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Search for B^0 Decays to Two Charged Leptons

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Abstract

We have searched for B^0 decays to two charged leptons and set 90% confidence level upper limits on the branching fractions: $\mathrm{B}(B^0 \to e^+e^-) < 5.9 \times 10^{-6}$, $\mathrm{B}(B^0 \to \mu^+\mu^-) < 5.9 \times 10^{-6}$, $\mathrm{B}(B^0 \to e^\pm\mu^\mp) < 5.9 \times 10^{-6}$, $\mathrm{B}(B^0 \to e^\pm\tau^\mp)$ $< 5.3 \times 10^{-4}$, and $\mathrm{B}(B^0 \to \mu^\pm\tau^\mp) < 8.3 \times 10^{-4}$.

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We report results from a search for B^0 decays to two charged leptons. The Standard Model allows B^0 decays to two electrons or two muons via box diagrams or loop diagrams shown in Fig. 1. Recent predictions for these branching fractions are 1.9×10^{-15} and 8.0×10^{-11} respectively [1], although extensions to the Standard Model which include additional Higgs doublets can enhance the rate [2]. The smallest previously published upper limits are $\mathrm{B}(B^0 \to e^+e^-) < 3 \times 10^{-5}$ [3] and $\mathrm{B}(B^0 \to \mu^+\mu^-) < 8.3 \times 10^{-6}$ [4]. The decays $B^0 \to e^\pm\mu^\mp, e^\pm\tau^\mp, \mu^\pm\tau^\mp$ are forbidden in the Standard Model by lepton number conservation. However, there are other models which allow lepton number non-conservation [5,6]. The previously published upper limit is $\mathrm{B}(B^0 \to e^\pm\mu^\mp) < 4 \times 10^{-5}$ [3].

We use data from the CLEO II detector [7] operating at the Cornell Electron Storage Ring (CESR). The sample consists of 1.34 fb^{-1} taken on the $\Upsilon(4S)$ resonance, corresponding to 1.47×10^6 $B\overline{B}$ events. An additional sample of 0.64 fb^{-1} accumulated 55 MeV below the $\Upsilon(4S)$ resonance is used to estimate the non-resonant background. We refer to these as the "on-resonance" and "off-resonance" data samples. The CLEO charged particle tracking system consists of a six-layer straw tube chamber, a ten-layer precision tracking chamber, and a 51-layer main drift chamber, all operated inside a 1.5 T magnetic field. Beyond the tracking chambers, but inside the magnet coil, are a time-of-flight system and an electromagnetic calorimeter consisting of 7800 CsI crystals. Outside the coil is a muon detection system consisting of chambers interspersed with iron.

Since B mesons at the $\Upsilon(4S)$ are produced nearly at rest, $B \to ee, \mu\mu, e\mu$ decays will consist of two nearly back-to-back tracks each with $p \approx 2.6$ GeV/c. To search for these candidates we select hadronic events with at least five charged tracks. Two oppositely charged, well-measured tracks must come from a common point consistent with the known event vertex. The direction of the thrust axis of the two candidate tracks must lie within a fiducial volume defined by $|\cos\theta| \leq 0.8$ (where θ is the angle with respect to the beam axis). We use the lepton energies (E_1, E_2) calculated assuming the appropriate particle mass hypothesis to compute the difference between their total energy and the beam energy, $\Delta E = E_1 + E_2 - E_{\mathrm{b}}$. The resolution in ΔE is 25 ± 2 MeV. We calculate a "beam constrained" mass from $m^2 = E_{\mathrm{b}}^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2$, i.e., by using the constraint $\Delta E = 0$ which improves the mass resolution by a factor of ten. The resolution in m is 2.5 ± 0.2 MeV, determined from fully reconstructed B decays. We define a 2 standard deviation (σ) signal region in ΔE and m. Electrons are identified using a likelihood function combining calorimeter and tracking information (E/p and dE/dx). Muons are identified by requiring that the tracks penetrate the muon chambers to a depth of at least 3 interaction lengths.

The main background arises from real and fake leptons from the process $e^+e^- \to q\overline{q}$, where $q = u, d, s, c$. Such events typically exhibit a two-jet structure and produce high momentum, approximately back-to-back tracks which satisfy the requirements imposed on our candidate events. We calculate the angle, θ_{T}, between the thrust axis of the candidate tracks and the thrust axis of all the remaining charged and neutral energy in the event. The distribution of $\cos\theta_{\mathrm{T}}$ is strongly peaked near ± 1 for $q\overline{q}$ events and is nearly flat for $B\overline{B}$ events. We require $|\cos\theta_{\mathrm{T}}| \leq 0.7$. The overall efficiency, ϵ, for detecting these modes is 0.32 ± 0.04.

We find no events in the signal regions for any of the three modes and set an upper limit (N_{UL}) of 2.3 events in each. The 90% confidence level upper limits on the branching fractions are given by $N_{\mathrm{UL}}/\epsilon N_{B^0}$. To conservatively account for the uncertainty in the efficiency determination, we reduce the efficiency by 1.28σ. Assuming equal production of charged and neutral B's, we obtain upper limits of 5.9×10^{-6} for each of the modes (Table I). These limits are significant improvements over those previously published.

To search for the modes $e\tau$ and $\mu\tau$, we look for tau decays to high momentum pions, which have relatively little background. High momentum pions from tau decays come mainly from the mode $\tau^-\to\pi^-\nu_\tau$, which has the advantage that there is only one neutrino in the final state. The final state we search for is thus $\pi^\mp\ell^\pm\nu$. We select hadronic events with at least five charged tracks. The total charged and neutral energy in the event (excluding the candidate tracks) is required to be between 2.5 and 6 GeV. Two oppositely charged, well-measured tracks must each come from a point consistent with the known event vertex. The pion momentum must be greater than 1.75 GeV/c, which will maximize the significance of any signal. This requirement keeps 42% of the pion spectrum [8] from $\tau\to\pi\nu$ decays. We choose two variables to define the signal region. The first is the momentum of the lepton, p_ℓ. If the B were exactly at rest, the lepton momentum would be monochromatic with $p_\ell\approx2.35$ GeV/c. Including the motion of the B, p_ℓ ranges from 2.2 to 2.5 GeV/c. The second variable used to discriminate between signal and background is the difference between the energy of the B candidate and the beam energy, $\Delta E = E_\pi + E_\ell + E_\nu - E_{\rm b}$ where the energy of the neutrino is given by $E_\nu = p_\nu = |\mathbf{p}_B - \mathbf{p}_\pi - \mathbf{p}_\ell|$. Since we do not know the direction of the B momentum, but we know its magnitude is small, we set $p_B = 0$ in calculating the momentum of the neutrino. Using this approximation the $B\to\ell\tau;\tau\to\pi\nu$ signal is well-contained in the region $|\Delta E| < 300$ MeV. In addition, other tau decays, such as $\tau^-\to\rho^-\nu$, contribute events to the signal region. This effect is included in our overall efficiency.

Pions are required to have dE/dx values within 2σ of the pion hypothesis. Since backgrounds are larger than in the $ee, \mu\mu, e\mu$ cases, we make more stringent requirements for lepton identification. The tighter requirement for electron candidates reduces the contamination from pions by a factor of 2. Muon candidates are required to penetrate the muon chambers to a depth of 7 interaction lengths.

To reduce continuum background we require that the angle, θ_T, between the thrust axis of the $\pi\ell$ system and the thrust axis of all the other tracks and showers in the event satisfy $|\cos\theta_T| < 0.7$. Additional discrimination between signal and $q\overline{q}$ background is provided by a Fisher discriminant technique [9]. The Fisher discriminant is a linear combination $\mathcal{F}\equiv\sum_{i=1}^{N}\alpha_i y_i$ where the coefficients, α, are chosen to maximize the separation in $\mathcal{F}$ between Monte Carlo signal and background samples. The 10 inputs, y_i, are the direction of the $\pi\ell$ thrust axis, and nine variables which measure the momentum flow of showers and tracks from the rest of the event in nine angular bins, each of 10°, centered about the $\pi\ell$ thrust axis. Fig. 2 shows the distribution of $\mathcal{F}$ for signal events from Monte Carlo and background events from off-resonance data [10]. Both signal and background distributions are well fitted by Gaussians whose means are separated by 1.0σ. We require $\mathcal{F} < 0.45$.

Detection efficiencies, ϵ, are estimated using a Monte Carlo simulation. We find the efficiencies for the $e\tau$ and $\mu\tau$ final states to be (1.43 ± 0.31)% and (1.19 ± 0.26)%, respectively.

We find 4 $e\tau$ candidates and 6 $\mu\tau$ candidates in the signal region (Fig. 3). In the signal region of the off-resonance data, we find 1 $e\tau$ candidate and 1 $\mu\tau$ candidate, leading to continuum background estimates of 2.1 ± 2.1 for each mode. In addition, $B\overline{B}$ backgrounds, estimated from Monte Carlo simulation, provide 2.8 ± 1.3 and 2.3 ± 1.0 events, respectively, approximately half of which come from $b\to c$ decays and half from $b\to u\ell\nu$ decays. Since the backgrounds are not well measured, we calculate conservative upper limits by ignoring background, and taking all events to be signal candidates. Using Poisson statistics, we find upper limits ($N_{\rm UL}$) of 8.0 $e\tau$ events and 10.5 $\mu\tau$ events. To conservatively account for the uncertainty in the efficiency determination, we reduce the efficiency by 1.28σ. We obtain upper limits (90% confidence level) on the branching fractions of $B \to e\tau$ and $B \to \mu\tau$ of 7.9×10^{-4} and 1.2×10^{-3}, respectively (Table I).

In summary, we find no evidence for decays of B^0 mesons into two charged leptons. Our upper limits are substantial improvements over previous limits on $B \to ee$, $B \to \mu\mu$, and $B \to e\mu$. Our limits on $B \to e\tau$ and $B \to \mu\tau$ are the first published results.

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[8] If the decay $B \to \ell\tau$ produces left-handed taus, then the efficiency of the pion momentum cut is increased by a factor of 1.5. The branching fraction upper limits are reduced by this factor.

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[10] To increase the statistics of the continuum sample shown in Fig. 2, we loosen the lepton identification requirements, the minimum pion momentum, and the event energy cut.

FIGURES

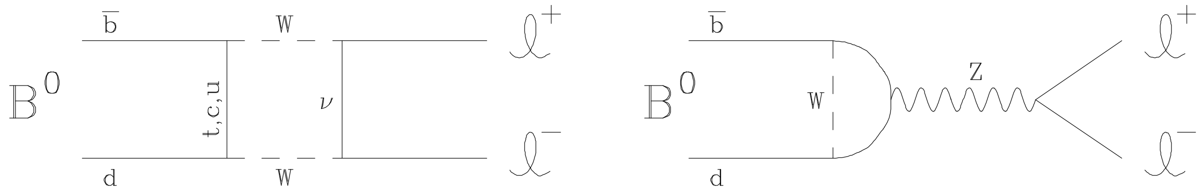

FIG. 1. Box and loop Feynman diagrams for $B^0 \to e^+e^-$, $B^0 \to \mu^+\mu^-$.

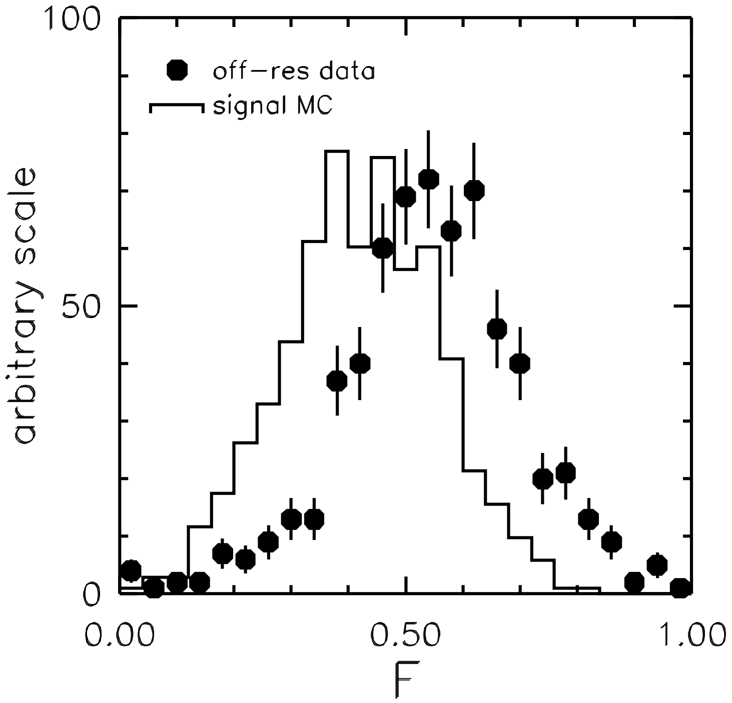

FIG. 2. Fisher output distribution for Monte Carlo signal events (solid line) and off-resonance data (points.)

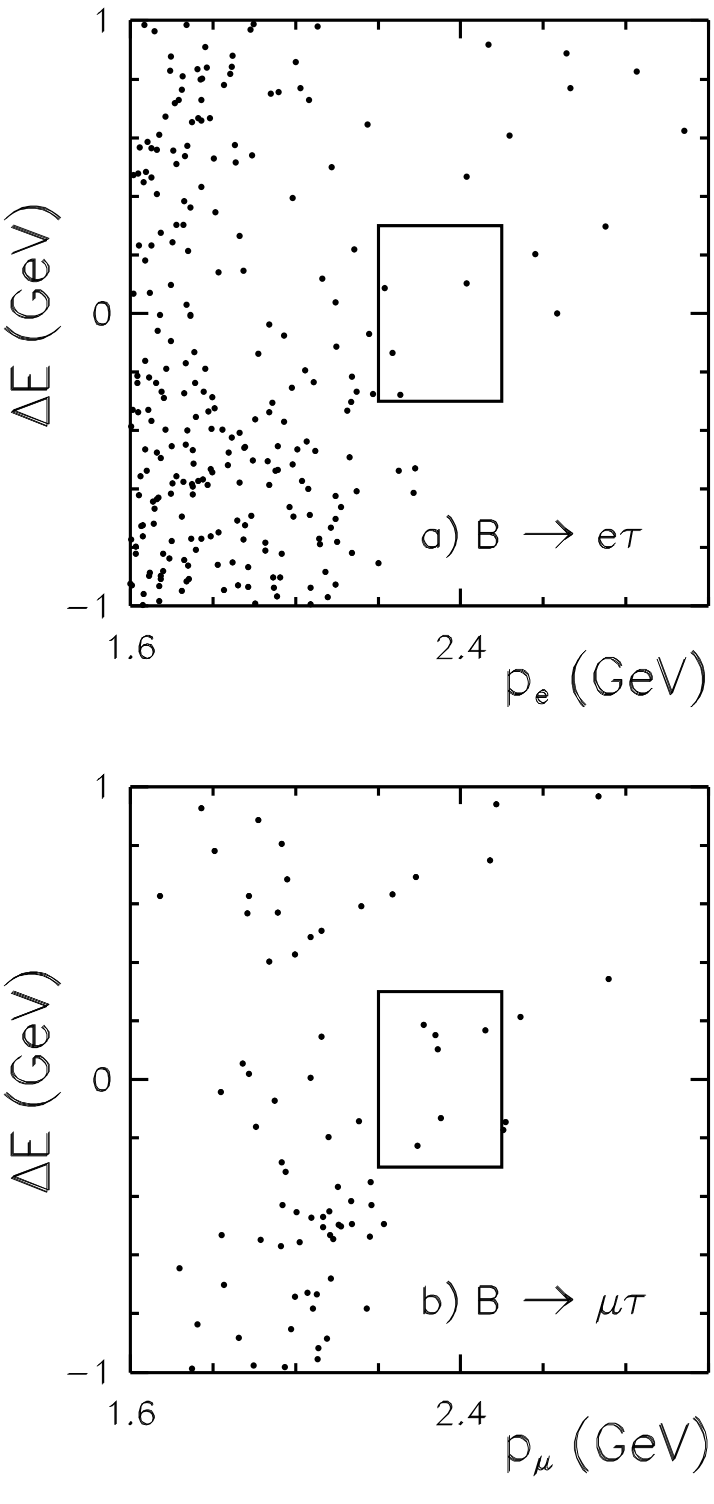

FIG. 3. ΔE vs. p_ℓ for (a) $e\tau$ and (b) $\mu\tau$ candidates. The signal region is indicated by the box.

TABLES

TABLE I. Summary of results and branching fraction upper limits (90% Confidence Level).

mode	N_{obs}	$N_{\rm UL}$	ϵ	Upper limit (90% CL)
$B^0 \to e^+e^-$	0	2.3	0.32±0.04	5.9×10^{-6}
$B^0 \to \mu^+\mu^-$	0	2.3	0.32±0.04	5.9×10^{-6}
$B^0 \to e^\pm\mu^\mp$	0	2.3	0.32±0.04	5.9×10^{-6}
$B^0 \to e^\pm\tau^\mp$	4	8.0	0.014±0.003	5.3×10^{-4}
$B^0 \to \mu^\pm\tau^\mp$	6	10.5	0.012±0.003	8.3×10^{-4}