Search for the Decay $B^+ \to K^+ \tau^\mp \mu^\pm$

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We present a search for the lepton flavor violating decay $B^+ \to K^+\tau^\mp\mu^\pm$ using 383×10^6 $B\bar{B}$ events collected by the *BABAR* experiment. The branching fraction for this decay can be substantially enhanced in new physics models. The kinematics of the tau from the signal B decay are inferred from the K^+, μ, and other B in the event, which is fully reconstructed in one of a variety of hadronic decay modes, allowing the signal B candidate to be fully reconstructed. We observe no excess of events over the expected background and set a limit of $\mathcal{B}(B^+ \to K^+\tau\mu) < 7.7 \times 10^{-5}$ at 90% confidence level, where the branching fraction is for the sum of the $K^+\tau^-\mu^+$ and $K^+\tau^+\mu^-$ final states. We use this result to improve a model-independent bound on the energy scale of flavor-changing new physics.

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Lepton flavor violation (LFV) thus far has only been observed in the neutrino sector [1–3]. Manifestations of LFV in B meson decays that have final states with charged leptons (e.g., $B \to K\ell\ell'$) are allowed in standard model interactions, if massive neutrinos are included [4], but such processes occur only at the one-loop level and are extremely suppressed by powers of m_ν^2/M_W^2. Branching fractions for lepton flavor violating B decays can be substantially enhanced in many extensions of the standard model [5–8]. The semileptonic decay $B \to K\tau\mu$ is likely to have higher sensitivity to new physics, when compared to leptonic decays such as $B^0 \to \tau\ell'$, since the latter is both helicity and Cabibbo-Kobayashi-Maskawa quark-mixing matrix (CKM) suppressed by a factor of $|V_{td}/V_{cb}|^2$. Some new physics models require flavor-changing neutral currents (FCNC's) to occur at the one-loop level, as in the standard model. In other extensions, such as models with a Z' or additional Higgs doublets, FCNC's occur naturally at the tree level, unless they are eliminated by imposing an *ad hoc* discrete symmetry.

A limit on the process $B \to K\tau\mu$, which involves the second and third generations of both quarks and leptons, would provide a unique and powerful constraint on model parameters of grand unified theories. Cheng, Sher, and Yuan [5,9] propose that in models with an extended Higgs sector the most natural value of the FCNC Yukawa couplings connecting generations i and j are proportional to $\sqrt{m_i m_j}/m_\tau$, which implies that FCNC's in these theories should be largest in processes involving the second and third generations. An observation of $B \to K\tau\mu$ would be an unambiguous sign of physics beyond the standard model. In this Letter, we present the results of a search for $B \to K\tau\mu$.

We use a data sample of 383×10^6 $B\bar{B}$ pairs produced by the PEP-II asymmetric-energy e^+e^- collider, running at the $\Upsilon(4S)$ resonance, collected by the *BABAR* experiment [10] at SLAC. Charged particles are identified using a Cerenkov radiation detector and dE/dx measurements in the tracking system. Instrumentation embedded within the iron of the flux return for the 1.5 T solenoid aids in the identification of muons. An electromagnetic CsI(Tl) crystal calorimeter (EMC) is used to reconstruct photons and identify electrons.

The analysis strategy is to reconstruct the $\Upsilon(4S) \to B^+B^-$ in the search for $B^+ \to K^+\tau\mu$ [11]. One of the B mesons ($B_{\rm tag}$) is fully reconstructed in one of a large number of hadronic final states, $B^- \to D^{(*)0}X^-$[12]. The X^- represents a system of charged and neutral hadrons with total charge -1 composed of $n_1\pi^\pm$, $n_2K^\pm$, $n_3K_S^0$, and $n_4\pi^0$, with $n_1 + n_2 \leq 5$, $n_3 \leq 2$, and $n_4 \leq 2$. The D^{*0} is reconstructed in the $D^0\pi^0$ and $D^0\gamma$ channels, the D^0 in the $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, and $K_S^0\pi^+\pi^-$ channels, and K_S^0 in the $\pi^+\pi^-$ channel. We search for the decay $B^+ \to K^+\tau\mu$ using the remaining tracks in the event. The momentum vector of the signal B candidate, $\vec{p}_{\rm sig}$, must be equal in magnitude and opposite in direction to that of $B_{\rm tag}$ in the center-of-mass (c.m.) frame. The τ candidate kinematic variables, E_τ and $\vec{p}_\tau$, are fully constrained by $\vec{p}_{\rm sig}$, the measured momenta of the K^+ and μ tracks, and the constraint $E_\tau = E_{\rm beam} - E_K - E_\mu$, where $E_{\rm beam}$ is the c.m. beam energy. The reconstructed τ invariant mass $m_\tau = \sqrt{E_\tau^2 - p_\tau^2}$ peaks sharply at the true τ mass for the signal.

Events are required to contain a $B_{\rm tag}$ candidate with $m_{\rm ES} \equiv \sqrt{E_{\rm beam}^2 - p_{\rm tag}^2} > 5.27\ {\rm GeV}/c^2$ and $E_{\rm tag}$ consistent with $E_{\rm beam}$ within 3 standard deviations, where $p_{\rm tag}$ and $E_{\rm tag}$ are the momentum and energy of the $B_{\rm tag}$ candidate in the c.m. frame. A $B_{\rm tag}$ meson is fully reconstructed in about 0.2% of Monte Carlo events where one $B^\pm$ decays to $K^\pm\tau\mu$. Even though the τ daughters are not needed to reconstruct m_τ, we require the τ in the signal B candidate to be consistent with a "one-prong" (i.e., one-charged-track) τ decay to reject combinatoric background. Therefore we require exactly three charged tracks in the event not associated with $B_{\rm tag}$ and with net charge opposite to that of $B_{\rm tag}$. Among these three tracks, we require a kaon candidate with charge opposite $B_{\rm tag}$, a muon candidate, and a third track (the τ daughter) with charge opposite the muon candidate. The event is rejected if any of the three tracks is consistent with a proton hypothesis or if either of the two nonkaon tracks is consistent with a kaon hypothesis. Signal candidates are divided into three categories based on the properties of the τ-daughter track: electron, muon, and pion.

The kaon, muon, and electron particle identification criteria used in this analysis have momentum-dependent efficiencies and misidentification probabilities (fake rates). The kaon candidate must pass loose selection criteria, based on the measured Cerenkov angle and dE/dx in the tracking system. Muon candidates, either from the B decay or from the τ decay, must pass minimum selection criteria that are 85% efficient for muons above 1.5 GeV/c and less than 10% efficient for pions and kaons. Tau daughter electrons must pass minimum electron selection criteria that are 95% efficient for electrons. More stringent electron and muon identification criteria for the tau daughter track are incorporated through a likelihood ratio described below. τ daughters that do not pass either the electron or muon criteria fall into the pion category.

For muon channel signal B candidates, there are two muons in the final state: one from the B decay (primary muon) and one from a leptonic τ decay. Of the two possible track assignments for the primary muon, we use the one that gives m_τ closest to the known τ mass. The bias in the background m_τ distribution for the muon channel from using this procedure is found to be negligible.

Semileptonic B decays can produce final states that appear identical to the signal. For example $B^+ \to \bar{D}^0\mu^+\nu_\mu$ followed by $\bar{D}^0 \to K^+\pi^-$ produces a $K^+\mu^+\pi^-\nu$ final state. If the $\bar{D}^0$ decays semileptonically, the final state is $K^+\mu^+\ell^-\nu\bar{\nu}$. These backgrounds are easily removed by requiring that the invariant mass, $m(K\pi)$, of the kaon candidate and the oppositely-charged, signal-track candidate, when this track is assumed to be a pion, be greater than 1.95 GeV$/c^2$. This requirement is greater than 50% efficient for the signal and removes about 99% of the background from $B\bar{B}$ events.

The $B^+ \to \bar{D}^0\mu^+\nu_\mu$ and $B^+ \to \bar{D}^{*0}\mu^+\nu_\mu$, with $\bar{D}^0 \to K^+\pi^-$, backgrounds also form the $D\mu\nu$ control sample, which we use to normalize the signal branching fraction. Events for the $D\mu\nu$ control sample are required to have $m(K\pi)$ in the range [1.845, 1.885] GeV$/c^2$ (within about 3 standard deviations of the D^0 mass). The neutrino momentum is calculated from $\vec{p}_{\rm tag}$ and the three tracks in the $D\mu\nu$ final state. We then compute

$$\Delta E_{D\mu\nu} = E_K + E_\mu + E_\pi + p_\nu - E_{\rm beam} = p_\nu - E_{\rm miss}. \tag{1}$$

We use $\Delta E_{D\mu\nu}$ rather than $m_{\rm miss} = \sqrt{E^2_{\rm miss} - p^2_\nu}$, similar to our m_τ reconstruction, because the expected $D^0\mu\nu$ missing mass is zero. The $\Delta E_{D\mu\nu}$ distribution for $D^0\mu\nu$ decays is centered at zero, while for $D^{*0}\mu\nu$ events, it is shifted by -150 MeV and slightly asymmetric, due to the missing neutral particle from the $D^{*0} \to (\pi^0, \gamma)D^0$ decay. We determine the yield of $D^0\mu\nu$ and $D^{*0}\mu\nu$ events simultaneously in an unbinned maximum likelihood fit of $\Delta E_{D\mu\nu}$ (Fig. 1).

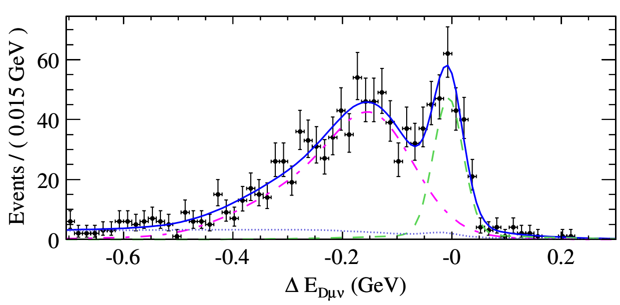

FIG. 1 (color online). Results of the $D\mu\nu$ control sample $\Delta E_{D\mu\nu}$ fit. The points with error bars are the data, the solid curve is the projection of the fit, the dashed (dot-dashed) curve is the $D^0\mu\nu$ ($D^{*0}\mu\nu$) component, and the dotted curve represents events from other sources.

For the $K^+\tau\mu$ signal, a non-negligible source of $B\bar{B}$ background in the sample remaining after the $m(K\pi)$ requirement comes from $B^+ \to (c\bar{c})K^+$ with $(c\bar{c}) \to \mu^+\mu^-$, where $(c\bar{c})$ is a charmonium resonance. This background mainly enters in the muon channel, but is also present in the pion channel. For the muon and pion channels this background is removed by requiring the invariant mass of the two nonkaon tracks, when both are assumed to be muons, to be outside of the ranges [3.03, 3.14] GeV$/c^2$ and [3.60, 3.75] GeV$/c^2$, which are centered on the J/ψ and $\psi(2S)$ resonances masses, respectively.

At this stage in the selection, the background is dominated by continuum events ($e^+e^- \to q\bar{q}$ with $q = u, d, s, c$). We suppress this background using a likelihood ratio

$$L_R = \frac{\prod_i P_s(x_i)}{\prod_i P_s(x_i) + \prod_i P_b(x_i)}, \tag{2}$$

where $\vec{x}$ is a vector of four discriminating variables (see below) and $P_s(x_i)$ ($P_b(x_i)$) is the probability density function (PDF), which describes the signal (background) for variable x_i. The PDFs are separate for each of the three signal categories. The four discriminating variables are: $|\cos\theta_{\rm thr}|$ the magnitude of the cosine of the c.m. angle between the $B_{\rm tag}$ thrust axis and the thrust axis of the rest of the event; $\sum E_{\rm cal}$ the total neutral EMC energy that is not associated with $B_{\rm tag}$; the quality of the primary lepton identification; and the quality of the secondary lepton identification (for electron and muon channel candidates). We require a minimum $E_{\rm cal}$ energy of 50 MeV (100 MeV) for clusters in the barrel (forward end cap) to be included in $\sum E_{\rm cal}$.

The $|\cos\theta_{\rm thr}|$ distribution is flat for signal and peaks near one for continuum. The $\sum E_{\rm cal}$ distribution peaks at zero for signal, while the background distribution is broad, peaking at around 1.5 GeV. The lepton quality is divided into four hierarchical, mutually-exclusive categories with fake rates decreasing with increasing quality rank. For the highest-quality muon candidate rank, the fake rates from pions and kaons are less than 2%. The highest-quality electron candidate rank has a fake rate of less than 0.1% for pions, as high as 3% for low-momentum kaons, and below 0.4% for kaons above 0.8 GeV$/c$. We fit signal and background Monte Carlo histograms of $|\cos\theta_{\rm thr}|$ and $\sum E_{\rm cal}$ to define $P_s(x_i)$ and $P_b(x_i)$ for those variables. We use the relative fractions in the four lepton quality categories in the Monte Carlo samples for $P_s(x_i)$ and $P_b(x_i)$ for the primary and secondary lepton variables.

We make a minimum L_R requirement for each of the three signal categories (electron, muon, and pion) which has been optimized to give the lowest signal branching fraction limit under the assumption of no signal in the data. The signal region in m_τ is defined to be [1.65, 1.90] GeV$/c^2$, which contains 90% of the signal. The signal selection efficiency (ϵ_i), including the L_R requirements, in the m_τ signal region is 3.17%, 2.04%, and

TABLE I. The number of events in the m_τ sidebands, $N_{\rm sb}$, for the Monte Carlo sample and the data; the ratio of background events, inside/outside the m_τ signal region, BG ratio; the expected number of background events, b_i, and number of observed data events, n_i, in the m_τ signal region; and the signal selection efficiency ϵ_i for each of the three channels. The first (second) uncertainty on ϵ_i is statistical (systematic).

Channel	$N_{\rm sb}$ (MC)	$N_{\rm sb}$ (data)	BG ratio	b_i	n_i	ϵ_i (%)
Electron	5.2 ± 1.3	5	0.10 ± 0.05	0.5 ± 0.3	1	$3.28 \pm 0.13 \pm 0.22$
Muon	0.7 ± 0.5	2	0.30 ± 0.15	0.6 ± 0.3	0	$2.09 \pm 0.10 \pm 0.19$
Pion	6.9 ± 1.6	14	0.13 ± 0.04	1.8 ± 0.6	2	$2.18 \pm 0.11 \pm 0.24$

2.13% for the electron, muon, and pion channels, respectively. The denominator of these ϵ_i is the same for all three and includes all τ decays. We have used a simple three-body phase space decay model to generate our signal Monte Carlo sample. The systematic uncertainty on ϵ_i is determined by varying the signal and background PDFs for each L_R. Because the signal branching fraction is determined from the ratio of the signal and $D\mu\nu$ yields in the data, many systematic uncertainties associated with tracking, particle identification, and the $B_{\rm tag}$ reconstruction cancel. The amount of background, b_i, in the m_τ signal region is estimated from the number of events outside the m_τ signal region (the m_τ sidebands) in the ranges [0,1.65] and $[1.9, 3.5]$ GeV$/c^2$ and the signal-to-sideband ratio from the background Monte Carlo sample.

The signal branching fraction for each channel ($\mathcal{B}_i$) is estimated using the relation

$$\mathcal{B}_i = (n_i - b_i)/(\epsilon_i S_0), \qquad (3)$$

where n_i is the observed number of events in the m_τ signal region, b_i is the expected background, ϵ_i is the signal efficiency, and S_0 is a common sensitivity factor given by

$$S_0 = \frac{N_{D\mu\nu}}{\mathcal{B}_{D\mu\nu}}\left(\frac{1}{\epsilon_{D\mu\nu}}\right)\left(\frac{\epsilon_{\rm tag}^{K\tau\mu}}{\epsilon_{\rm tag}^{D\mu\nu}}\right), \qquad (4)$$

where $N_{D\mu\nu}$, $\mathcal{B}_{D\mu\nu}$, and $\epsilon_{D\mu\nu}$ are the fitted yield, total branching fraction, and selection efficiency for the $D\mu\nu$ control sample and $\epsilon_{\rm tag}^{K\tau\mu}$ and $\epsilon_{\rm tag}^{D\mu\nu}$ are the $B_{\rm tag}$ efficiencies for the signal and $D\mu\nu$ samples, respectively. The last factor ($\epsilon_{\rm tag}^{K\tau\mu}/\epsilon_{\rm tag}^{D\mu\nu}$) is determined from the Monte Carlo samples and close to 1 (0.922 ± 0.052) since the topology of the events in the signal and $D\mu\nu$ samples is very similar. We find $N_{D\mu\nu} = 867 \pm 52$ with $\epsilon_{D\mu\nu} = 0.345 \pm 0.008$ and $\mathcal{B}_{D\mu\nu} = (3.29 \pm 0.22) \times 10^{-3}$ [13], which gives $S_0 = (7.0 \pm 0.7) \times 10^5$.

The m_τ signal region in the data was kept blind during the development of the analysis, to avoid experimenter's bias. After all analysis decisions were made, we "opened the box" and found 1, 0, and 2 events in the m_τ signal region for the electron, muon, and pion channels, respectively. These totals are consistent with our expectations from background only, which are given in Table I. Distributions of m_τ for the data and for the signal Monte Carlo sample are shown in Fig. 2. The numbers of background events in the m_τ sidebands are consistent with our expectations from the Monte Carlo sample.

The central value for the signal branching fraction is $\mathcal{B} = (0.8^{+3.5}_{-2.3}) \times 10^{-5}$, where the uncertainties include both statistical and systematic sources. The three channels were combined by maximizing the likelihood, which is defined as the product of three Poisson probabilities in n_i, where the mean is given by Eq. (3). Uncertainties on the b_i, ϵ_i, and S_0 parameters, which determine the Poisson mean for each channel, were included by convolving the Poisson PDFs with Gaussians in b_i, ϵ_i, and S_0. The uncertainties on $\mathcal{B}$ correspond to the points where the log likelihood drops by 0.5 with respect to the maximum log likelihood value. We have verified, with a Monte Carlo study, that this maximum likelihood technique is unbiased and that the uncertainties are a reasonable estimate of 1 standard deviation. We find a 90% confidence level upper limit on the signal branching fraction of $\mathcal{B} < 7.7 \times 10^{-5}$ using the prescription of Feldman and Cousins [14] for defining the confidence belt. The central value and upper limit on the signal branching fraction are both limited by statistical uncertainties.

In conclusion, we present the first search for the forbidden decay $B^+ \to K^+\tau\mu$ using 383×10^6 $B\bar{B}$ pairs collected by the *BABAR* experiment. The observed events are consistent with the background-only hypothesis. We set an upper limit of $\mathcal{B} < 7.7 \times 10^{-5}$ on the signal branching fraction at 90% confidence level. This result can be used

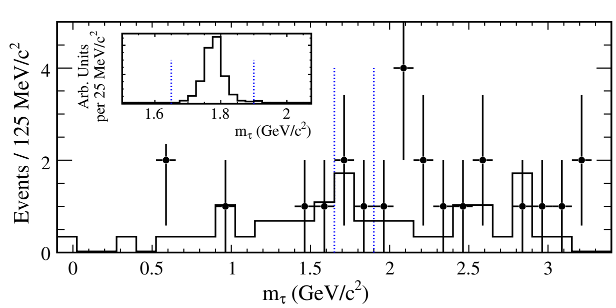

FIG. 2 (color online). Distributions of m_τ after all selection criteria have been applied for the data (points with error bars), background Monte Carlo sample (main histogram), and signal Monte Carlo sample (inset histogram). The dotted vertical lines show the m_τ signal region $[1.65, 1.90]$ GeV$/c^2$.

to improve the model-independent bound on the energy scale of new physics in flavor-changing operators reported in [6] from >2.6 TeV to >13 TeV.

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