Improved Limits on Lepton Flavor Violating Tau Decays to $\ell\phi$, $\ell\rho$, $\ell K^*$, and $\ell\bar{K}^*$

B. Aubert, Y. Kuryotakis, J. P. Lees, V. Poireau, E. Principe, X. Prudent, V. Tisserand, J. Garra Tico, E. Grauges, M. Martinelli, A. Palano, M. Pappagallo, G. Eigen, B. Stugu, L. Sun, M. Battaglia, D. N. Brown, L. T. Kerth, Yu. G. Kolomensky, G. Lynch, I. L. Ospienkov, T. Kackmann, T. Tanabe, C. M. Hawkes, N. Soni, A. T. Watson, H. Koch, T. Schroeder, D. J. Asgeirsson, B. G. Fulsom, C. Hearty, T. S. Mattison, J. A. McKenna, M. Barrett, A. Khan, A. Randle-Conde, V. E. Blinov, A. D. Bukin, A. R. Buzykaev, V. P. Dzhurbin, V. B. Golubev, A. P. Omuchin, S. I. Seredinakov, Yu. I. Skovpen, E. P. Solodov, K. Yu. Todyshev, M. Bondioli, S. Curry, I. Eschrich, D. Kirkby, J. A. Lankford, P. Lund, M. Mandelkern, E. C. Martin, D. P. Stoker, S. Abachi, C. Buchanan, H. Atmacan, J. W. Gary, F. Liu, O. Long, G. M. Vitug, Z. Yasin, L. Zhang, V. Sharma, C. Campagnari, T. M. Hong, D. Kovalskyi, M. A. Mazur, J. D. Richman, T. W. Beck, A. M. Eisner, C. A. Heusch, J. Kroeseberg, W. S. Lockman, A. J. Martinez, T. Schalk, B. A. Schumm, A. Seiden, L. O. Winstrom, C. H. Cheng, D. A. Doll, B. Echenard, F. Fang, D. G. Hitlin, I. Narsky, T. Piatenko, F. C. Porter, R. Andreassen, G. Mancinelli, B. T. Meadows, K. Mishra, M. D. Sokoloff, P. C. Bloom, W. T. Ford, A. Gaz, J. F. Hirschauer, M. Nagel, U. Naumenko, J. G. Smith, S. R. Wagner, R. Ayad, A. Soffer, W. H. Toki, R. J. Wilson, E. Feltresi, A. Hauke, H. Jaspers, T. M. Karbach, J. Merkel, A. Petzold, B. Spaan, K. Wacker, M. J. Kobel, R. Nogowski, K. R. Schubert, R. Schwartz, A. Volk, D. Bernard, G. R. Bonneaud, E. Latour, M. Verderi, P. J. Clark, S. Player, J. E. Watson, M. Andreotti, D. T. Beli, C. Bozzi, R. Calabrese, A. Cecchi, G. Cinabotto, E. Fioravanti, P. Franchini, E. Luppi, M. Munerato, M. Negrini, A. Petrella, L. Piemontese, V. Santoro, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, S. Pacetti, P. Patteri, I. M. Peruzzi, M. Piccolo, M. Rama, A. Zallo, R. Controni, E. Guido, M. Lo Vetere, M. R. Monge, S. Pasquali, C. Patrignani, E. Robutti, S. Tosi, K. S. Chaisanguanthum, M. Morii, A. Ademetz, J. Marks, S. Schenk, U. Uwer, F. U. Bernlochner, V. Klose, H. M. Lacker, D. J. Bard, P. D. Duncey, M. Tibbetts, P. K. Behera, M. J. Charles, U. Mallik, J. Cochran, H. B. Crawley, L. Dong, V. Eyges, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubini, Y. Y. Gao, A. V. Gritsan, Z. J. Guo, N. Arnaud, J. Béquilléux, A. D’Orazio, M. Davier, D. Derkach, J. Firmino da Costa, G. Grosdidier, F. Le Diberder, L. Pellegrini, A. M. Lutz, B. Malescu, S. Pruvot, P. Roudeau, M. H. Schune, J. Serrano, V. Sordini, A. Stocchi, G. Wormser, D. J. Lange, D. M. Wright, I. Bingham, J. P. Burke, C. A. Chavez, J. R. Fry, E. Gabathuler, R. Granet, D. E. Hutchcroft, D. J. Payne, C. Touramanis, A. J. Bevan, C. K. Clarke, F. Di Lodovico, S. Racco, M. Sigamani, G. Cowan, S. Parmeswaran, A. C. Wren, D. N. Brown, C. L. Davis, A. G. Denig, M. Fritsch, K. E. Alway, J. Bailey, R. J. Barlow, G. Jackson, G. D. Lafferty, T. J. West, J. J. Yi, J. Anderson, C. Chen, A. Jawahery, D. A. Roberts, G. Simi, J. M. Tuggle, C. Dallapiccola, E. Salvati, S. Saremi, R. Cowan, D. Dujnic, P. H. Fisher, S. W. Henderson, G. Sciolli, M. Spitznagel, R. K. Yamamoto, M. Zhao, P. M. Patel, S. H. Robertson, M. Schram, A. Lazaro, V. Lombardo, F. Palombo, S. Stracka, J. M. Bauer, L. Cremaldi, R. Godang, R. Kroeger, D. J. Summers, H. W. Zhao, M. Simard, P. Taras, D. Nardo, L. Lista, D. Monorchio, G. Onorato, C. Sciaccia, G. Raven, H. L. Snoek, C. P. Jessop, J. Knoepfel, J. M. LoSecco, W. F. Wang, L. A. Corwin, H. Konsche, R. Kagan, J. P. Morris, A. M. Rahimi, J. J. Regensburger, S. J. Sekula, Q. K. Wong, N. L. Blount, J. Braun, F. Frey, O. Ignonkina, J. A. Kolb, M. Lu, R. Rahmat, N. B. Sinev, D. Strom, J. Strobel, E. Torrence, G. Castelli, N. Gagliardi, M. Margoni, M. Morandin, M. Possolo, M. Rotondo, F. Simonetto, R. Stroili, C. Voci, P. del Amo Sanchez, E. Ben-Haim, H. Brient, J. Chauveau, O. Hamon, Ph. Lerusse, G. Marchiori, J. Ocariz, A. Perez, J. Prendik, S. Sitt, L. Gladney, M. Biasini, E. Manoni, C. Angelini, G. Batignani, S. Bettarini, G. Calderini, M. Carpinelli, M. Cervelli, F. Forti, M. A. Giorgi, A. Lusiani, M. Morganti, N. Neri, E. Paoloni, G. Rizzo, J. J. Walsh.
We search for the neutrinoless, lepton-flavor-violating tau decays \( \tau^- \rightarrow \ell^- V^0 \), where \( \ell \) is an electron or muon and \( V^0 \) is a vector meson reconstructed as \( \phi \rightarrow K^+ K^- \), \( \rho \rightarrow \pi^+ \pi^- \), \( K^+ \pi^- \), \( t \rightarrow K^- \pi^+ \). The analysis has been performed using 451 fb\(^{-1}\) of data collected at an \( e^+ e^- \) center-of-mass energy near 10.58 GeV with the BABAR detector at the PEP-II storage rings. The number of events found in the data is compatible with the background expectation, and upper limits on the branching fractions are set in the range \( (2.6 - 19) \times 10^{-8} \) at the 90% confidence level.

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Lepton-flavor violation (LFV) involving tau leptons has never been observed, and recent experimental results have placed stringent limits on the branching fractions for 2- and 3-body neutrinoless tau decays \( 1, 2, 3 \). Many descriptions of physics beyond the Standard Model (SM) predict such decays \( 4, 5 \); and certain models \( 6, 7 \).
specifically predict semileptonic tau decays such as $\tau \rightarrow \ell \phi/\rho/K^*/K^\ast$ ($\tau \rightarrow \ell^{-} V^0$), with rates as high as the current experimental limits [3]. An observation of these decays would be a clear signature of physics beyond the SM, while improved limits will further constrain models of new physics.

This paper presents a search for LFV in a set of eight neutrinoless decay modes $\tau \rightarrow \ell^{-} V^0$ [3], where $\ell$ is an electron or muon and $V^0$ is a neutral vector meson decaying to two charged hadrons ($V^0 \rightarrow h^+ h^- $) via one of the following four decay modes: $\phi \rightarrow K^+ K^-$, $\rho \rightarrow \pi^+ \pi^-$, $K^* \rightarrow K^+ \pi^-$, $K^\ast \rightarrow \pi^+ K^-$. This analysis is based on data recorded by the Babar detector at the PEP-II asymmetric-energy $e^+ e^-$ storage rings operated at the SLAC National Accelerator Laboratory. The Babar detector is described in detail in Ref. [11]. The data sample consists of 410 fb$^{-1}$ recorded at an $e^+ e^-$ center-of-mass (c.m.) energy $\sqrt{s} = 10.58$ GeV, and 40.8 fb$^{-1}$ recorded at $\sqrt{s} = 10.54$ GeV. With a calculated cross section for tau pairs of $\sigma_{\tau \tau} = 0.919 \pm 0.003$ nb [3, 10] at the stated luminosity-weighted $\sqrt{s}$, this data set corresponds to the production of about 830 million tau decays.

We use a Monte Carlo (MC) simulation of lepton-flavor-violating tau decays to optimize the search. Tau-pair events including higher-order radiative corrections are generated using KK2f [10]. One tau decays via two-body phase space to a lepton and a vector meson, with the meson decaying according to the measured branching fractions [12]. The other tau decays via SM processes simulated with TAUOLA [13]. Final state radiative effects are simulated for all decays using PHOTOS [14]. The detector response is modeled with GEANT4 [15], and the simulated events are then reconstructed in the same manner as data. SM background processes are modeled with a similar software framework.

We search for the signal decay $\tau \rightarrow \ell^{-} V^0 \rightarrow \ell^- h^+ h^-$ by reconstructing $e^+ e^- \rightarrow \tau^+ \tau^-$ candidates in which three charged particles, each identified as the appropriate lepton or hadron, have an invariant mass and energy close to that of the parent tau lepton. Candidate signal events are first required to have a "3-1 topology," where one tau decay yields three charged particles, while the second tau decay yields one charged particle. This requirement on the second tau decay greatly reduces the background from continuum multi-hadron events. Events with four well-reconstructed tracks and zero net charge are selected, and the tracks are required to point toward a common region consistent with $\tau^+ \tau^-$ production and decay. The polar angle of all four tracks in the laboratory frame is required to be within the calorimeter acceptance. Pairs of oppositely-charged tracks are ignored if their invariant mass, assuming electron mass hypotheses, is less than 30 MeV/$c^2$. Such tracks are likely to be from photon conversions in the traversed material. The event is divided into hemispheres in the $e^+ e^-$ c.m. frame using the plane perpendicular to the thrust axis, as calculated from the observed tracks and neutral energy deposits. The signal (3-prong) hemisphere must contain exactly three tracks while the other (1-prong) hemisphere must contain exactly one. Each of the charged particles found in the 3-prong hemisphere must be identified as a lepton or hadron candidate appropriate to the search channel. The relevant particle identification capabilities of the Babar detector are described in Ref. [2].

To further suppress backgrounds from quark pair production, Bhabha scattering events, and SM tau pair production, we apply additional selection criteria separately in the eight different search channels. Specific cut values are shown in Tab. I. All selection criteria are optimized to provide the smallest expected upper limit on the branching fraction in the background-only hypothesis. Resonant decays are selected with cuts on the invariant mass of the two hadrons in the 3-prong hemisphere ($m_{hh}$). The invariant mass of the 1-prong hemisphere ($m_{1-pr}$) is calculated from the charged and neutral particles in that hemisphere and the total missing momentum in the event. As the missing momentum in signal events results from one or more neutrinos in the 1-prong hemisphere, this mass is required to be near the tau mass. Background events from quark pair production are suppressed with cuts on the missing transverse momentum in the event ($p_T^{miss}$), the scalar sum of all transverse momenta in the c.m. frame ($p_T^{c.m.}$), and the number of photons in the 1-prong and 3-prong hemispheres ($n_{\gamma_{pr}}$, $n_{\gamma_{3pr}}$). To reduce the background contribution from radiative Bhabha and di-muon events, the 1-prong and 3-prong momentum vectors must not be collinear in the c.m. frame. For the same reason, the 1-prong track must not be identified as an electron for the $\tau \rightarrow e^- \rho$ search.

| Channel | $e\phi$ | $\mu\phi$ | $e\rho$ | $\mu\rho$ | $eK^*$ | $\mu K^*$ | $eK^\ast$ | $\mu K^\ast$ |
|---------|-------|--------|------|------|-------|-------|-------|-------|
| $m_{hh}$ min | 0.000 | 0.005 | 0.6 | 0.6 | 0.8 | 0.82 | 0.80 | 0.78 |
| $m_{hh}$ max | 1.040 | 1.035 | 0.92 | 0.96 | 1.0 | 1.08 | 1.04 | 1.00 |
| $m_{1-pr}$ min | 0.3 | 0.4 | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 | 0.3 |
| $m_{1-pr}$ max | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| $p_T^{miss}$ min | 0.4 | 0.3 | 0.4 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 |
| $p_T^{c.m.}$ min | 0.5 | - | - | 0.6 | - | 0.3 | - | - |
| $n_{\gamma_{pr}}$ max | 4 | 3 | 3 | 1 | 1 | 3 | 2 | - |
| $n_{\gamma_{3pr}}$ max | 3 | 1 | 1 | 2 | 1 | 2 | 1 | 1 |

As a final discriminant, we require candidate signal events to have an invariant mass and total energy in the 3-prong hemisphere consistent with a parent tau lepton. These quantities are calculated from the measured track momenta, assuming lepton and hadron masses that correspond to the neutrinoless tau decay in each search channel. The energy difference is defined as...
\[ \Delta E \equiv E_{\text{rec}}^* - E_{\text{beam}}^* \], where \( E_{\text{rec}}^* \) is the total energy of the tracks observed in the 3-prong hemisphere and \( E_{\text{beam}}^* \) is the beam energy, with both quantities calculated in the c.m. frame. The mass difference is defined as \( \Delta M \equiv M_{\text{EC}} - m_\tau \) where \( M_{\text{EC}} \) is calculated from a kinematic fit to the 3-prong track momenta with the energy constrained to be \( \sqrt{s}/2 \) in the c.m. frame, and \( m_\tau = 1.777 \text{ GeV}/c^2 \) is the tau mass. While the energy constraint significantly reduces the spread of \( \Delta M \) values, it also introduces a correlation between \( \Delta M \) and \( \Delta E \), which must be taken into account when fitting distributions in this 2-dimensional space.

Detector resolution and radiative effects broaden the signal distributions in the \( (\Delta M, \Delta E) \) plane. Because of the correlation between \( \Delta M \) and \( \Delta E \), the radiation of photons from the incoming \( e^+e^- \) particles produces a tail at positive values of \( \Delta M \) and negative values of \( \Delta E \). Radiation from the final-state leptons, which is more likely for electrons than muons, leads to a tail at low values of \( \Delta E \). Rectangular signal boxes (SB) in the \( (\Delta M, \Delta E) \) plane are defined separately for each search channel. As with previous selection criteria, the SB boundaries are chosen to provide the smallest expected upper limit on the branching fraction. The expected upper limit is estimated using only MC simulations and data events in the sideband region, as described below. Figure 1 shows the observed data in the Large Box (LB) of the \( (\Delta M, \Delta E) \) plane, along with the SB boundaries and the expected signal distributions. Table 1 lists the channel-specific dimensions of the SB. While a small fraction of the signal events lie outside the SB, the effect on the final result is negligible. To avoid bias, we use a blinded analysis procedure with the number of data events in the SB remaining unknown until the selection criteria are finalized and all crosschecks are performed.

| Mode | \( \epsilon \phi \) | \( \epsilon \rho \) | \( \epsilon K^+ \) | \( \epsilon K^- \) | \( \mu \phi \) | \( \mu \rho \) | \( \mu K^+ \) | \( \mu K^- \) |
|------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( \Delta M_{\text{min}} \) | -0.02 | -0.02 | -0.02 | -0.015 | -0.008 | -0.01 | -0.01 | -0.01 | -0.008 |
| \( \Delta M_{\text{max}} \) | 0.015 | 0.02 | 0.02 | 0.02 | 0.015 | 0.01 | 0.01 | 0.01 | -0.01 |
| \( \Delta E_{\text{min}} \) | 0.013 | -0.10 | -0.15 | -0.125 | -0.09 | -0.06 | -0.08 | -0.08 | -0.08 |
| \( \Delta E_{\text{max}} \) | 0.10 | 0.06 | 0.08 | 0.06 | 0.06 | 0.04 | 0.04 | 0.04 | 0.06 |

There are three main classes of background events remaining after the selection criteria are applied: charm quark production (c\( \bar{c} \)), low-multiplicity continuum \( e^+e^- \to u\bar{u}/d\bar{d}/s\bar{s} \) events (uds), and SM \( \tau^+\tau^- \) pair events. The background from two-photon production is negligible. These three background classes have distinct distributions in the \( (\Delta M, \Delta E) \) plane. The uds events tend to populate the plane evenly, with a fall-off at positive values of \( \Delta E \). Events in the c\( \bar{c} \) sample exhibit peaks at positive values of \( \Delta M \) due to \( D \) and \( D_s \) mesons, and are generally restricted to negative values of \( \Delta E \). The \( \tau^+\tau^- \) background events are restricted to negative values of both \( \Delta E \) and \( \Delta M \).

The expected background rates in the SB are determined by fitting a set of 2-dimensional probability density functions (PDFs) to the observed data in the grand sideband (GS) region of the \( (\Delta M, \Delta E) \) plane. The GS region is defined as the LB minus the SB. The shapes of the PDFs are determined by fits to the \( (\Delta M, \Delta E) \) distributions of background MC samples in the LB, as described in Ref. 1. The present analysis makes use of the same parameterization as Ref. 1 for the \( \Delta E \) spectra, except for the case of the \( c\bar{c} \) spectrum in some search channels. In these cases, combinations of polynomial and Gaussian functions are used. The choice of PDF for the \( \Delta M \) spectrum of the uds samples is the same as used in Ref. 1, while the \( \tau^+\tau^- \) and \( c\bar{c} \) \( \Delta M \) spectra are modeled with Gaussian and polynomial functions, or the Crystal Ball function. All shape parameters, including a rotation angle accounting for the correlation between \( \Delta E \) and \( \Delta M \), are determined from the fits to MC samples.

Once the shapes of the three background PDFs are determined, an unbinned extended maximum likelihood fit to the data in the GS region is used to find the expected background count in the SB. The fits to the background MC samples and to data are performed separately for each of the eight search channels.

We estimate the signal event selection efficiency with a MC simulation of lepton-flavor violating tau decays. Between 20% and 40% of the MC signal events pass the 3-1 topology requirement. The efficiency for identification of the three final-state particles ranges from 42% for \( \tau^- \to \mu^- K^* \) to 82% for \( \tau^- \to e^- \rho \). The total efficiency for signal events to be found in the SB is shown in Table III and ranges from 4.1% to 8.0%. This efficiency includes the branching fraction for the vector meson decay to charged daughters, as well as the branching fraction for 1-prong tau decays.

The particle identification efficiencies and misidentification probabilities have been measured with control samples both for data and MC events, as a function of particle momentum, polar angle, and azimuthal angle in the laboratory frame. The systematic uncertainties related to the particle identification have been estimated from the statistical uncertainty of the efficiency measurements and from the difference between data and MC efficiencies. These uncertainties range from 1.7% for \( \tau^- \to e^- \rho \) to 9.0% for \( \tau^- \to \mu^- \rho \). The modeling of the tracking efficiency and the uncertainty from the 1-prong tau branching fraction each contribute an additional 1% uncertainty. Furthermore, the uncertainty on the intermediate branching fractions \( B(\phi, K^+, K^- \to h^+h^-) \) contributes a 1% uncertainty. All other sources of uncertainty in the signal efficiency are found to be negligible, including the statistical limitations of the MC signal samples, modeling of radiative effects by the generator, track momentum resolution, trigger performance,
and the choice of observables used for event selection.

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. Uncertainties related to the fits to the background samples are estimated by varying the background shape parameters according to the covariance matrix and repeating the fits, and range from 3.8% to 10%. Uncertainties related to the fits for the background yields in the GS are estimated by varying the yields within their errors, and range from 4.1% to 16%. The total uncertainty on the background estimates is shown in Table III. Crosschecks of the background estimation are performed by comparing the number of events expected and observed in sideband regions immediately neighboring the SB for each search channel. No major discrepancies are observed.

The number of events observed \( N_{\text{obs}} \) and the number of background events expected \( N_{\text{bgd}} \) are shown in Table III. The POLE calculator [18], based on the method of Feldman and Cousins [19], is used to place 90% CL upper limits on the number of signal events \( N_{\text{UL}}^0 \), which includes uncertainties on \( N_{\text{bgd}} \) and on the selection efficiency \( \varepsilon \). For the \( \tau^+ \to \mu^+ \phi \) search, the POLE calculation results in a two-sided interval at 90% CL for the number of signal events: \([0.39-8.65]\). Upper limits on the branching fractions are calculated according to \( B_{\text{UL}}^0 = N_{\text{UL}}^0/(2\varepsilon L\sigma_{\tau+\tau^-}) \), where the values \( \varepsilon \) and \( \sigma_{\tau+\tau^-} \) are the integrated luminosity and \( \tau^+\tau^- \) cross section, respectively. The uncertainty on the product \( \varepsilon L\sigma_{\tau+\tau^-} \) is 1.0%. Table III lists the upper limits on the branching fractions, as well as the expected upper limit \( B_{\text{exp}}^0 \), defined as the mean upper limit expected in the background-only hypothesis.

The 90% CL upper limits on the \( \tau \to \ell \phi/\rho/K^*/\bar{K}^* \) branching fractions are in the range \((2.6-19) \times 10^{-8}\), and these limits represent improvements over the previous experimental bounds [3] in almost all search channels. 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), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MES (Russia), MEC (Spain), and STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.
* Deceased
† Now at Temple University, Philadelphia, Pennsylvania 19122, USA
‡ Now at Tel Aviv University, Tel Aviv, 69978, Israel
§ Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
** Now at University of South Alabama, Mobile, Alabama 36688, USA
†† Also with Laboratoire de Physique Nucléaire et de Hautes Énergies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France
¶ Also with Università di Sassari, Sassari, Italy

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