**Searches for lepton-number-violating \(B\) decays at CLEO, \(\text{BaBar}\), and Belle**

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1 Introduction

CLEO, \(\text{BaBar}\), and Belle have searched for lepton-number-violation (LNV) in \(B\) meson decays at \(e^+e^-\) colliders. In the Standard Model (SM), lepton number \(L\) is conserved in low-energy collisions and decays, and the lepton flavor numbers for the three lepton families are conserved if neutrinos are massless. A number of mechanisms for LNV have been proposed including multi-Higgs-boson extensions, leptoquarks and Majorana neutrinos.

A common theme among the experiments is the use of two discriminating variables calculated in the center-of-mass frame (CM) \((\Delta E = E_B^* - \sqrt{s}/2\) and \(m_{ES} = m_{\text{cand}} = M_{bc} = \sqrt{s/4 - p_B^*t^2}\), where \(E_B^*\) and \(p_B^*\) are the CM energy and momentum of the reconstructed \(B\) meson candidate), and event-shape discriminants. The signal events peak at zero for \(\Delta E\), at approximately the \(B\) meson mass for \(m_{ES}\), and the event-shape is spherical; for the backgrounds, \(\Delta E\) and \(m_{ES}\) are smoothly varying, while the event-shape is more jet-like. The major backgrounds are continuum production of quark pairs \(e^+e^- \rightarrow q\bar{q}\) \((q = u, d, s\) and \(c)\), semileptonic \(B\) decays which produce a lepton, and other \(B\bar{B}\) decays where a hadron is mis-identified as a lepton.

2 Recent results from CLEO, \(\text{BaBar}\), and Belle

CLEO reused the techniques for their search for \(B \rightarrow X_\ell \ell^+\ell^-\) to look for \(B^+ \rightarrow h^-e^+e^+, h^-e^+\mu^+\) and \(h^-\mu^+\mu^+\) where \(h^- = K^-, K^{*-}, \pi^-\) and \(\rho^-\), based on 9.6 million \(B\bar{B}\) events. There are three main sources of background: \(B\) decays of the type \(B \rightarrow XJ/\psi\) and \(B \rightarrow X\psi(2S)\); other \(B\) decays, with two apparent leptons (either real leptons or hadrons misidentified as leptons); and continuum processes

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\(^{1}\)On behalf of the Belle and \(\text{BaBar}\) collaborations
with two apparent leptons. The backgrounds from $J/\psi$ and $\psi(2S)$ were severe in the searches for $B \to X \ell^+ \ell^-$ as the decays provided two opposite sign leptons but here they contribute less than 0.1 event per decay mode after careful lepton identification.

An unbinned maximum likelihood (ML) method is used to discriminate between signal events and the remaining two background sources. The variables are: the missing event energy, $E_{\text{miss}} \equiv 2E_{\text{beam}} - \sum E_{\text{det}}$, where $\sum E_{\text{det}}$ denotes the sum of energies of all the detected particles in the event; a Fisher discriminant $F$ based on the event-shape; $M_{\text{cand}}$; and $\Delta E$. Loose cuts of $|E_{\text{miss}}| < 2 \text{ GeV}$, $5.2 < M_{\text{cand}} < 5.3 \text{ GeV}/c^2$ and $|\Delta E| < 0.25 \text{ GeV}$ are applied. The branching fraction for the signal and the yields for the two backgrounds are free parameters in the ML. No evidence for the decays is found and all modes have a statistical significance of less than 1.2 standard deviations. 90% confidence level (CL) upper limits (UL) are placed on the branching fractions as shown in Table 1. The upper limits range from $1.0 \times 10^{-6}$ to $8.3 \times 10^{-6}$.

| Mode       | $S$  | UL | Mode       | $S$  | UL | Mode       | $S$  | UL |
|------------|------|----|------------|------|----|------------|------|----|
| $K^- e^+ e^+$ | 0.6σ | 1.0 | $K^- e^+ \mu^+$ | 0.0σ | 2.0 | $K^- \mu^+ \mu^+$ | 0.0σ | 1.8 |
| $K^{*-} e^+ e^+$ | 0.0σ | 2.8 | $K^{*-} e^+ \mu^+$ | 0.0σ | 4.4 | $K^{*-} \mu^+ \mu^+$ | 0.5σ | 8.3 |
| $\pi^- e^+ e^+$ | 0.0σ | 1.6 | $\pi^- e^+ \mu^+$ | 0.0σ | 1.3 | $\pi^- \mu^+ \mu^+$ | 0.0σ | 1.4 |
| $\rho^- e^+ e^+$ | 1.1σ | 2.6 | $\rho^- e^+ \mu^+$ | 0.3σ | 2.2 | $\rho^- \mu^+ \mu^+$ | 1.0σ | 5.0 |

Table 1: CLEO results with the statistical significance $S$ and 90% confidence level upper limits UL ($\times 10^{-6}$) on the branching fraction (including systematic error) [1].

$\text{Belle}$ has repeated the CLEO search for the four modes $B^+ \to h^- \mu^+ \mu^+$ and $B^+ \to h^- e^+e^+$, where $h^- = K^-$ or $\pi^- [2]$ and they also reuse the techniques developed for their $B \to K^{(*)}\ell^+\ell^-$ analyses, using a data sample of $471 \pm 3$ million $B\overline{B}$ pairs. The key difference with CLEO is the ML function used. The two main backgrounds from continuum events and $B\overline{B}$ decays are suppressed through the use of a ML ratio $R$ constructed from boosted decision tree discriminants (BDTs). Before the ML fit, a selection on $R$ retains 85% of the simulated signal events while rejecting more than 95% of the background. The selection efficiency for simulated signal is 13%-48%.

The signal branching fraction and background yields are extracted from the data with an unbinned ML using $m_{ES}$ and $R$. The signal $m_{ES}$ distributions are taken from data using a Gaussian shape unique to each final state, with the mean and width determined from fits to the analogous final states in the $B^+ \to J/\psi (\to \ell^+\ell^-)h^+$ events from the data. No significant yields are observed and the results of the ML fits to the data are summarized in Table 2.

Belle have performed the first searches for the decays $B^+ \to D^- e^+e^+$, $D^- e^+\mu^+$ and $D^- \mu^+\mu^+$ using a data sample containing 772 million $B\overline{B}$ pairs [3]. As the CKM matrix element $|V_{ub}| > |V_{ub}|$, these decays could be enhanced by an order of magnitude compared to $B^+ \to h^- \ell^+\ell^+$. Belle look for an energetic same-sign dilepton and
its for the baryon- and lepton-number violating decays maximizing the figure of merit, $\epsilon$ into a single likelihood ratio, $R$. Combine it with a $D$ pair.

Candidate $D^-$ mesons are reconstructed in the $D^- \rightarrow K^+ \pi^- \pi^-$ decay. The three tracks from the $D^-$ candidate are fit to a common vertex and are required to have a $K^+ \pi^- \pi^-$ invariant mass $(M_{K\pi\pi})$ within approximately $\pm 10$ MeV/$c^2$ from the nominal $D^-$ mass. The $M_{K\pi\pi}$ distribution is fit to two Gaussian functions with a common mean in a mass window $\pm 3$ times the width of the narrower Gaussian component. The average multiplicity of $D^-$ candidates is 1.3 per event.

The continuum background is rejected using a Fisher discriminant $F$ based on event-shape variables, and $\cos \theta_B$, the cosine of the polar angle of the $B$ candidate flight direction in the CM frame. Semileptonic decays such as $B \rightarrow D^- \ell^+ \nu_{\ell} X$ have missing energy due to the undetected neutrino and the two reconstructed leptons do not come from the same vertex. These events can be rejected using the missing energy $E_{\text{miss}}$ and $\delta z$, the separation between the impact parameter of the two leptons in the beam direction. The four variables, $F$, $\cos \theta_B$, $E_{\text{miss}}$ and $\delta z$, are combined together into a single likelihood ratio, $R_s$. The optimal requirement on $R_s$ is determined by maximizing the figure of merit, $\epsilon_s/(a/2 + \sqrt{N_b})$, where $\epsilon_s$ is the MC signal efficiency, $N_b$ is the number of expected background events in the signal region, and $a$ is set to zero.

After applying the $R_s$ requirements, 5, 23 and 40 events remain in the background region for the $e^+e^+$, $e^+\mu^+$ and $\mu^+\mu^+$ modes, respectively. The signal efficiencies are evaluated to be 1.2% - 1.9%. The expected numbers of background events in the signal region are 0.18, 0.83 and 1.44 events for the $e^+e^+$, $e^+\mu^+$ and $\mu^+\mu^+$ modes, respectively. Figure 4 shows the $M_{bc}-\Delta E$ distributions of the selected events. No events are observed in the signal region. Table 3 summarises the upper limits achieved.

$\bar{B} \bar{B}$ has performed the first measurement of the branching fraction upper limits for the baryon- and lepton-number violating decays $B^0 \rightarrow \Lambda^+ \ell^-$, $B^- \rightarrow \Lambda \ell^-$ and $B^- \rightarrow \bar{\Lambda} \ell^-$ [4] with 471 $\pm$ 3 million $BB$ pairs. The $\Lambda^+_c$ and $\Lambda$ candidates are reconstructed through the decay modes $\Lambda^+_c \rightarrow pK^-\pi^+$ and $\Lambda \rightarrow p\pi^-$, respectively. The

| Mode           | Events | Yield | $S$ ($\sigma$) | $B \times 10^{-8}$ | $B_{UL} \times 10^{-8}$ |
|----------------|--------|-------|----------------|-------------------|-------------------------|
| $B^+ \rightarrow \pi^- e^+ e^+$ | 123    | $0.6^{+2.3}_{-2.7}$ | 0.4 | $0.27^{+1.1}_{-1.2} \pm 0.1$ | 2.3 |
| $B^+ \rightarrow K^- e^+ e^+$   | 42     | $0.7^{+1.8}_{-1.2}$ | 0.5 | $0.49^{+1.3}_{-0.8} \pm 0.1$ | 3.0 |
| $B^+ \rightarrow \pi^- \mu^+ \mu^+$ | 228    | $0.0^{+3.2}_{-2.0}$ | 0.0 | $0.03^{+3.1}_{-3.2} \pm 0.6$ | 10.7 |
| $B^+ \rightarrow K^- \mu^+ \mu^+$ | 209    | $0.5^{+3.5}_{-2.5}$ | 0.2 | $0.45^{+3.2}_{-2.7} \pm 0.4$ | 6.7 |

Table 2: $\bar{B} \bar{B}$ results, showing the total events in the sample, signal yield and its statistical uncertainty, significance $S$, branching fraction $B$, and 90% CL branching fraction upper limit $B_{UL}$ [2].
Figure 1: The $M_{bc}-\Delta E$ distributions of $D^-e^+e^+$ (left), $D^-e^+\mu^+$ (middle) and $D^-\mu^+\mu^+$ (right) final states in data. The (red) boxes indicate the signal regions.

Table 3: Belle results for the $B^+ \rightarrow D^-\ell^+\ell^+$ search; $\epsilon$ is the signal reconstruction efficiency; $N_{\text{obs}}$ is the number of events in the signal region; $N_{\text{exp}}^{\text{bkg}}$ is the expected number of background events, and UL is the branching fraction 90% CL upper limit [3].

| Mode       | $\epsilon$ [%] | $N_{\text{obs}}$ | $N_{\text{exp}}^{\text{bkg}}$ | UL [10^{-6}] |
|------------|-----------------|------------------|-------------------------------|--------------|
| $B^+ \rightarrow D^-e^+e^+$ | 1.2             | 0                | $0.18 \pm 0.13$              | < 2.6        |
| $B^+ \rightarrow D^-e^+\mu^+$ | 1.3             | 0                | $0.83 \pm 0.29$              | < 1.8        |
| $B^+ \rightarrow D^-\mu^+\mu^+$ | 1.9             | 0                | $1.10 \pm 0.33$              | < 1.1        |

Final state tracks for both the $\Lambda_c^+$ and $\Lambda$ decays are constrained to a common spatial vertex and their invariant mass is constrained to the $\Lambda_c^+$ or $\Lambda$ mass. The candidates are required to be within $\pm 15$ MeV/c² of the nominal $\Lambda_c^+$ mass and $\pm 4$ MeV/c² of the nominal $\Lambda$ mass. $B$ meson candidates are formed by combining baryon candidate with a $\mu^-$ or $e^-$ and constraining them to a common point. Bremsstrahlung energy recovery is performed for electrons. Background from $e^+e^- \rightarrow e^+e^-\gamma$ events in the $\Lambda\ell$ channel are eliminated by requiring more than four charged tracks in the event.

Candidate selection is optimized using a figure of merit (see above) with $a = 5$. A neural net (NN) is used to provide further discrimination between signal and background such that about 90% of the signal is retained and about 50% of the background is rejected. The remaining background after selection for the $\Lambda_c^+\ell^-\ell^-$ modes is composed of roughly equal amounts of $B\bar{B}$ and continuum events, while the background for the $\Lambda\ell$ modes is almost entirely continuum.

The variables $\Delta E$ and $m_{ES}$ are used in the ML fit to the two $\Lambda\ell$ modes; the $\Lambda_c^+\ell^-$ decay has more background and the NN is used as a third discriminating variable. No significant signal is observed and an upper limit is calculated for the branching fraction for each decay mode, as shown in Table 4.
| Mode                  | $N_{\text{cand}}$ | $B \times 10^{-8}$ | $\epsilon$ (%) | $B_{90\%} \times 10^{-8}$ |
|----------------------|------------------|---------------------|-----------------|-----------------------------|
| $B^0 \rightarrow \Lambda^+ \mu^-$ | 814              | $-4^{+71}_{-56}$   | 26.3 ± 0.9      | 180                         |
| $B^0 \rightarrow \Lambda^0 e^-$   | 651              | $190^{+130}_{-90}$ | 25.7 ± 0.7      | 520                         |
| $B^- \rightarrow \Lambda \mu^-$   | 320              | $-2.3^{+3.5}_{-2.5}$ | 28.7 ± 0.9      | 6.2                         |
| $B^- \rightarrow \Lambda e^-$     | 194              | $1.2^{+3.7}_{-2.6}$ | 27.2 ± 0.6      | 8.1                         |
| $B^- \rightarrow \Lambda \mu^-$   | 192              | $1.5^{+2.0}_{-1.7}$ | 31.3 ± 1.0      | 6.1                         |
| $B^- \rightarrow \Lambda e^-$     | 74               | $-0.9^{+0.7}_{-0.0}$ | 30.0 ± 0.6      | 3.2                         |

Table 4: Summary of number of candidates ($N_{\text{cand}}$), branching fraction central value ($B$), signal efficiency ($\epsilon$), and branching fraction 90% CL UL ($B_{90\%}$) [4].

Figure 2: Branching fraction upper limits for $B$ meson LNV decays from CLEO [1], BABAR [2, 4], Belle [3], and LHCb [5].

References

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