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Search for Inclusive $b \to sl^+l^-$

CLEO Collaboration

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Abstract

We have searched for the effective FCNC decays $b \to sl^+l^-$ using an inclusive method. We set the following upper limits on the branching ratios $\mathcal{B}(b \to se^+e^-) < 5.7 \times 10^{-5}$, $\mathcal{B}(b \to s\mu^+\mu^-) < 5.6 \times 10^{-5}$, and $\mathcal{B}(b \to se^\pm\mu^\mp) < 2.2 \times 10^{-5}$ (at 90 % C.L.).

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Flavor Changing Neutral Currents (FCNC) are forbidden to first order in the Standard Model. Second order loop diagrams, known as penguin and box diagrams, can generate effective FCNC which lead to $b \to s$ transitions. These processes are of considerable interest because they are sensitive to V_{ts}, the Cabibbo-Kobayashi-Maskawa matrix element which will be very difficult to measure in direct decays of the top quark. These processes are also sensitive to non-Standard Model physics [1], since charged Higgs bosons, new gauge bosons or supersymmetric particles can contribute via additional loop diagrams.

The electromagnetic penguin decay $b \to s\gamma$ was first observed by CLEO in the exclusive mode $B \to K^*\gamma$ with $\mathcal{B}(B \to K^*\gamma) = (4.2 \pm 0.8 \pm 0.6) \times 10^{-5}$ [2]. The inclusive rate for the decay $B \to X_s\gamma$ was measured to be $\mathcal{B}(b \to s\gamma) = (2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$ [3]. Inclusively measured rates are more interesting because they can be directly related to underlying quark transitions without large theoretical uncertainties in formation probabilities for specific hadronic final states. The measured inclusive $b \to s\gamma$ rate is consistent with Standard Model calculations.

The $b \to sl^+l^-$ decay rate is expected in the Standard Model to be nearly two orders of magnitude lower than the rate for $b \to s\gamma$ decays. Nevertheless, the $b \to sl^+l^-$ process has received considerable attention since it offers a deeper insight into the effective Hamiltonian describing FCNC processes in B decays [4]. While $b \to s\gamma$ is only sensitive to the absolute value of the C_7 Wilson coefficient in the effective Hamiltonian, $b \to sl^+l^-$ is also sensitive to the sign of C_7 and to the C_9 and C_{10} coefficients, where the relative contributions vary with l^+l^- mass. These three coefficients are related to three different processes contributing to $b \to sl^+l^-$: electromagnetic and electroweak penguins, and a box diagram. Processes beyond the Standard Model can alter both the magnitude and the sign of the Wilson coefficients. The higher-order QCD corrections for $b \to sl^+l^-$ are smaller than for the electromagnetic penguin and have been calculated in next-to-leading order [5,6].

Several experiments (UA1 [7], CLEO [8], CDF [9]) have searched for the exclusive decays $B \to Kl^+l^-$ and $B \to K^*l^+l^-$ and set upper limits at the level of $(1-2) \times 10^{-5}$ at 90% confidence level (C.L.). Combining electron and muon modes, the previous generation of the CLEO experiment set an inclusive limit: $\mathcal{B}(b \to sl^+l^-) < 1.2 \times 10^{-3}$ (90 % C.L.) [10]. The UA1 experiment [7] searched for inclusive $b \to s\mu^+\mu^-$ at the endpoint of the dilepton mass distribution ($M(\mu^+\mu^-) > 3.9$ GeV) which comprises about a tenth of the total rate. Extrapolating to the full phase space UA1 claims a limit of $< 5 \times 10^{-5}$ (90 % C.L.). However, a simulation of the UA1 acceptance shows that UA1 overestimated their efficiency by at least a factor of three.

In this Letter, we present results of the search for inclusive $b \to s\mu^+\mu^-$, $b \to se^+e^-$ and $b \to se^\pm\mu^\mp$. The latter decay violates conservation of electron and muon lepton numbers and thus can only originate from processes beyond the Standard Model. The data were obtained with the CLEO II detector at the Cornell Electron Storage Ring. A sample with an integrated luminosity of 3.1 fb^{-1} was collected on the $\Upsilon(4S)$ resonance. This sample contains $(3.29 \pm 0.06) \times 10^6$ produced $B\bar{B}$ pairs. For background subtraction we also use 1.6 fb^{-1} of data collected just below the $\Upsilon(4S)$. CLEO II is a general purpose solenoidal spectrometer described in detail in Ref. [11].

The data selection method is very similar to the reconstruction method presented in our previous measurement of the $b \to s\gamma$ rate [3], with the γ candidate replaced by a lepton pair. We select events that pass general hadronic event criteria based on charged track multiplicity, visible energy and location of the event vertex. The highest energy pair of oppositely charged leptons is then selected. Electron candidates are required to have an energy deposition in the calorimeter nearly equal to the measured momentum, and to have a specific ionization in the drift chamber (dE/dx) consistent with that expected for an electron. Muon candidates are identified as charged tracks with matching muon-detector hits at absorber depths of at least three nuclear interaction lengths. In the $\mu^+\mu^-$ channel, one muon is required to penetrate at least five interaction lengths. We then look for a combination of hadronic particles, denoted X_s, with a kaon candidate and 0-4 pions, which together with the selected lepton pair satisfy energy-momentum constraints for the B decay hypothesis, $B \to X_s l^+ l^-$:

$$\chi_B^2 = \left(\frac{M_B - 5.279}{\sigma_M}\right)^2 + \left(\frac{E_B - E_{beam}}{\sigma_E}\right)^2 < 30$$

where $M_B = \sqrt{E_{beam}^2 - P_B^2}$, and E_B, P_B are measured energy and momentum of the B candidate. The kaon candidate is a charged track with dE/dx and time of flight (ToF) consistent with the kaon hypothesis, or a $K_S^0 \to \pi^+\pi^-$ candidate identified by a displaced vertex and invariant mass cut. The pion candidate is a charged track with dE/dx and ToF consistent with the pion hypothesis, or a $\pi^0 \to \gamma\gamma$ candidate. At most one π^0 is allowed in the X_s combination. In each event we pick the combination that minimizes overall χ^2, which includes χ_B^2 together with contributions from dE/dx, ToF, K_S^0 and π^0 mass deviations, where relevant.

To suppress continuum background we require the event to have $H_2/H_0 < 0.45$, where H_i are Fox-Wolfram moments [12]. We also require $|\cos\theta_{tt}| < 0.8$, where θ_{tt} is the angle between the thrust axis of the candidate B and the thrust axis of the rest of the event. To suppress $B\bar{B}$ background we require the mass of the X_s system to be less than 1.8 GeV. The dominant $B\bar{B}$ background comes from two semileptonic decays of B or D mesons, which produce the lepton pair with two undetected neutrinos. Since most signal events are expected to have zero or one neutrino, we also require the mass of the undetected system in the event to be less than 1.5 GeV. By excluding the mode with $X_s = K\pi^+\pi^-\pi^0$, we reduce the simulated $B\bar{B}$ background by additional 21% while reducing the signal efficiency by only 6%.

In Fig. 1, we plot for on- and off-resonance data, the dilepton mass, $M(l^+l^-)$, for the selected events with the B consistency cut, $\chi_B^2 < 6$. Unlike the $b \to s\gamma$ analysis, the continuum background is small. The peaks at the ψ and ψ' masses that are observed in the on-resonance data are due to the long distance interactions, $b \to cW^-$, $W^- \to \bar{c}s$, with the $c\bar{c}$ pair hadronizing into a $\psi^{(\prime)}$ which then decays to a lepton pair. Using cuts on $M(X_s)$ to identify K and K^*, we measure the branching ratios for $B \to \psi^{(\prime)}K^{(*)}$ and obtain results consistent with a recent CLEO publication [13]. For further analysis, we exclude events with $M(l^+l^-)$ near the ψ and ψ' masses (± 0.1 GeV for $\mu^+\mu^-$, $-0.3, +0.1$ GeV for e^+e^-, no cut for $e^\pm\mu^\mp$). The exclusion region is wider in the e^+e^- channel because of the radiative tail. After these cuts and continuum subtraction, we observe 10 ± 5 $X_s e^+e^-$, 12 ± 6 $X_s\mu^+\mu^-$, and 18 ± 8 $X_s e^\pm\mu^\mp$ events in the data. From the Monte Carlo simulation of generic $B\bar{B}$ events we expect 9 ± 1, 16 ± 2 and 39 ± 3 background events, respectively. Therefore, no evidence for signal is found in the data and we proceed to set limits on these decay rates.

To avoid systematics related to absolute normalization of the $B\bar{B}$ Monte Carlo, instead of counting events after the $\chi^2_B < 6$ cut, we loosen this cut to 30 and fit the observed χ^2_B distributions in the on- and off-resonance data. We allow for signal contribution, as well as $B\bar{B}$ and continuum backgrounds. The signal is expected to peak sharply at zero, whereas the backgrounds have flatter distributions (see Fig. 2a). The shapes of all these contributions are fixed from the Monte Carlo simulation, while the normalizations are allowed to float. The relative normalization for continuum background between the on- and off-resonance data is fixed to the known ratio of integral luminosities and cross-sections. The fits give the following signal amplitudes: 7 ± 7, 1 ± 7, and -18 ± 10 events for $X_s e^+e^-$, $X_s\mu^+\mu^-$, and $X_s e^\pm\mu^\mp$ respectively. As an example, the fit to the $X_s e^+e^-$ data is displayed in Fig. 2b-c.

To calculate the signal efficiency and to predict the χ^2_B signal distribution we generated $b \to sl^+l^-$ Monte Carlo events. The parton level distributions for $b \to se^+e^-$ and $b \to s\mu^+\mu^-$ are predicted from the effective Hamiltonian containing Standard Model contributions. The next to leading order calculations were used [6]. At present, the effect of gluon bremsstrahlung on the outgoing $s-$quark is only partially included in the theoretical calculations. After our ψ and ψ' veto cuts, the long distance interactions are expected to constructively interfere with the short distance contributions. Estimates of these interference effects are model dependent. The most recent calculation predicts modifications of the short distance rate by only about 2% [15] compared to 20% predicted by some earlier simplified models [16]. We neglect long distance interactions in our Monte Carlo. Since no theoretical calculations for the non-Standard Model decay $b \to se^\pm\mu^{mp}$ exist, we use a phase space model for these decays. To account for Fermi motion of the b quark inside B meson we have used the spectator model by Ali *et al.* [14]. The particle content of the X_s system was modeled with the conventional method of quark hadronization from JETSET [17]. For better accuracy of the simulations, when $M(X_s)$ is in the K or K^* mass region, the event is regenerated according to the theoretical predictions for the exclusive $B \to K^{(*)}l^+l^-$ decays by Greub *et al.* [18]. The estimated efficiencies are 5.2%, 4.5% and 7.3% for e^+e^-, $\mu^+\mu^-$ and $e^\pm\mu^\mp$ modes respectively.

To estimate the systematic error due to uncertainty in the χ^2_B signal and background shapes, we divide Monte Carlo sample into low and high multiplicity channels which produces the largest shape variation. This shape variation changes the upper limits by 9%, 19% and 20 % for the e^+e^-, $\mu^+\mu^-$ and $e^\pm\mu^\mp$ channels respectively. Uncertainties in detector simulation are dominated by charged tracking systematics and are estimated to be 14%. Variations of the spectator model parameters [3] result in changes of the selection efficiency by (12 ± 4)%, (30±4)%, and (11±4)%, respectively. The larger uncertainty in the $\mu^+\mu^-$ channel is a result of the lack of muon identification for $P_\mu < 1$ GeV/c. Uncertainty in X_s hadronization is 9%. Adding these sources of systematic errors in quadrature, we estimate the total systematic errors to be 22%, 39% and 28%, respectively.

Using a Gaussian likelihood integrated over positive signal values, we find upper limits using statistical errors only. We then loosen these limits by one unit of systematic uncertainty.

The final results are $\mathcal{B}(b \to se^+e^-) < 5.7 \times 10^{-5}$, $\mathcal{B}(b \to s\mu^+\mu^-) < 5.6 \times 10^{-5}$, and $\mathcal{B}(b \to se^\pm\mu^\mp) < 2.2 \times 10^{-5}$ (at 90 % C.L.). The results are consistent with the Standard Model predictions [14], $(0.8\pm0.2)\times10^{-5}$, $(0.6\pm0.1)\times10^{-5}$, and 0, respectively. The limit on $\mathcal{B}(b \to se^+e^-)$ is more than an order of magnitude more restrictive than the previous limits. The limit on $\mathcal{B}(b \to s\mu^+\mu^-)$ is also significantly tighter than UA1 limit after correcting for the efficiency (see discussion above). Furthermore, in contrast with the UA1 measurement, the present analysis is sensitive to a much wider range of $M(l^+l^-)$. Therefore, our extrapolation to the full phase space is more reliable and we are sensitive to a broader range of processes beyond the Standard Model.

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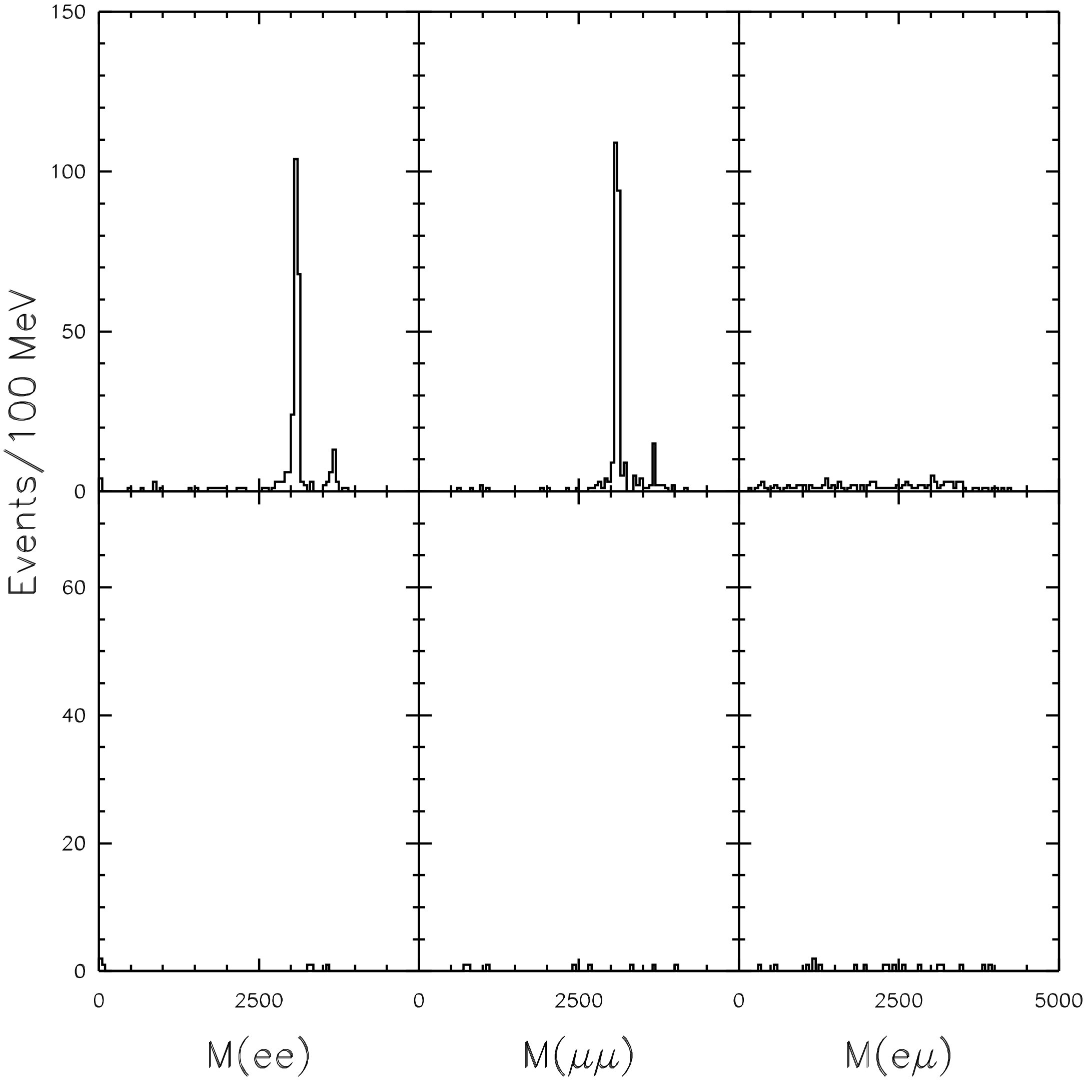

FIG. 1. $M(l^+l^-)$ distributions for the on- (top) and off-resonance (bottom) data with the $\chi^2_B < 6$ cut. The scaling factor between the off- and on-resonance data is 1.9.

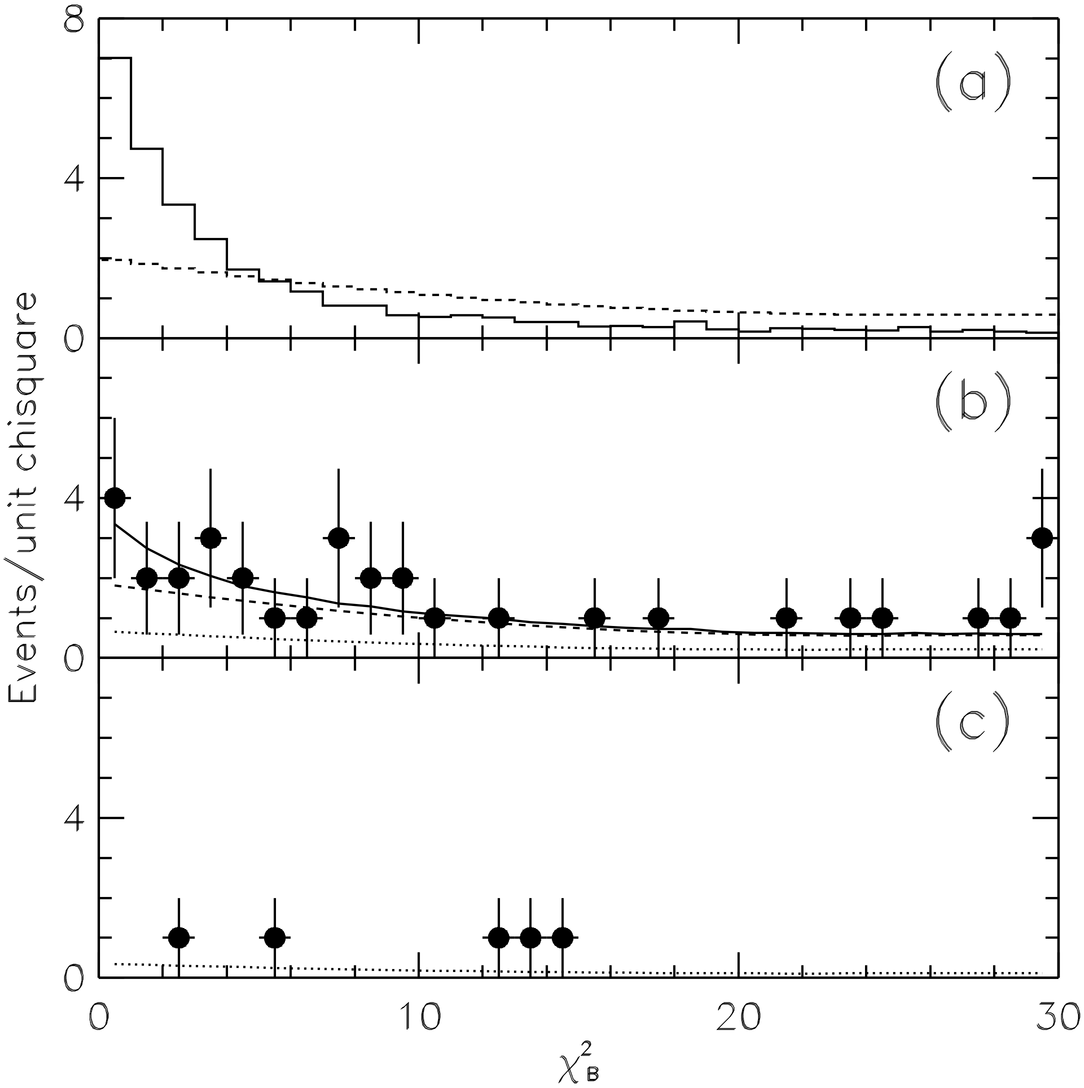

FIG. 2. χ_B^2 distributions for $X_s e^+ e^-$ data. (a) The difference between the expected distribution for the signal (solid histogram) and $B\bar{B}$ background (dashed histogram). Both distributions are normalized to the same area. (b) The fit to the on-resonance data (points with error bars). The sum of all fitted contributions is shown by solid line. The fitted background contribution ($B\bar{B}$ plus continuum) is shown by dashed line. The estimated continuum background, indicated by a dotted line, is simultaneously constrained to the off-resonance data (c).