepsilon L\sigma_{\tau\tau})\), where \(N_{\text{UL}}^{bkgd}\) is the 90% CL upper limit for the number of signal events when \(N_{\text{obs}}\) events are observed with \(N_{\text{bkgd}}\) background events expected. The values \(\varepsilon, L,\) and \(\sigma_{\tau\tau}\) are the selection efficiency, luminosity, and \(\tau^+\tau^-\) cross section, respectively. The estimates of \(L = 91.5\,\text{fb}^{-1}\) and \(\sigma_{\tau\tau} = 0.89\,\text{nb}\) are correlated [19], and the uncertainty on the product \(L\sigma_{\tau\tau}\) is 2.3%. The branching fraction upper limits have been calculated including all uncertainties using the technique of Cousins and Highland [20] following the implementation of Bar-

![Figure 2: Distribution of \(\Delta M\) for data (solid histogram) and background PDFs (solid curves) for events with \(\Delta E\) in the signal region indicated in Fig. 1. Expected signal distributions are shown (dashed histogram) for a branching fraction of \(10^{-6}\).](image-url)
The 90% CL upper limits on the $\tau^+ \rightarrow \ell^+ \ell^+ \ell^-$ branching fractions, shown in Table II are in the range $(1 - 3) \times 10^{-7}$.

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