Search for the Lepton Family Number Violating Decays $B^\circ \to e^\pm\tau^\mp, \mu^\pm\tau^\mp$

Daniel E. Roberts

Physics Department, Florida State University, Tallahassee, FL, 32306

Abstract

We report on a search, using the CLEO detector, for the lepton-family-number violating decays $B^\circ \to e^\pm\tau^\mp, \mu^\pm\tau^\mp$ where $\tau^\mp \to \pi^\mp\nu_\tau$. The search is conducted on a sample of 9.70×10^6 $B\bar{B}$ events, and ν_τ candidates are inferred by studying the missing energy of each event. This method of reconstructing the neutrino kinematics has hitherto not been applied to such a search. No evidence of the decays were found. New upper limits on the branching fractions for these decays have been calculated: $B(B^\circ \to \tau^\pm e^\mp) < 2.7\times10^{-4}$ at 90% *C.L.* and $B(B^\circ \to \tau^\pm \mu^\mp) < 3.2\times10^{-4}$ at 90% *C.L.*

Introduction

Until recently, it was believed that lepton family number is conserved. However, with independent experiments observing the oscillation of neutrinos, we know that neutrinos have mass and therefore that lepton family number conservation is not necessary.

The decay modes of interest, $B^\circ \to e^\pm\tau^\mp, \mu^\pm\tau^\mp$, while forbidden by the standard model are believed possible, however very suppressed. Upper limits on branching fractions of the decays are B($B^\circ \to e^\pm\tau^\mp$) < 5.3×10^{-4} (90% *C.L.*) and B($B^\circ \to \mu^\pm\tau^\mp$) < 8.3×10^{-4} (90% *C.L.*). The previous branching fraction limits were obtained from the work by Ammar *et al*[1] and are the only published results.

Some theory is in place which permits lepton family number violation: for example, flavor-changing models and leptoquark models[2-4]. A simple extension of the standard model allowing lepton family number violation is an additional Higgs doublet[3,5].

The search for these decays involves several tricks: *event reconstruction*, *neutrino reconstruction*, and *continuum suppression*. Implementing these tricks the data analysis code contains criteria, that the data must satisfy, which identify signal candidates. This code was tested on Monte Carlo simulations of the signal decays to ascertain its effectiveness at isolating a signal and to gain insight into the characteristics of such decays to aid in identification. Data from the CLEO II.V detector at the Cornell Electron Storage Ring (CESR) taken on the $\Upsilon(4S)$ resonance corresponding to 9.70×10^6 $B\bar{B}$ events were used.

Lepton Number and Conservation

The standard model accommodates three leptons and their respective neutrinos and six corresponding anti-leptons, six quarks in three colors each and their eighteen respective anti-particles, and twelve mediators that provide interactions among leptons and quarks. In interactions involoving these sixty particles, certain values are conserved. The most familiar is charge. Another is lepton number, however this does not correspond to a symmetry in the theory. When particles interact, experimental observations suggest that the lepton number on the left side of the interaction must be the same as that on the right. The conservation of lepton number, however, is not limited to the generic number. Rather, the number of *each type* of lepton has to be the same on both sides of the interaction. This is called *lepton family number conservation*. For example, the standard model prohibits the following interaction:

$$\mu^- \rightarrow e^- \gamma, \tag{1}$$

because the muon number and electron number on the left and right sides of the interaction are different. However the following interaction does conserve lepton family number and is thus permitted by the standard model:

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e. \tag{2}$$

This strict conservation rule, it seems, is now antiquated. Until recently the elusive neutrino was believed to have zero mass. Researchers at Japan's Super Kamiokande neutrino detector observed events that support massive neutrinos. Recently researchers at the Sudbury Neutrino Observatory (SNO) in Canada verified the results at Super Kamiokande. The non-zero mass neutrino can oscillate, or change flavor, from one type to another with some lifetime. The ability to oscillate makes *lepton family number conservation* unnecessary since an oscillation from one neutrino to another inherently violates *lepton family number conservation*.

The experimental evidence motivates this work and the testing of models beyond the standard model that do allow *lepton family number violation*[2-5].

CLEO II and CLEO II.V

The CLEO detector is in the form of concentric cylinders each of which provides unique and important information about an e^+e^- event. Near the center of CLEO is the drift chamber which houses thousands of high voltage wires immersed in a gas mixture and a high magnetic field. Charged particles created in an e^+e^- annihilation are curved in the magnetic field and ionize the gases in the chamber which *drift* into the wires thus generating a signal. It is this portion of the detector that reveals information about particle momentum.

The Ring Imaging Cherenkov Counter (RICH) is the next detector an escaping particle encounters. This portion of CLEO is sensitive to the "shock wave" that results when a charged particle travels faster than light in a medium. Light waves propagate at c in a vacuum however are impeded in material so that their velocity is slower. Therefore in a medium, particles can travel at speeds faster than light but still slower than the limiting velocity. When this happens, the light waves emitted by a charged particle in motion stack up much in the same way as sound waves stack up in a cone behind supersonic objects in air. This shockwave, called Cherenkov radiation, is detected in the RICH.

The next outer layer is the cesium-iodide scintillating crystal calorimeter. As electrons and photons pass through the calorimeter, they deposit energy by creating secondary showers of particles which emit light. This light is detected by photodiodes.

The outermost layer of CLEO is the muon system, which consists of alternating wire chambers and layers of iron. Muons are the only particles that can penetrate this portion of the detector and so if a particle leaves a track in the muon detector, that particle is identified as a muon.

The aforementioned sections of CLEO are the same among CLEO II and CLEO II.V. The differences between the two detectors are the types of gases in the drift chamber and CLEO II.V has a silicon detector at its core which measures the positions of the resulting particles of an event as they fly off.

For purposes of comparison, two thirds of the Monte Carlo data is derived from CLEO II.V detector specifications and one third is derived from CLEO II.

Monte Carlo

Monte Carlo (MC) simulations, regardless of the physics involved, are used to simulate random or stochastic processes. The decay of elementary particles is a random process and is therefore modeled well using Monte Carlo. A simple Monte Carlo algorithm for an arbitrary physical system is as follows: choose an event to take place; evaluate the probability for that event to take place; generate a pseudo-random number and compare it to the probability; depending on the relative values of the probability and the pseudo-random number, accept or reject the event; repeat until simulation is completed.

Monte Carlo simulations of the decays of interest are generated by forcing one of the B mesons in the $B\bar{B}$ pair to decay to one of the signal modes and the other to decay randomly. The details of the decays and the detector interactions (*e.g.* trajectory, etc.) are also random and are thus simulated in the Monte Carlo code.

On Searching

Determining whether or not a particular interaction was detected by a detector is like searching for a needle in a stack of needles; it involves a few data analysis tricks and much computation. Our search centers around the $\Upsilon(4S)$ resonance, which is a local maximum of b quark production at about 10.5 GeV and is just enough energy to produce a $B\bar{B}$ meson pair nearly at rest. Knowing that the four momentum of the $\Upsilon(4S)$ at CESR is $(0, 2E_{beam})$ and that the CLEO detector is nearly hermetic, the following equations for the missing energy and momentum, respectively, should give useful values describing the missing particles [6]:

$$E_{miss} \equiv 2E_{beam} - \sum_{particles} E_i \tag{3}$$

$$\vec{p}_{miss} \equiv - \sum_{particles} \vec{p}_i \tag{4}$$

Using a data sample, $B^\circ \to l^\pm \pi^\mp \nu_\tau$ events, where π and ν_τ are daughters of a τ and l is either an electron or a muon, are reconstructed to test for signal candidacy. A leptonic B° decay involving a neutrino cannot be completely reconstructed because of the undetected neutrino. However, assuming that the neutrino is the only missing particle and adding up the momenta of the other particles, we can reconstruct the neutrino where the missing momentum of the event, eq. 4, is attributed to the neutrino.

Some problems stand in our way of reconstructing the neutrino. Two tracks due to the same particle or a particle curling in the drift chamber may be misconstrued by CLEO as two particles. Particles can go down the beam pipe in which case they are missed. Neutral particles often are undetected. Particle showers can be created in the calorimeter that are due to a particle already detected. If this shower is interpreted as another particle then our approximation of the total missing energy will be too great. To remedy some of these problems we set requirements which "*skim*" the data and reject these problematic events.

The momenta of the charged particles are given by the tracks left in the drift chamber of CLEO. A charged particle is then identified by measuring its time of flight or its ionization energy loss. Therefore, given a particle's momentum detected by the drift chamber, and the time it takes the particle to cover a certain distance or its ionization energy loss, the mass and thus the identity of the particle can be discerned. Apart from their tracks left in the drift chamber, electrons deposit energy in the calorimeter and muons trigger the muon detector. These areas of the detector also aid in clarifying the identity of a particle. Once the charged particles and the neutrino are reconstructed, the entire event can be reconstructed and tested for signal candidacy.

A signal candidate was found by matching a lepton to a pion of opposite charge and requiring that $p_\pi > 1.75\ GeV/c$. This requirement on the momentum of the pion maximizes the signal with respect to background[1] and helps reduce background pion production. The difference in energy between the beam and the sum of the lepton, neutrino, and pion energies is given in the following equation:

$$\Delta E \ = \ (E_\nu + E_l + E_\pi) - E_{beam} \tag{5}$$

where E_ν is assigned the magnitude of the missing momentum because the resolution of the momentum is much greater than that for the energy due to the tracks and showers deposited in the detector[7]. The composition of eq. 5 differs from that of ΔE in [1], in which $E_\nu = p_\nu = |\vec{p}_B - \vec{p}_\pi - \vec{p}_l|$, where $\vec{p}_B$ is the momentum of the signal B. Signal event candidates also had a lepton momentum in the region 2.2-2.5 GeV/c and a ΔE between -0.2 and 0.3 GeV. The 2.2-2.5 GeV/c requirement in lepton momentum is on account of the motion of the parent B. If the B were produced at rest the lepton would be monochromatic in momentum; $p_l \approx 2.35$. Because there is a small amount of residual energy after the $B\bar{B}$ production at the Υ(4S) the signal B has a small momentum which spreads the daughter lepton momentum from monochromaticity. The following is a summary of the additional cuts applied to the sample which a signal must pass:

$\Delta Q = 0 \rightarrow$ *charge conservation*
$|\Delta Q| = 1 \rightarrow$ ν *reconstruction for missing track*
$\Delta Q = 0$: $|\cos\theta_T| \leq 0.7 \rightarrow$ *continuum suppression*
$|\Delta Q| = 1$: $|\cos\theta_T| \leq 0.6 \rightarrow$ *continuum suppression*
Track number $\geq 5 \rightarrow$ *background suppression*
"V cut" $\rightarrow$ *continuum suppression*
Number of leptons $= 1 \rightarrow$ ν *reconstruction*
KINCD, TNG $\rightarrow$ *good quality tracks*
$\cos\theta_{lep} \ > \ 0 \rightarrow$ *background suppression*
$|\cos\theta_\nu| \ < \ 0.96 \rightarrow$ *good neutrino reconstruction*
psicut $\rightarrow B \rightarrow J\psi X$ *suppression*
μ *depth* $> \ 7.0$ *good muon detection*

Figures 1-8 are plots of ΔE *vs.* p_l for signal MC, generic $B\bar{B}$ background MC, $b{\rightarrow}u$ background MC, and data, respectively.

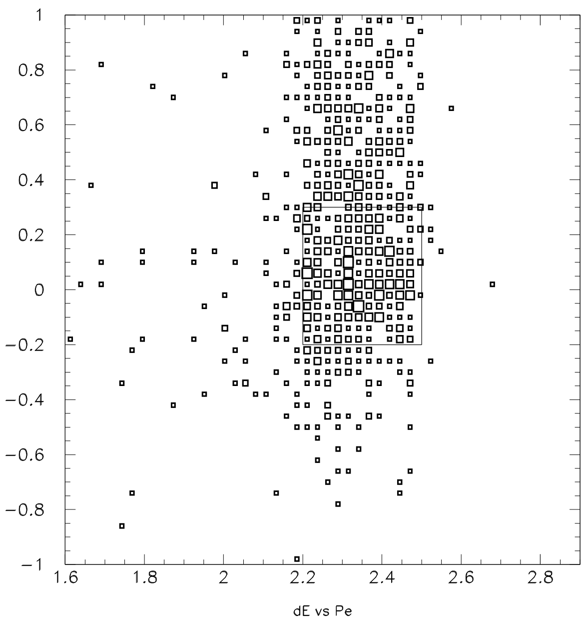

FIGURE 1. $\Delta E(GeV)$ vs $p_e(GeV/c)$ candidates for signal MC. The box indicates the signal region.

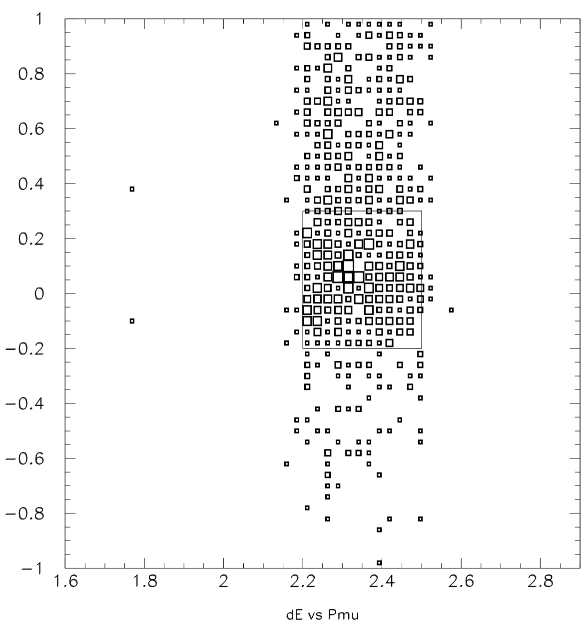

FIGURE 2. $\Delta E(GeV)$ vs $p_\mu(GeV/c)$ candidates for signal MC. The box indicates the signal region.

Calculating an Upper Limit

This data analysis code, designed to lower the branching fraction limits and search for the decay modes, was tested on Monte Carlo simulations of the signal decays. The purpose

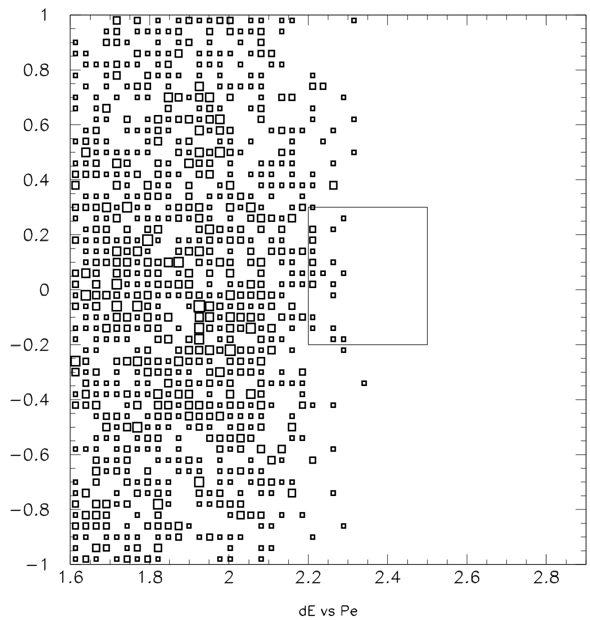

FIGURE 3. $\Delta E(GeV)$ *vs* $p_e(GeV/c)$ candidates for generic $B\bar{B}$ background MC. The box indicates the signal region.

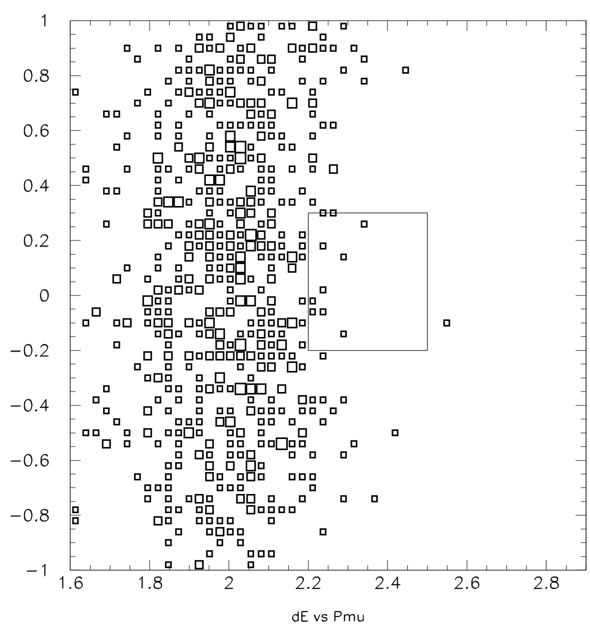

FIGURE 4. $\Delta E(GeV)$ *vs* $p_\mu(GeV/c)$ candidates for generic $B\bar{B}$ background MC. The box indicates the signal region.

of testing the code on Monte Carlo simulations is to gain insight into how a particular decay would be interpreted by the detector and how efficient our code is at isolating the signal. Efficiencies are given by the following equation: $\epsilon = \frac{number\ of\ reconstructed\ signal\ events}{number\ of\ generated\ events}$ in signal Monte Carlo. The efficiencies for the $e\tau$ and $\mu\tau$ modes were measured to be $(0.700\pm0.037)\%$ and $(0.843\pm0.040)\%$ (Table 2), respectively. To obtain a conservative limit, ϵ was reduced by 1.28σ where $\sigma = 1/\sqrt{number\ of\ signal\ events}$ in signal Monte Carlo and is arrived at by the

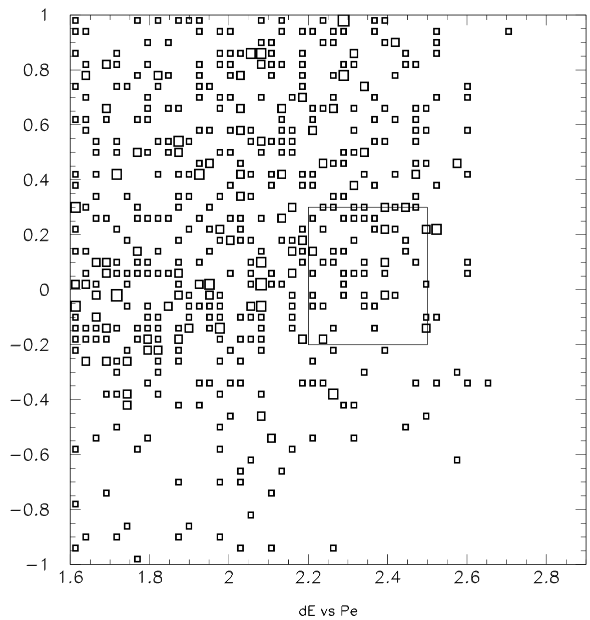

FIGURE 5. $\Delta E(GeV)$ *vs* $p_e(GeV/c)$ candidates for $b \rightarrow u$ MC. The box indicates the signal region.

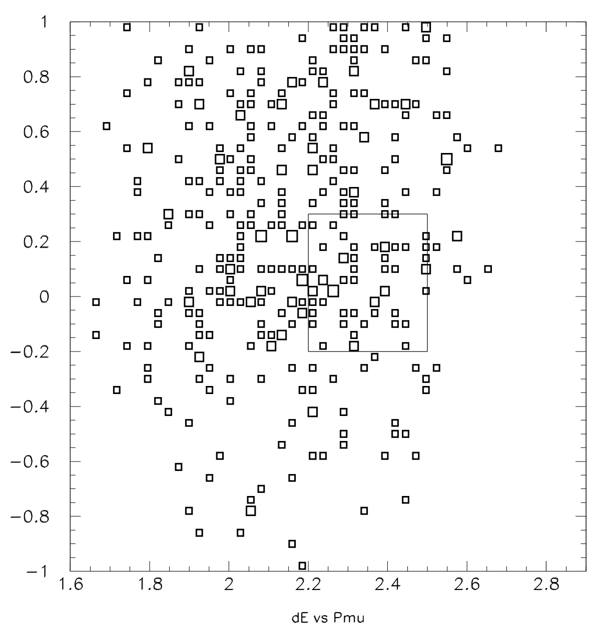

FIGURE 6. ΔE *vs* p_μ candidates for $b \rightarrow u$ MC. The box indicates the signal region.

systematic uncertainty in Poisson statistics. The coefficient 1.28 is related to the 90% $C.L.$ Once we optimize our code to be effective on Monte Carlo decays we have predictive power with a substantial confidence about what is happening in the data.

Two forms of $B\bar{B}$ background were considered: *generic* $B\bar{B}$ (*mostly* $b \rightarrow c$), *and semileptonic* $b \rightarrow u$ *processes* ($B^\circ \rightarrow \pi^+ l^- \nu_l$). The latter is inherently problematic because it is the same mode as the final state of our signal decay. Monte Carlo simulations of both types

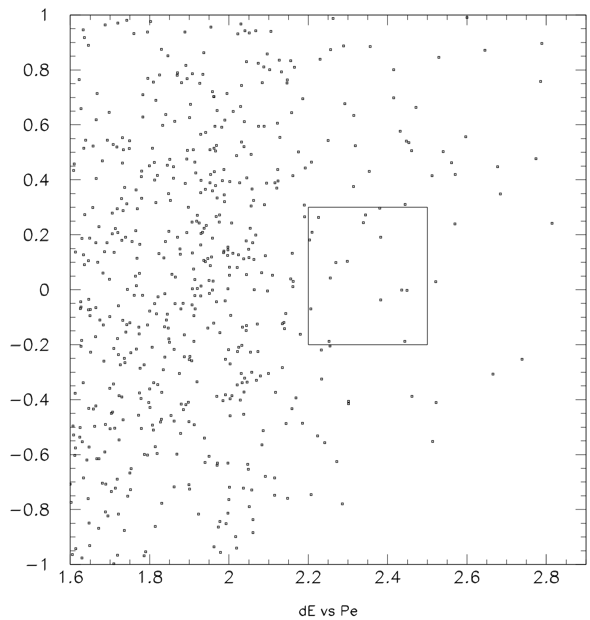

FIGURE 7. $\Delta E(GeV)$ *vs* $p_e(GeV/c)$ candidates for data. The box indicates the signal region.

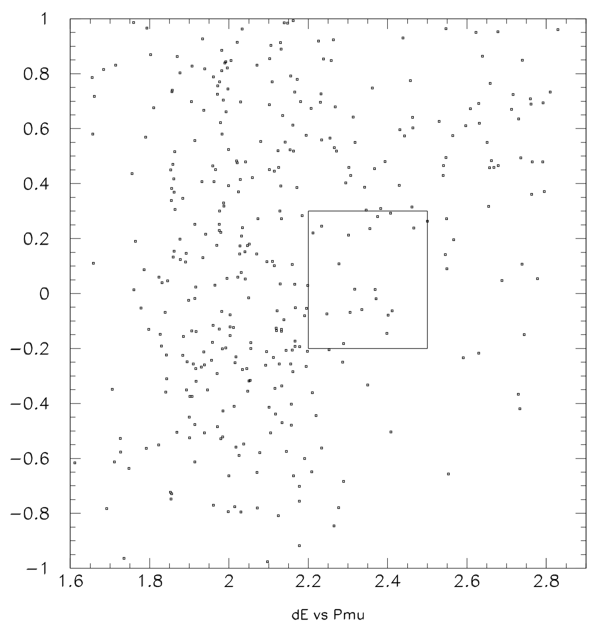

FIGURE 8. $\Delta E(GeV)$ *vs* $p_\mu(GeV/c)$ candidates for data. The box indicates the signal region.

of background were generated and those events in the $\Delta E/p_l$ signal box corresponded to the background contribution to our event candidates. The number of events in the signal box was scaled to the number of $B\bar{B}$ events in the data because the number of generated background events was different from that of the data. For the $e\tau$ and $\mu\tau$ modes the number of signal events in the *generic* $B\bar{B}$ Monte Carlo were 5.4±1.2 and 1.8±0.6 (Table 1), respectively. For the $e\tau$ and $\mu\tau$ modes the number of signal events in the $b\to u$ Monte Carlo were 8.3±1.2 and 9.5±1.3 (Table 1), respectively. All standard deviations were calculated using Poisson statistics. For conservative background estimates we divided the previous background contributions, after scaling, by 2.

Using CLEO II and II.V data samples from the Υ(4S) resonance corresponding to $N_{B\bar{B}} = 9.70\times10^6$ $B\bar{B}$ events, the analysis code was applied. There were 16 events in the signal box for the $e\tau$ mode and and 21 events in the signal box for the $\mu\tau$ mode (Table 1).

We used the Feldman/Cousins approach for the upper limit at 90% *C.L.*of the signal number, N_{UL} (Table 2), based on the number of signal events in data and estimated background[8]. This method is based on Poisson statistics and gives N_{UL} accounting for some assumed background. Finally the branching fraction upper limit is given by:

$$B(B^\circ \to \tau^\pm l^\mp) = \frac{N_{UL}}{\epsilon N_{B\bar{B}}} \tag{6}$$

TABLE 1. Number of events in signal region for each decay mode and each sample origin.

Sample Origin/Decay Mode	$B^\circ \to \tau^\pm e^\mp$	$B^\circ \to \tau^\pm \mu^\mp$
Data	16	21
$B\bar{B}$ MC	5.4±1.2	1.8±0.6
$b \to u$ MC	8.3±1.2	9.5±1.3
Continuum	???	???

TABLE 2. Signal region results and branching fraction upper limits (90% confidence level).

Mode	N_{UL}	ϵ	Upper Limit (90% *C.L.*)
$B^\circ \to \tau^\pm e^\mp$	16.99	(0.700±0.037)%	2.7×10^{-4}
$B^\circ \to \tau^\pm \mu^\mp$	24	(0.843±0.040)%	3.2×10^{-4}

Results

The branching fraction upper limits are as follows: $B(B^\circ \to \tau^\pm e^\mp) < 2.7\times10^{-4}$ at 90% *C.L.* and $B(B^\circ \to \tau^\pm \mu^\mp) < 3.2\times10^{-4}$ at 90% *C.L.* (Table 2). This is an improvement on the only other published results on a search for these modes by Ammar *et al*[1]: $B(B^\circ \to \tau^\pm e^\mp) < 5.3\times10^{-4}$ at 90% *C.L.* and $B(B^\circ \to \tau^\pm \mu^\mp) < 8.3\times10^{-4}$ at 90% *C.L.* In their work they assumed that the $B\bar{B}$ pair was produced exactly at rest, an approximation we did not have to make, and they did not use the new technique of *neutrino reconstruction.*

Future Work

Many shortcuts had to be taken during this project in order to reach a result given the time constraints. With ample time these steps not here taken would afford a more thorough search. The following is a summary of steps that ideally such an interaction search would employ to attain higher resolution of results. A study of how the polarization of the signal decays affects the efficiency should be performed. The choice of the cuts a candidate signal must pass, except ΔE, p_{lepton} and p_π, were optimized for a different signal analysis. A more thorough analysis would be specific to the relevant signal modes. More Monte Carlo simulations should be run to secure better Monte Carlo systematic uncertainty. As well, one should consider the rates that hadron tracks are misinterpreted as electron and muon candidates. To better understand the effects of background one should study the continuum (*off-resonance*) background contributions and improve the estimate of $B\bar{B}$ contributions, especially for the $b \to u$ decay.

Conclusion

We used a new *neutrino reconstruction* technique to search for the decays $B^\circ \to e^\pm \tau^\mp$, $\mu^\pm \tau^\mp$. No evidence of these decays was found. An improved upper limit was placed on the branching fraction for each of the two modes.

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