

Search for Lepton-Flavor Violation in the Decay $\tau^- \rightarrow \ell^\mp h^\pm h^-$

The *BABAR* Collaboration

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Abstract

A search for the lepton-flavor-violating decay of the tau into one charged lepton and two charged hadrons has been performed using 221.4 fb^{-1} of data collected at an e^+e^- center-of-mass energy around 10.58 GeV with the *BABAR* detector at the PEP-II storage ring. In all 14 decay modes considered, the numbers of events found in data are compatible with the background expectations. Upper limits on the branching fractions are set in the range $(0.7 - 4.8) \times 10^{-7}$ at 90% confidence level. All results are preliminary.

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1 INTRODUCTION

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 $\mathcal{B}(\mu \rightarrow eee) < 1.0 \times 10^{-12}$ [2] at 90% confidence level (CL). Recent results from neutrino oscillation experiments [3] show that LFV does indeed occur, although the branching fractions expected in charged lepton decays due to neutrino mixing alone are probably no more than 10^{-14} [4].

In tau decays, the most stringent limit on LFV is $\mathcal{B}(\tau^- \rightarrow \mu^+ e^- e^-) < 1.1 \times 10^{-7}$ at 90% CL [5]. Many extensions to the Standard Model (SM), particularly models seeking to describe neutrino mixing, predict enhanced LFV in tau decays over muon decays with branching fractions from 10^{-10} up to the current experimental limits [6]. 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 paper presents preliminary results of a search for the decays¹ $\tau^- \rightarrow \ell^\mp h^\pm h^-$ where ℓ represents an electron or muon and h represents a pion or kaon. In total there are 14 distinct final states consistent with charge conservation. The best existing limits on the branching fractions for these decay modes currently come from CLEO, and range from $(2 - 8) \times 10^{-6}$ at 90% CL [7].

2 THE BABAR DETECTOR AND DATASET

The data used in this analysis were collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage ring. The data sample consists of 205.3 fb^{-1} recorded at $\sqrt{s} = 10.58 \text{ GeV}$ and 16.1 fb^{-1} recorded at $\sqrt{s} = 10.54 \text{ GeV}$. With an estimated luminosity-weighted cross section for tau pairs of $\sigma_{\tau\tau} = (0.89 \pm 0.02) \text{ nb}$ [8], this data sample contains over 390 million tau decays.

The *BABAR* detector is described in detail elsewhere [9]. Charged-particle (track) momenta are measured with a 5-layer double-sided silicon vertex tracker and a 40-layer drift chamber inside a 1.5-T superconducting solenoidal magnet. An electromagnetic calorimeter (EMC) consisting of 6580 CsI(Tl) crystals is used to identify electrons and photons, a ring-imaging Cherenkov detector and energy loss in the drift chambers are used to identify charged hadrons, and the instrumented magnetic flux return (IFR) is used to identify muons.

A Monte Carlo (MC) simulation of LFV tau decays is used to study the performance of this analysis. Simulated tau-pair events including higher-order radiative corrections are generated using KK2f[8] with one tau decaying to one lepton and two hadrons with a 3-body phase space distribution, while the other tau decays according to measured rates [10] simulated with TAUOLA[11]. Final state radiative effects are simulated for all decays using PHOTOS[12]. The detector response is simulated with GEANT4 [13], and the simulated events are then reconstructed in the same manner as data.

3 ANALYSIS METHOD

The analysis procedure is similar to that used in our published $\tau^- \rightarrow \ell^- \ell^+ \ell^-$ analysis [5]. All possible lepton and hadron combinations consistent with charge conservation are considered, leading to fourteen distinct decay modes ($e^- K^+ K^-$, $e^- K^+ \pi^-$, $e^- \pi^+ K^-$, $e^- \pi^+ \pi^-$, $\mu^- K^+ K^-$, $\mu^- K^+ \pi^-$, $\mu^- \pi^+ K^-$, $\mu^- \pi^+ \pi^-$, $e^+ K^- K^-$, $e^+ K^- \pi^-$, $e^+ \pi^- \pi^-$, $\mu^+ K^- K^-$, $\mu^+ K^- \pi^-$, $\mu^+ \pi^- \pi^-$). The signature of this process is three charged particles, one identified as either an electron or muon, and each of

¹Throughout this paper, charge conjugate decay modes also are implied.

the other two identified as either a pion or kaon, with an invariant mass and energy equal to that of the parent tau lepton.

3.1 SELECTION

Candidate signal events in this analysis are required to have a “1-3 topology,” where one tau decay yields three charged particles (3-prong), while the second tau 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. The event is divided into two hemispheres using the plane perpendicular to the thrust axis, calculated from the observed tracks and unassociated EMC energy deposits in the center-of-mass (CM) frame. One hemisphere must contain exactly one track while the other must contain exactly three, defining the 1-3 topology. Pairs of oppositely charged tracks identified as photon conversions in the detector material with an e^+e^- invariant mass below $30\text{ MeV}/c^2$ are ignored.

One 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 EMC energy to track momentum (E/p), the ionization loss in the tracking system (dE/dx), and the shape of the shower in the EMC. Muons are identified by hits in the IFR and small energy deposits in the EMC. Muons with momentum less than $0.5\text{ GeV}/c$ cannot be identified because they do not penetrate far enough into the IFR. Each of the other two charged particles found in the 3-prong hemisphere must be identified as either a pion or a kaon.

The particle identification requirements alone are not sufficient to suppress certain backgrounds, particularly those from light quark $q\bar{q}$ production and SM $\tau^+\tau^-$ events, therefore additional selection criteria are required. The selection requirements, most of which are the same for all 14 decay modes, are as follows:

- no neutral clusters (photon candidates) with energy ($E_\gamma > 100\text{ MeV}$) in the EMC. This restriction removes mostly $q\bar{q}$ backgrounds and some SM tau-pair events;
- the polar angle of the missing momentum in the lab frame, Θ_{miss} , is required to be in the range $0.25\text{ rad} < \Theta_{\text{miss}} < 2.4\text{ rad}$. This cut is effective at reducing two-photon and Bhabha backgrounds;
- the total transverse momentum in the event in the CM frame, p_T^{CM} , must be greater than $0.2\text{ GeV}/c$. The cut on p_T^{CM} is also effective against Bhabha and two-photon events;
- the mass of the one-prong hemisphere, m_{1pr} , calculated from the four-momentum of the track in the 1-prong hemisphere and the missing momentum in the event, is required to satisfy $0.6\text{ GeV}/c^2 < m_{1pr} < 1.9\text{ GeV}/c^2$ for $e^\mp h^\pm h^-$ final states and $0.8\text{ GeV}/c^2 < m_{1pr} < 1.9\text{ GeV}/c^2$ for $\mu^\mp h^\pm h^-$ final states. The one-prong mass requirement is particularly effective at removing $q\bar{q}$ backgrounds as well as the remaining two-photon contribution;
- to remove any remaining Bhabha background, the momentum of the one-prong track in the CM frame, p_{1pr}^{CM} , is required to be less than $4.5\text{ GeV}/c$ for the $e^-\pi^+\pi^-$ and $e^+\pi^-\pi^-$ final states.

In addition, particle ID vetoes are applied to specific selection channels. For the ehh decay modes, except for eKK , the 1-prong track must not be identified as an electron. This requirement is useful to reduce possible four-fermion $eehh$ background events produced from two-photon or

Bhabha-like processes. For the decay modes with only pions ($e^-\pi^+\pi^-$, $e^+\pi^-\pi^-$, $\mu^-\pi^+\pi^-$, $\mu^+\pi^-\pi^-$) or the mixed kaon-pion modes ($e^-K^+\pi^-$, $e^-\pi^+K^-$, $e^+K^-\pi^-$, $\mu^-K^+\pi^-$, $\mu^-\pi^+K^-$, $\mu^+K^-\pi^-$), the lepton candidate also must not pass the kaon criteria.

3.2 ($\Delta M, \Delta E$) OBSERVABLES

To reduce backgrounds further, candidate signal events are required 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 observed track momenta assuming the corresponding lepton and hadron masses in each decay mode. The energy difference is defined as $\Delta E \equiv E_{\text{rec}}^{\text{CM}} - E_{\text{beam}}^{\text{CM}}$, where $E_{\text{rec}}^{\text{CM}}$ is the total energy of the tracks observed in the 3-prong hemisphere and $E_{\text{beam}}^{\text{CM}}$ 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_{rec} is the reconstructed invariant mass of the three tracks and $m_\tau = 1.777 \text{ GeV}/c^2$ is the tau mass [14].

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 ΔE . Radiation from the final-state lepton produces a tail towards low values of ΔM which is more likely for electrons than muons. Rectangular signal regions are defined separately for each decay mode as follows. For all fourteen decay modes, the energy difference ΔE must be in the range $[-100, +50] \text{ MeV}$. For the modes with muons, the mass difference ΔM is required to be in the range $[-20, +20] \text{ MeV}/c^2$, while for the electron modes the range is $[-30, +20] \text{ MeV}/c^2$.

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 for the signal box tuning are estimated using only Monte Carlo simulations, not candidate signal events. Figure 1 shows the observed data for all fourteen selection channels in the $(\Delta M, \Delta E)$ plane, along with the signal region boundaries and the expected signal distributions. To avoid bias, a blind analysis procedure was adopted with the number of data events in the signal region remaining unknown until the selection criteria were finalized and all systematic studies had been performed.

3.3 SELECTION EFFICIENCY

The efficiency of the selection for signal events is estimated with a MC simulation of LFV tau decays. About 40% of the MC signal events pass the initial 1-3 topology requirement. From 20% to 70% of these preselected events pass the particle ID criteria, depending upon the final state, and 70% fall within the signal region in the $(\Delta M, \Delta E)$ plane. The final selection requirements accept from 17% to 27% of these remaining signal MC events. The final efficiency for signal events to be found in the signal region is shown in Table 1 for each decay mode and ranges from 2.1% to 3.8%. This efficiency includes the 85% branching fraction for 1-prong tau decays.

The particle ID efficiencies and misidentification probabilities are not taken from Monte Carlo, but rather measured using tracks in kinematically-selected data samples. These values are parameterized as a function of particle momentum, polar angle, and azimuthal angle in the laboratory frame. The control samples used to characterize the lepton ID performance include radiative Bhabha, radiative $\mu^+\mu^-$, two-photon $e^+e^-\ell^+\ell^-$, and $J/\psi \rightarrow \ell^+\ell^-$ events. The control sample used to characterize the hadron ID performance is the decay $D^* \rightarrow D^0\pi$, $D^0 \rightarrow K\pi$. These data-derived efficiencies are then used to determine the probability that a simulated MC particle will be identified (or misidentified) as an electron, muon, pion, or kaon.

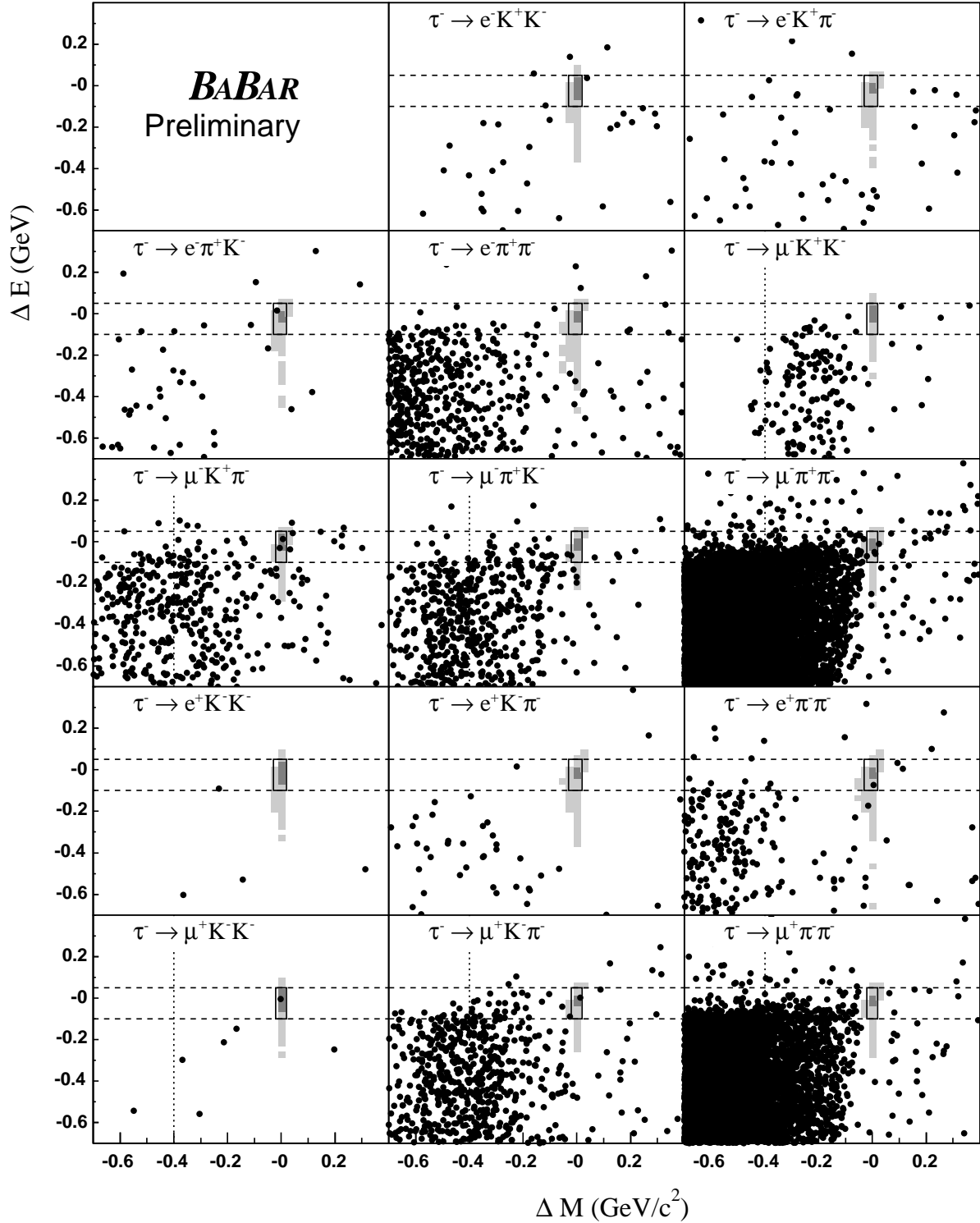


Figure 1: Observed data shown as dots in the $(\Delta M, \Delta E)$ plane and the boundaries of the signal region for each decay mode. The dark and light shading indicates contours containing 50% and 90% of the selected MC signal events, respectively. The regions shown in Fig. 2 are indicated by dashed lines. The vertical dotted lines show the lower ΔM boundary of the grand sideband (GS) region for the μhh final states. The other GS boundaries are the plot borders.

Table 1: Efficiency estimates, the number of expected background events (N_{bgd}) in the signal region, the number of observed events (N_{obs}) in the signal region, and the 90% CL upper limit for each decay mode.

Mode	Eff. [%]	N_{bgd}	N_{obs}	UL at 90% CL
$e^- K^+ K^-$	3.77 ± 0.16	0.22 ± 0.06	0	$1.4 \cdot 10^{-7}$
$e^- K^+ \pi^-$	3.08 ± 0.13	0.32 ± 0.09	0	$1.7 \cdot 10^{-7}$
$e^- \pi^+ K^-$	3.10 ± 0.13	0.14 ± 0.06	1	$3.2 \cdot 10^{-7}$
$e^- \pi^+ \pi^-$	3.30 ± 0.15	0.81 ± 0.15	0	$1.2 \cdot 10^{-7}$
$\mu^- K^+ K^-$	2.16 ± 0.12	0.24 ± 0.08	0	$2.5 \cdot 10^{-7}$
$\mu^- K^+ \pi^-$	2.97 ± 0.16	1.67 ± 0.32	2	$3.2 \cdot 10^{-7}$
$\mu^- \pi^+ K^-$	2.87 ± 0.16	1.04 ± 0.20	1	$2.6 \cdot 10^{-7}$
$\mu^- \pi^+ \pi^-$	3.40 ± 0.19	2.99 ± 0.42	3	$2.9 \cdot 10^{-7}$
$e^+ K^- K^-$	3.85 ± 0.16	0.04 ± 0.04	0	$1.5 \cdot 10^{-7}$
$e^+ K^- \pi^-$	3.19 ± 0.14	0.16 ± 0.06	0	$1.8 \cdot 10^{-7}$
$e^+ \pi^- \pi^-$	3.40 ± 0.15	0.41 ± 0.10	1	$2.7 \cdot 10^{-7}$
$\mu^+ K^- K^-$	2.06 ± 0.11	0.07 ± 0.10	1	$4.8 \cdot 10^{-7}$
$\mu^+ K^- \pi^-$	2.85 ± 0.16	1.54 ± 0.28	1	$2.2 \cdot 10^{-7}$
$\mu^+ \pi^- \pi^-$	3.30 ± 0.18	1.46 ± 0.23	0	$0.7 \cdot 10^{-7}$

The lepton identification has been designed to give very low mis-identification rates at the expense of some efficiency. The electron ID is expected to be 81% efficient in signal $\ell^\mp h^\pm h^-$ events with a mis-ID rate of 0.1% for pions and 0.2% for kaons expected in generic $\tau^+ \tau^-$ events. The muon ID is 44% efficient for signal events, with a mis-ID rate of 1.0% for pions and 0.4% for kaons. The hadronic identification is designed to classify the hadronic candidates as pions or kaons, but is not intended to distinguish hadrons from leptons. Since the dominant backgrounds contain many pions (and some kaons), stricter requirements on identifying hadrons do not improve the analysis. The pion ID is 92% efficient with a mis-ID rate of 12% for kaons, while the kaon ID is 81% efficient with a 1.4% mis-ID rate for pions. The pion ID criteria also has a very high mis-ID rate for muons (98%) and electrons (38%) which means that the $\mu^- \pi^+ \pi^-$ channel is also rather sensitive to other LFV tau decay modes like $\tau \rightarrow \mu^- \mu^+ \mu^-$.

3.4 BACKGROUND ESTIMATES

There are two main classes of background remaining after the selection criteria are applied: low multiplicity $q\bar{q}$ events (mainly continuum light-quark production) and SM $\tau^+ \tau^-$ events. These background classes have distinctive distributions in the $(\Delta M, \Delta E)$ plane: $q\bar{q}$ events tend to populate the plane uniformly, while $\tau^+ \tau^-$ backgrounds are restricted to negative values of both ΔE and ΔM . Backgrounds from Bhabha and $\mu^+ \mu^-$ events (which were important for our $\tau \rightarrow \ell \ell \ell$ analysis [5]) are found to be negligible in the $\tau^- \rightarrow \ell^\mp h^\pm h^-$ decay modes. The two-photon backgrounds are also found to be negligible, although studies show they would look very similar to $q\bar{q}$ backgrounds.

For each background class, a probability density function (PDF) describing the shape of the background distribution in the $(\Delta M, \Delta E)$ plane is determined by fitting an analytic function to the Monte Carlo prediction as described in more detail below. These two PDFs are then combined with coefficients determined by a fit to the observed data in the $(\Delta M, \Delta E)$ plane in a grand sideband

(GS) region which excludes the signal region. The resulting function describes the event rate seen in the GS region and is then used to predict the expected background rate in the signal region.

The GS region, shown in Fig. 1, is defined as the rectangle bounded by $(-700 \text{ MeV}/c^2 < \Delta M < 400 \text{ MeV}/c^2)$ for $e^\mp h^\pm h^-$ final states, $(-400 \text{ MeV}/c^2 < \Delta M < 400 \text{ MeV}/c^2)$ for $\mu^\mp h^\pm h^-$ final states, and $(-700 \text{ MeV} < \Delta E < 400 \text{ MeV})$ for both, excluding the signal region. For the $q\bar{q}$ backgrounds, an analytic PDF is constructed from the product of two PDFs $P_{M'}$ and $P_{E'}$, where $P_{M'}(\Delta M')$ is a Gaussian and $P_{E'}(\Delta E') = (1 - x/\sqrt{1+x^2})(1 + ax + bx^2 + cx^3)$ with $x = (\Delta E' - d)/e$ [15]. The $(\Delta M', \Delta E')$ axes have been rotated slightly from $(\Delta M, \Delta E)$ to better fit the expected distributions. The resulting $q\bar{q}$ PDF is described by eight fit parameters, including the rotation angle, which are determined by fits to MC $q\bar{q}$ background samples for each decay mode. The $\tau^+\tau^-$ PDF function $P_{M'}(\Delta M')$ is the sum of a Gaussian and a bifurcated Gaussian, while the functional form of $P_{E'}(\Delta E')$ is the same as the $q\bar{q}$ PDF above. To properly model the kinematic limit in tau decays, a similar coordinate transformation is performed to get $\Delta M'$ and $\Delta E'$, except that the axes are not required to remain orthogonal.² This method reproduces well the slightly wedge-shaped background distribution seen from tau decays in Figure 1 for the $\mu\pi\pi$ final states. In total there are 12 free parameters describing this PDF, and all are determined by fits to MC $\tau^+\tau^-$ samples, including the two coordinate transformation angles.

With the shapes of the two 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 fourteen decay modes. Figure 2 shows the data and the background PDFs for values of ΔE in the signal range.

4 SYSTEMATIC STUDIES

The largest systematic uncertainty for the signal efficiency is due to the uncertainty in measuring the particle ID efficiencies. This uncertainty³ is determined from the statistical precision of the particle ID control samples, and ranges from 0.7% for $e^-\pi^+\pi^-$ to 3.8% for $\mu^-K^+K^-$. The modeling of the tracking efficiency contributes an additional 2.5% uncertainty, while the statistical uncertainty of the MC signal samples ranges from 1% to 2%. All other sources of uncertainty are found to be small, including the modeling 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 20% across the Dalitz plane, provided the invariant mass for any pair of particles from the LFV decay is less than $1.4 \text{ GeV}/c^2$.

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 used to determine the background rates is the largest uncertainty and varies from 14% to 140% depending upon the decay mode. Additional uncertainties of 10% are estimated by varying the fit procedure and changing the functional form of the background PDFs. The uncertainty on the branching fraction of SM tau decays with one or two kaons in the final state contributes 0-14% to the uncertainty on the estimated background.

²The transformation is $\Delta M' = \cos \beta_1 \Delta M + \sin \beta_1 \Delta E$ and $\Delta E' = \cos \beta_2 \Delta E - \sin \beta_2 \Delta M$. The coefficients β_1 and β_2 are also fit from the predicted MC background distributions.

³All uncertainties quoted in the text are relative.

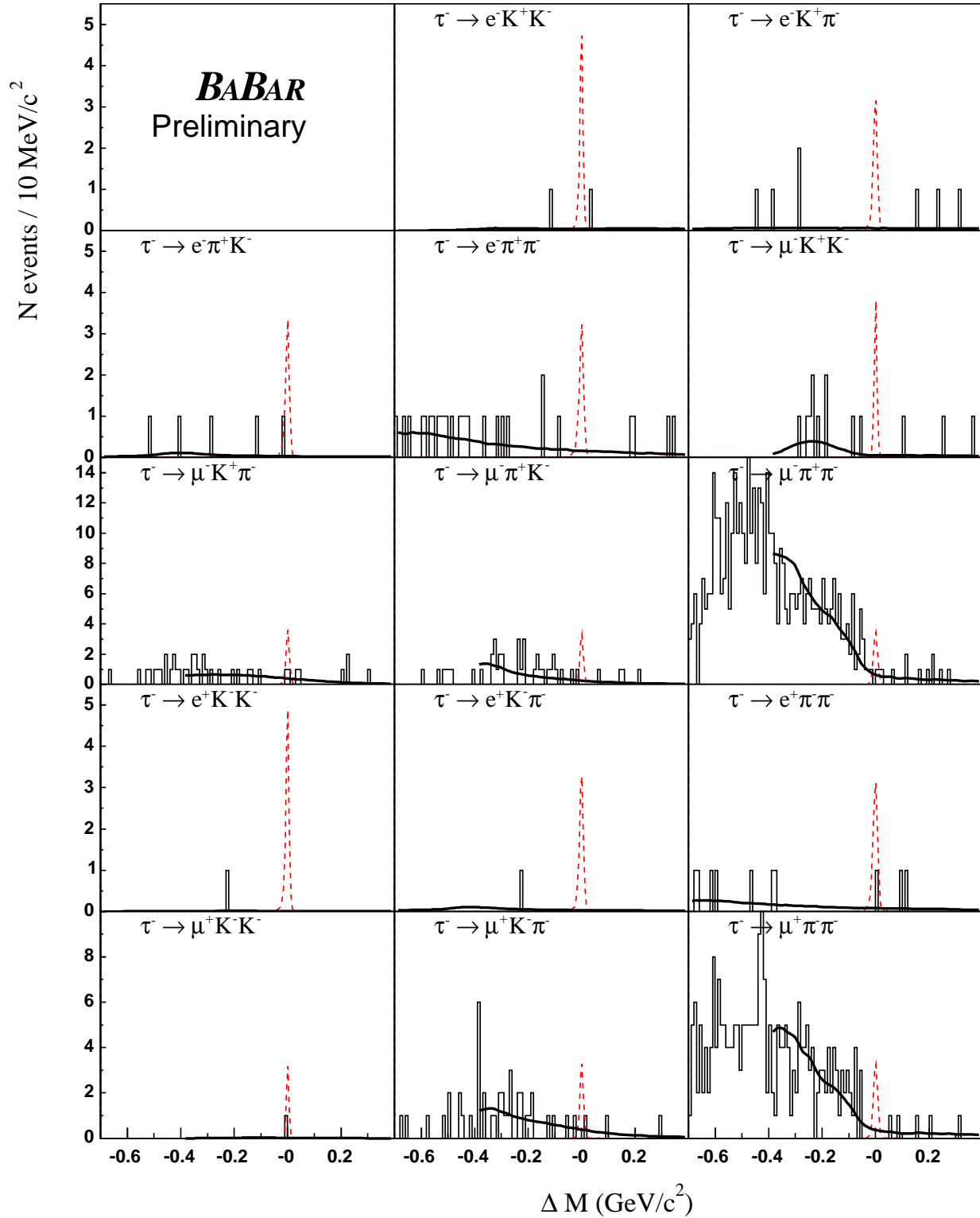


Figure 2: Distribution of ΔM for data (solid histogram) and background PDFs (solid curves) for events with ΔE in the range $[-100, +50]$ MeV as indicated in Fig. 1. Expected signal distributions are shown (dashed histogram) for a branching fraction of $5 \cdot 10^{-7}$.

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 as shown in Table 2. Good agreement is seen between the observed data and background expectations.

Table 2: The number of events expected (left) and observed (right) in the regions just neighboring the signal region. These "neighbor boxes" have the same dimension as the original signal region for each decay mode, but have been offset by the width or height of the signal region in the $(\Delta M, \Delta E)$ plane.

Mode	left		top		right		bottom	
$e^- K^+ K^-$	0.22	0	0.05	1	0.24	1	0.30	0
$e^- K^+ \pi^-$	0.31	0	0.10	0	0.31	0	0.35	0
$e^- \pi^+ K^-$	0.15	0	0.05	0	0.13	0	0.18	0
$e^- \pi^+ \pi^-$	0.89	0	0.36	1	0.76	0	0.93	0
$\mu^- K^+ K^-$	0.30	1	0.04	0	0.21	0	0.33	0
$\mu^- K^+ \pi^-$	1.81	0	0.16	0	1.37	2	1.79	1
$\mu^- \pi^+ K^-$	1.30	1	0.14	0	0.84	0	1.09	3
$\mu^- \pi^+ \pi^-$	4.66	10	0.97	0	2.09	1	2.68	0
$e^+ K^- K^-$	0.05	0	0.00	0	0.03	0	0.05	0
$e^+ K^- \pi^-$	0.17	0	0.07	0	0.14	0	0.19	0
$e^+ \pi^- \pi^-$	0.43	0	0.13	0	0.37	0	0.43	1
$\mu^+ K^- K^-$	0.08	0	0.01	0	0.06	0	0.08	0
$\mu^+ K^- \pi^-$	1.87	2	0.23	0	1.26	0	1.83	0
$\mu^+ \pi^- \pi^-$	2.42	3	0.52	0	1.15	1	1.54	0

5 RESULTS

The numbers of events observed (N_{obs}) and the background expectations (N_{bgd}) are shown in Table 1, with no significant excess found in any decay mode. Upper limits on the branching fractions are calculated according to $\mathcal{B}_{UL}^{90} = N_{UL}^{90} / (2\varepsilon\mathcal{L}\sigma_{\tau\tau})$, where N_{UL}^{90} is the 90% CL upper limit for the number of signal events when N_{obs} events are observed with N_{bgd} background events expected. The values ε , \mathcal{L} , and $\sigma_{\tau\tau}$ are the selection efficiency, luminosity, and $\tau^+\tau^-$ cross section, respectively. The estimates of $\mathcal{L} = 221.4 \text{ fb}^{-1}$ and $\sigma_{\tau\tau} = 0.89 \text{ nb}$ are correlated,⁴ and the uncertainty on the product $\mathcal{L}\sigma_{\tau\tau}$ is 2.3%. The upper limits on the branching fraction have been calculated including all uncertainties using the technique of Cousins and Highland [16] following the implementation of Barlow [17]. The 90% CL upper limits on the $\tau^- \rightarrow \ell^\mp h^\pm h^-$ branching fractions, shown in Table 1, are in the range $(0.7 - 4.8) \times 10^{-7}$. These limits represent an order of magnitude improvement over the previous experimental bounds [7].

⁴The luminosity is measured using the observed $\mu^+\mu^-$ rate, and the $\mu^+\mu^-$ and $\tau^+\tau^-$ cross sections are both estimated with KK2f.

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