



Fermi National Accelerator Laboratory

FERMILAB-Conf-97/173-E

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Rare B Decays to Leptons

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July 1997

Published Proceedings of the *2nd International Conference on B Physics and CP Violation*,
Honolulu, Hawaii, March 24-27, 1997

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FERMILAB Conf-97/173-E
CDF/PUB/BOTTOM/PUBLIC/4194
June 29, 1997

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Invited talk at the
2nd International Conference on B Physics and CP Violation
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RARE B DECAYS TO LEPTONS

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We review results from CLEO, LEP and the Tevatron experiments on rare decays of B hadrons to final states including charged leptons.

1 Introduction

There has been a lot of theoretical and experimental interest in the study of rare decays of B hadrons. They can be a good probe to the Cabibbo-Kobayashi-Maskawa (CKM) matrix of the quark mixing. They can also be indications of new physics beyond the Standard Model (SM) if they are observed at higher rates than predicted.

In this talk we review experimental results from CLEO, LEP and the Tevatron experiments on the following decay modes.

- $B \rightarrow K^{(*)}\ell^+\ell^-$
- $B^0 \rightarrow \ell^+\ell^-$
- $B^+ \rightarrow \ell^+\nu$

The first two modes belong to flavor-changing neutral-current (FCNC) decays¹. In the Standard Model, the FCNC decays are prohibited at tree level; they can proceed only through CKM-suppressed higher order processes. The last mode, pure leptonic decays, is both helicity- and CKM-suppressed. As we shall see none of the above modes is observed yet, but they hold promises for the future as we increase the amount of available experimental data.

2 Search for $B \rightarrow K^{(*)}\ell^+\ell^-$ decays

The decay $B \rightarrow K^{(*)}\ell^+\ell^-$ can proceed through the penguin and box diagrams shown in Figure 1. The CKM matrix element involved is $|V_{ts}|$. The lepton pair can be resonant, for example, J/ψ or $\psi(2S)$ meson. The resonant processes are indistinguishable from the internal spectator decays $b \rightarrow cW^- \rightarrow c\bar{c}s$. Therefore, we look for non-resonant part of the lepton pair mass spectrum in

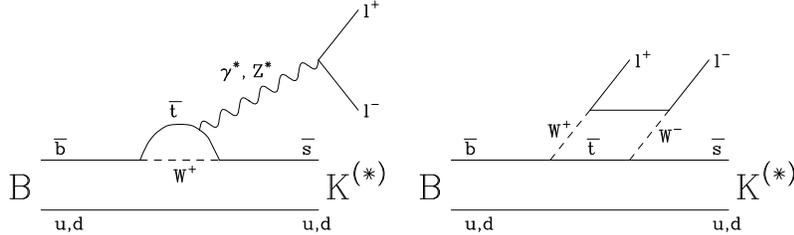


Figure 1: Feynman diagrams responsible for $B \rightarrow K^{(*)} \ell^+ \ell^-$ decay.

the FCNC decay. A SM prediction² for the branching fraction of the inclusive process $B \rightarrow X_s \ell^+ \ell^-$ is $(5.7 \pm 0.9) \times 10^{-6}$.

The exclusive modes $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ and $B^+ \rightarrow K^+ \ell^+ \ell^-$ are searched for by a few experiments. The branching fractions of order 10^{-6} and 10^{-7} are expected, respectively.

The DELPHI experiment at LEP looks for the $B^0 \rightarrow K^{*0} \ell^+ \ell^-$ decay among 1.3 M hadronic Z^0 decays³. The $K^+ \pi^-$ decay mode of the K^{*0} meson is used. A lepton pair candidate (electrons and muons) is selected and combined with a K^{*0} candidate to form a B^0 candidate. The $K^{*0} \ell^+ \ell^-$ mass vs. $\ell^+ \ell^-$ mass spectra are studied. For the muon mode, all $\mu^+ \mu^-$ pairs are consistent with ψ particles. For the electron mode there are two candidates with low $e^+ e^-$ mass. However, they fail tighter kaon identification cuts, leaving no candidate for the signal. The upper limit on the branching fraction is placed to be^a

$$\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^- + B^0 \rightarrow K^{*0} e^+ e^-) < 2.4 \times 10^{-3} \quad (90\% \text{ CL, DELPHI}). \quad (1)$$

The CDF experiment at Fermilab also looks for these decays⁴. Both B^+ and B^0 decays are searched for among 20 pb^{-1} of data using muons. Figure 2 shows the $\mu^+ \mu^-$ mass spectra for events within the B signal region. Outside the shaded resonant regions, 3 (7) candidates are observed for the B^+ (B^0) decay with estimated background of 5.0 ± 1.2 (7.2 ± 1.5) events. The upper limits on the branching fractions of

$$\begin{aligned} \mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) &< 1.0 \times 10^{-5}, \\ \mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-) &< 2.5 \times 10^{-5} \quad (\text{CDF}) \end{aligned} \quad (2)$$

are placed by normalizing to observed $B \rightarrow J/\psi K^{(*)}$ signals.

The CLEO experiment also looks for the decays using 2 fb^{-1} of data. The mass resolution of a few MeV/c^2 is achieved by using the beam-constrained

^aIn the remainder of this talk, all upper limits quoted are at 90% CL.

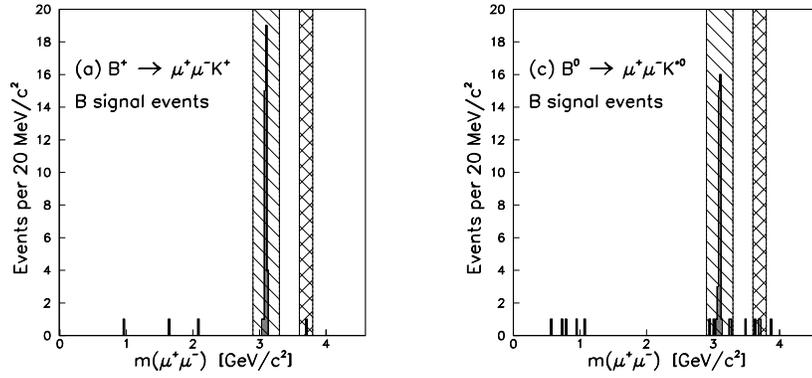


Figure 2: Dimuon invariant mass distributions for $B \rightarrow K^{(*)} \mu^+ \mu^-$ candidates at CDF.

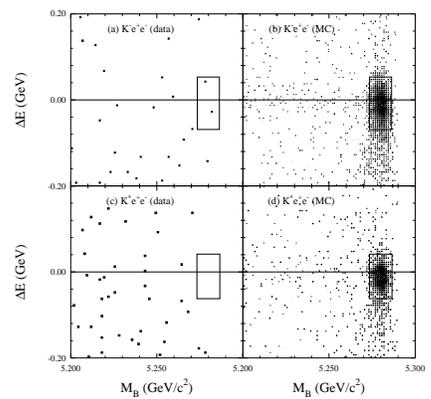


Figure 3: CLEO results on search for $B \rightarrow K^{(*)} \ell^+ \ell^-$ decays. Beam constrained mass vs. energy difference distributions.

mass $M_{\text{beam}} \equiv \sqrt{E_{\text{beam}}^2 - (\Sigma \vec{p})^2}$, where E_{beam} is the beam energy and the sum is taken over daughter particles. They study this mass vs. the difference ΔE between the beam and reconstructed energies. Figure 3 shows such two-dimensional distributions for real data and Monte Carlo expectations. For the $B^+ \rightarrow K^+ e^+ e^-$ mode two candidates are observed in the signal region. No candidates are seen in any other mode. The upper limits are obtained to be⁵

$$\begin{aligned} \mathcal{B}(B^+ \rightarrow K^+ e^+ e^-) &< 1.2 \times 10^{-5}, \\ \mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) &< 0.9 \times 10^{-5}, \\ \mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-) &< 1.6 \times 10^{-5}, \\ \mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-) &< 3.1 \times 10^{-5} \text{ (CLEO)}. \end{aligned} \quad (3)$$

CLEO also looks for the exotic decays leading to $e^\pm \mu^\mp$ pairs in the same data sample. The following upper limits are placed on the branching fractions:

$$\begin{aligned} \mathcal{B}(B^+ \rightarrow K^+ e^\pm \mu^\mp) &< 1.2 \times 10^{-5}, \\ \mathcal{B}(B^0 \rightarrow K^{*0} e^\pm \mu^\mp) &< 2.7 \times 10^{-5} \text{ (CLEO)}. \end{aligned} \quad (4)$$

3 Search for $B^0 \rightarrow \ell^+ \ell^-$ decays

The decay $B^0 \rightarrow \ell^+ \ell^-$ can proceed with the loop and box diagrams shown in Figure 4. The relevant CKM matrix element is V_{td} or V_{ts} , depending on the parent B meson species. The SM prediction is of order 10^{-10} (10^{-9}) for the B^0 (B_s^0) meson in the muon mode, and is five orders of magnitude smaller for the electrons due to helicity suppression.

The CLEO experiment has looked for these decays among 1.34 fb^{-1} of data. The leptons are nearly monoenergetic, due to the small momentum of the B mesons produced at the $\Upsilon(4S)$ resonance. No candidates are observed in either $\mu\mu$, ee or $e\mu$ mode, and upper limits are placed on the branching fractions to be⁶

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow e^+ e^-) &< 5.9 \times 10^{-6}, \\ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) &< 5.9 \times 10^{-6}, \\ \mathcal{B}(B^0 \rightarrow e^\pm \mu^\mp) &< 5.9 \times 10^{-6} \text{ (CLEO)}. \end{aligned} \quad (5)$$

The exotic decays $B^0 \rightarrow e^\pm \tau^\mp, \mu^\pm \tau^\mp$ are also looked for using the $\tau^- \rightarrow \pi^- \nu_\tau$ mode. The neutrino momentum is reconstructed from missing momentum, and ΔE vs. lepton momentum distributions are studied. Four (six) candidates are seen for the $e\tau$ ($\mu\tau$) mode. The upper limits on the branching fractions

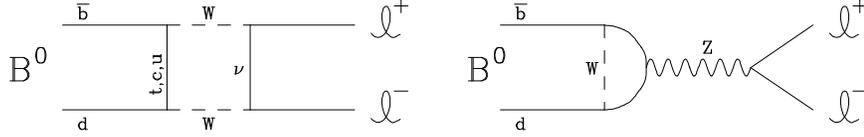


Figure 4: Feynman diagrams responsible for $B^0 \rightarrow l^+ l^-$ decay.

are placed to be

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow e^\pm \tau^\mp) &< 5.3 \times 10^{-4}, \\ \mathcal{B}(B^0 \rightarrow \mu^\pm \tau^\mp) &< 8.3 \times 10^{-4} \text{ (CLEO)}, \end{aligned} \quad (6)$$

where the candidates are assumed to be signal.

The CDF experiment has searched for the decay using muons. The result based on 20 pb^{-1} of data has been published⁴. Here a preliminary result with full data sample (110 pb^{-1}) is reported. CDF is sensitive to both B^0 and B_s^0 meson decays. Figure 5 shows the $\mu^+ \mu^-$ mass spectrum near the B meson mass. No candidates are seen in either meson signal region. The upper limits on the branching fraction are obtained to be⁷

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) &< 2.6 \times 10^{-7}, \\ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) &< 7.7 \times 10^{-7} \text{ (CDF)}, \end{aligned} \quad (7)$$

where the normalization comes from a CDF measurement of the B^0 meson production cross section. The B_s^0 meson cross section is assumed to be 1/3 of the B^0 meson. CDF also has a result on the exotic decay $B^0 \rightarrow e^\pm \mu^\mp$ using 44 pb^{-1} of data:

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow e^\pm \mu^\mp) &< 3.3 \times 10^{-6}, \\ \mathcal{B}(B_s^0 \rightarrow e^\pm \mu^\mp) &< 1.8 \times 10^{-5} \text{ (CDF)}. \end{aligned} \quad (8)$$

The L3 experiment at LEP also has looked for those decays among 3.5 M hadronic Z^0 decays. Figure 5 shows the dilepton mass spectra for ee , $\mu\mu$ and $e\mu$ channels. The following upper limits on the branching fractions are obtained⁸.

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow e^+ e^-) &< 1.4 \times 10^{-5}, \\ \mathcal{B}(B_s^0 \rightarrow e^+ e^-) &< 5.4 \times 10^{-5}, \\ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) &< 1.0 \times 10^{-5}, \\ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) &< 3.8 \times 10^{-5}, \\ \mathcal{B}(B^0 \rightarrow e^\pm \mu^\mp) &< 1.6 \times 10^{-5}, \\ \mathcal{B}(B_s^0 \rightarrow e^\pm \mu^\mp) &< 4.1 \times 10^{-5} \text{ (L3)}. \end{aligned} \quad (9)$$

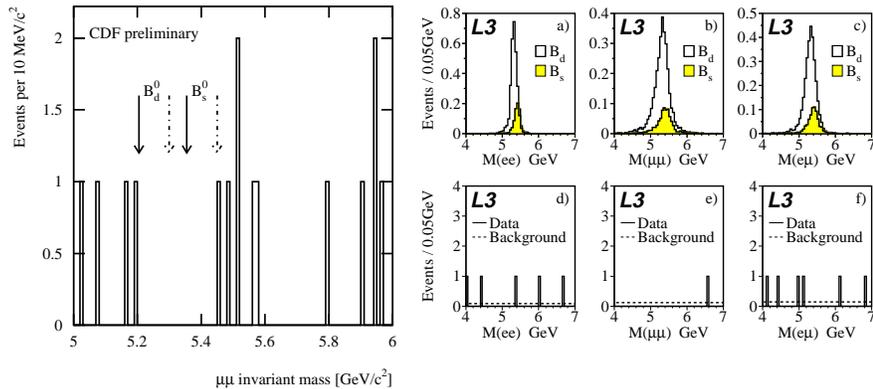


Figure 5: Left: $\mu^+\mu^-$ invariant mass distribution from CDF $B^0 \rightarrow \mu^+\mu^-$ search. Arrows show signal mass windows. Right: $\ell^+\ell^-$ invariant mass distributions from L3 $B^0 \rightarrow \ell^+\ell^-$ search. Top plots are Monte Carlo expectations and bottom plots are real data with dashed lines showing estimated background level.

4 Search for $B^+ \rightarrow \ell^+\nu$ decays

Now we turn to pure leptonic decays of the B^+ meson. This process proceeds with an annihilation of the \bar{b} quark and the spectator u quark into a virtual W^+ boson. Thus the decay width is proportional to $f_B^2|V_{ub}|^2$, where f_B is the B meson decay constant. Once the CKM matrix element $|V_{ub}|$ is determined well from $b \rightarrow u\ell\nu$ transition, one can extract the decay constant from this measurement. Or, one can compare the rate of this decay mode with the oscillation frequency Δm_d of the $B^0\bar{B}^0$ mixing, which is proportional to $f_B^2|V_{td}|^2$. From the two quantities, one can probe the ratio $|V_{ub}|/|V_{td}|$.

The SM predictions are of order 10^{-5} for the $B^+ \rightarrow \tau^+\nu$ mode, and are suppressed by factors of 225 and 10^7 for the muonic and electronic modes.

The CLEO experiment looks for those leptonic decays with 2.0 fb^{-1} of data⁹. For the $\tau^+\nu$ mode, the leptonic τ decay $\tau^+ \rightarrow \ell^+\nu_\ell\bar{\nu}_\tau$ is used. Thus the signature is the existence of one lepton in the final state, and the rest of the event should add up to the other B meson, B^- . The energy difference ΔE and the beam-constrained mass M_{beam} for the B^- meson are reconstructed and their distributions are fit simultaneously with expected signal and background components. The main background comes from semileptonic decay $b \rightarrow \ell\nu X$. Figure 6(a) shows the lepton momentum spectra after ΔE and M_{beam} are required to be in signal regions. The signal of -9 ± 36 events is estimated, and an upper limit on the branching fraction is placed. CLEO also looks for the $B^+ \rightarrow \mu^+\nu$ and $e^+\nu$ decays. These leptons are harder and essentially

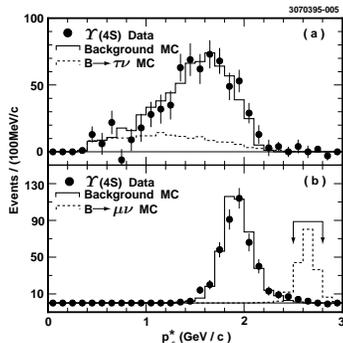


Figure 6: CLEO results on search for $B \rightarrow \ell^+ \nu$ decays. (a) Lepton momentum spectrum for $B^+ \rightarrow \tau^+ \nu, \tau^+ \rightarrow \ell^+ \nu \ell^+ \bar{\nu}_\tau$ search. (b) Muon momentum spectrum for $B^+ \rightarrow \mu^+ \nu$ search.

monochromatic (one half of the B meson mass). The background arises from $b \rightarrow u\ell\nu$ and continuum events. Figure 6(b) shows the muon momentum spectrum. Three candidates are observed but are consistent with background. A similar result is obtained for the electron mode. The upper limits on the branching fractions are:

$$\begin{aligned}
 \mathcal{B}(B^+ \rightarrow \tau^+ \nu) &< 2.2 \times 10^{-3}, \\
 \mathcal{B}(B^+ \rightarrow \mu^+ \nu) &< 2.1 \times 10^{-5}, \\
 \mathcal{B}(B^+ \rightarrow e^+ \nu) &< 1.5 \times 10^{-5} \text{ (CLEO)}.
 \end{aligned}
 \tag{10}$$

The ALEPH experiment also has searched for the $B^+ \rightarrow \tau^+ \nu$ decay among 3.6 M hadronic Z^0 decays¹⁰. The inclusive decay of the τ^+ lepton is used, leading to a large missing energy in one hemisphere. A lepton in the search hemisphere is vetoed to suppress semileptonic b and c decays. To purify $b\bar{b}$ events, a lifetime B tag is applied to the opposite hemisphere. Figure 7 shows the missing energy distribution. The background comes from finite detector resolution, residual b and c semileptonic decays, and semileptonic $B \rightarrow \tau\nu X$ decay. Two events are observed in the signal region (> 35 GeV), where 45 events would be expected if the branching fraction was 1.0×10^{-2} . The upper limit is obtained to be

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) < 1.6 \times 10^{-3} \text{ (ALEPH)}.
 \tag{11}$$

Since this search looks for a large missing energy, it is sensitive to the decay $b \rightarrow s\nu\bar{\nu}$ as well. An upper limit of 7.7×10^{-4} is obtained for this mode, where the SM prediction is $(4.0 \pm 1.5) \times 10^{-5}$.

The L3 experiment has looked for the $B^+ \rightarrow \tau^+ \nu$ decay among 1.5 M hadronic Z^0 decays using exclusive decays of the τ^+ lepton. Both the leptonic

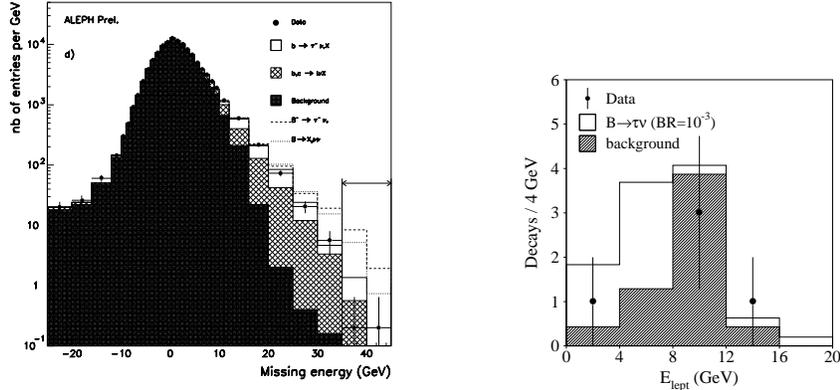


Figure 7: Left: Missing energy distribution in ALEPH $B \rightarrow \tau^+ \nu$ search. Horizontal arrows indicate a signal region. Dashed histogram is an expected signal distribution for a branching fraction of 1.0×10^{-2} . Right: Lepton energy distribution in L3 search for $B \rightarrow \tau^+ \nu$ decay with $\tau^+ \rightarrow \ell^+ \nu_\ell \bar{\nu}_\tau$.

decay and the hadronic decay $\tau^+ \rightarrow X^+ \bar{\nu}_\tau$ are used. A large missing energy is required, as well as a lepton/hadron candidate which is inconsistent with coming from the primary vertex. The B^+ meson momentum is reconstructed using missing momentum in the event, and required to be greater than 30 GeV/c. Also a low additional activity is required in the search hemisphere to suppress $b \rightarrow \ell \nu X$ background. Figure 7(right) shows the lepton energy distribution. For the hadronic decay mode, a tighter requirement on the particle activity in the search hemisphere is applied. The upper limit of

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) < 5.7 \times 10^{-4} \quad (\text{L3}) \quad (12)$$

is obtained¹¹ by combining the two τ^+ decay modes.

5 Search for $B^+ \rightarrow \ell^+ \nu \gamma$ decays

The decay $B^+ \rightarrow \ell^+ \nu \gamma$ can proceed as follows. The pseudoscalar B meson can emit a hard photon and turn into a virtual vector or axial-vector meson B^* , which can in turn decay to a $\ell^- \nu$ pair. Since the B^* meson has spin one, the leptonic decay is not helicity-suppressed. The branching fraction is expected to be of order 10^{-7} , independent of the lepton species¹². This is of the same order as the $B^+ \rightarrow \mu^+ \nu$ decay. The CLEO experiment has looked for this decay among 2.7 M $B\bar{B}$ events. A pair of hard lepton and photon is

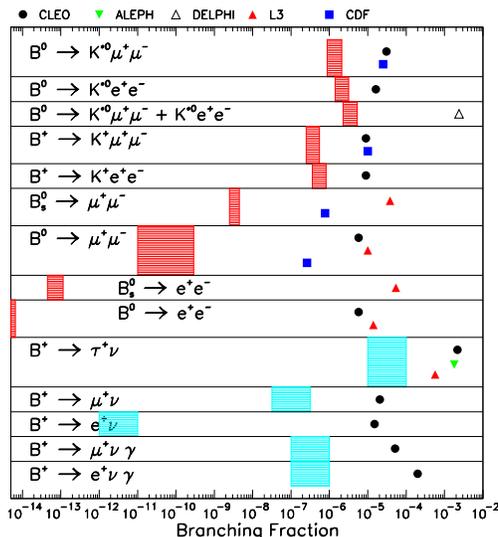


Figure 8: Summary of rare decay search results. Points show 90% CL upper limits on the branching fractions. Shaded boxes show ranges of Standard Model predictions.

the signature, where the rest of the event should form the B^- meson. The neutrino energy and momentum are reconstructed from the photon and lepton energy using energy-momentum conservation. Then a signal is looked for as a match between them (massless neutrino). Zero and five candidates are found for muon and electron modes. The main background arises when a lepton produced in semileptonic decay $b \rightarrow \ell \nu X$ is paired with a photon from a π^0 decay, and is estimated to be a fraction of an event. The five candidates in the electron modes are studied carefully and there is no evidence that they come from other background sources. To obtain upper limits they are treated as signal. The results are ¹³

$$\begin{aligned} \mathcal{B}(B^+ \rightarrow \mu^+ \nu \gamma) &< 5.2 \times 10^{-5}, \\ \mathcal{B}(B^+ \rightarrow e^+ \nu \gamma) &< 2.0 \times 10^{-4} \text{ (CLEO)}. \end{aligned} \quad (13)$$

6 Conclusion

We have reviewed experimental results on the following rare decays of the B hadrons: $B \rightarrow K^{(*)} \ell^+ \ell^-$, $B^0 \rightarrow \ell^+ \ell^-$ and $B^+ \rightarrow \ell^+ \nu(\gamma)$. A number of results are available from CLEO, LEP and Tevatron experiments. The current status

of the experimental limits is illustrated in Figure 8. Although none of the modes is observed yet, some are within an order of magnitude of the Standard Model predictions, and are expected to be observed at future B factories or at the upgraded Tevatron by the early next millennium.

Acknowledgments

I would like to thank the members of the local organizing committee for an enjoyable conference. I would also like to thank the following people who provided me with valuable information during the preparation of my talk and this manuscript: E. Thorndike (CLEO), A. Litke and R. Forty (ALEPH), M. Battaglia and J.-P. Engel (DELPHI), and A. Nippe and J. Alcaraz (L3).

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