Rare B Decays from CLEO, with Emphasis on $b \to s\gamma$

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Abstract

A CLEO search for the decay $B^{\pm} \to \tau^{\pm}\nu$ yields the upper limit $Br(B \to \tau\nu) < 2.2 \times 10^{-3}$ at 90% c.l. Searches for exclusive, charmless, hadronic B decays yield several new or improved upper limits. An update on the $\pi^-\pi^+/K^-\pi^+$ study gives $Br(\bar{B}^0 \to \pi^-\pi^+) < 2.2 \times 10^{-5}$, $Br(\bar{B}^0 \to K^-\pi^+) < 1.9 \times 10^{-5}$, at 90% c.l., and $Br(\bar{B}^0 \to K^-\pi^+) + Br(\bar{B}^0 \to \pi^-\pi^+) = (1.8 \pm {}^{0.6}_{0.5}) \times 10^{-5}$. A search for $B \to K^{(*)}\ell^+\ell^-$ gives upper limits on branching ratios $\sim 10^{-5}$. A search for examples of $b \to d\gamma$ decays gives an upper limit $\Gamma(B \to \rho/\omega\gamma)/\Gamma(B \to K^*\gamma) < 0.34$ at 90% c.l., suggesting $|V_{td}/V_{ts}| < 0.7$. The inclusive $b \to s\gamma$ branching ratio is measured to be (2.32 $\pm$ 0.51 $\pm$ 0.29 $\pm$ 0.32) $\times 10^{-4}$, where the first error is statistical, the second error is the additive systematic error from uncertainty in yield, and the third error is the multiplicative systematic error from uncertainty in efficiency. Upper and lower limits on the branching ratio, at 95% c.l., are $1 \times 10^{-4} < Br(b \to s\gamma) < 4 \times 10^{-4}$. The upper limit implies a lower limit on the mass of a charged Higgs with Model II coupling of 260 GeV. The upper and lower limits on the branching ratio restrict the allowed region of the $\Delta\kappa - \lambda$ space describing anomalous $WW\gamma$ couplings, eliminating half of the area allowed by $\bar{p}p \to W\gamma X$ measurements.

1. Introduction

I will present CLEO results from five recent analyses. My main emphasis is on a measurement of the inclusive rate for $b \to s\gamma$. The data sample for all analyses is $2fb^{-1}$ at the Υ(4S), 2 million $B\bar{B}$ events, 6 million continuum background events. The continuum is a major background for 4 of the 5 analyses. We have $1fb^{-1}$ of data taken just below the resonance, to use for subtractions.

2. $B^{\pm} \to \tau^{\pm}\nu$

We have searched for $B^{\pm} \to \tau^{\pm}\nu$. In the Standard Model, this decay proceeds via annihilation to $W^{\pm}$, has a rate proportional to $f_B^2|V_{ub}|^2$, and a branching ratio $\sim 5 \times 10^{-5}$. Our search has nowhere near that sensitivity, and so is a search for non-standard-model physics, in particular a charged Higgs with a large $\tan\beta$. We search for $B \to \tau\nu$ by looking for the leptonic decay of the τ. In such events, all detectable particles except the lepton are from the other B. We compute the mass and energy of this collection of particles, and look for a peak in the $M - E$ plane. The signal would have such a peak, the background not. We find no evidence for signal and obtain a 90% c.l. upper limit of 2.2×10^{-3} for the branching ratio, implying M_{Higgs} (in GeV) must be greater than $1.5 \times \tan\beta$.

3. Exclusive, Charmless, Hadronic B Decays

The second analysis is a search for exclusive, charmless, hadronic B decays. These will proceed either via a $b \to u$ spectator diagram, a $b \to s$ or $b \to d$ penguin diagram, or a combination of the two. Some of these decays (e.g. $B \to \pi^+\pi^-$) are candidates for CP violation measurements via $B^0 - \bar{B}^0$ mixing, some (e.g. $B \to K^-\pi$) for direct CP violation searches, some for understanding "penguin pollution" backgrounds to $B \to \pi\pi$ or hadronic phases in $B \to K\pi$. Some (e.g. $B \to K^{(*)}\phi$) are examples of pure penguins. Our search uses the conventional B reconstruction method, augmented by a powerful continuum suppression technique. For channels other than $K^-\pi^+$ and $\pi^-\pi^+$, we have no strong evidence for a signal. Upper limits, and an update to our result[1] on $K^-\pi^+$ and $\pi^-\pi^+$ are given in Table 1. Improvements over previous upper limits[2] are typically a factor of 5. In several cases we are close to theoretical predictions.

Table 1. Upper limits on (measurements of) the branching ratios, previous upper limits (measurements), and theoretical predictions. Upper limits are at the 90% confidence level. Previous limits are taken from Ref. [2].

Mode	Upper Limit on BR (10^{-5})	Previous UL (10^{-5})	Theory (10^{-5})
$\pi^0\pi^0$	1.0	–	0.03-0.10
$\pi^\pm\rho^\mp$	9.5	52	1.9-8.8
$\pi^0\rho^0$	2.9	40	0.07-0.23
$\pi^+\pi^0$	2.3	24	0.6-2.1
$\pi^+\rho^0$	4.1	15	0.0-1.4
$K^0\pi^0$	6.3	–	0.5-0.8
$K^{*+}\pi^-$	23.8	38	0.1-1.9
$K^{*0}\pi^0$	3.5	–	0.3-0.5
$K^+\rho^-$	4.3	–	0.0-0.2
$K^0\phi$	10.7	42	0.1-1.3
$K^{*0}\phi$	3.9	32	0.0-3.1
$\phi\phi$	4.8	–	–
$K^+\pi^0$	3.2	–	0.3-1.3
$K^0\pi^+$	6.8	10	1.1-1.2
$K^{*0}\pi^+$	6.0	15	0.6-0.9
$K^+\rho^0$	2.6	8	0.01-0.06
$K^+\phi$	1.4	9	0.1-1.5
$K^{*+}\phi$	9.0	130	0.0-3.1
$\pi^+\pi^-$	2.2	2.9	1.0-2.6
$K^+\pi^-$	1.9	2.6	1.0-2.0
K^+K^-	0.7	0.7	–
$\pi^+\pi^- + K^+\pi^-$	$(1.8^{+0.6}_{-0.5})$	$(2.4^{+0.8}_{-0.7})$[1]	
$K^-e^+e^-$	1.2	6	0.06
$\bar{K}^{*0}e^+e^-$	1.6	29	0.6
$K^-\mu^+\mu^-$	0.9	17	0.06
$\bar{K}^{*0}\mu^+\mu^-$	3.1	2.3	0.3
$K^-e^\pm\mu^\mp$	1.2	2×640	0
$\bar{K}^{*0}e^\pm\mu^\mp$	2.7	–	0

4. $B \to K^{(*)}\ell^+\ell^-$

The third analysis is a search for $B \to K^{(*)}\ell^+\ell^-$, examples of the parton level process $b \to s\ell^+\ell^-$. This process happens in the Standard Model, with small QCD corrections and a very small rate, so it is a good place to look for non-standard-model effects such as a tree-level violation of the GIM mechanism. As a matter of course, one simultaneously searches for the lepton-number-violating decays $b \to s\mu e$ along with $b \to se^+e^-$ and $b \to s\mu^+\mu^-$. In our search, we suppress the continuum background with event-shape cuts, suppress $B \to K^{(*)}\psi$, $\psi \to \ell^+\ell^-$ with a dilepton mass cut, and use conventional B reconstruction techniques. We see no evidence for signal, and give upper limits in Table 1.

5. $B \to \rho/\omega\gamma$

The fourth analysis is a search for examples of $b \to d\gamma$ decays, in particular $B^0 \to \rho^0\gamma$, $B^0 \to \omega\gamma$, and $B^\pm \to \rho^\pm\gamma$. One expects that the ratio of widths for $b \to d\gamma$ and $b \to s\gamma$ will equal $|V_{td}/V_{ts}|^2$, although concerns have been expressed that non-perturbative QCD corrections and long range effects may complicate this simple picture. In our search, there is a background from the continuum, which we suppress using event-shape cuts. There is a background to $B^0 \to \rho^0\gamma$ from $B^0 \to K^{*0}\gamma$, $K^{*0} \to K^+\pi^-$, illustrating the rule that last year's discovery[3] is this year's background. Using kinematic variables, we devise a cut that keeps 50% of the signal and 5% of the background. Our search yields no evidence for $B \to \rho^0\gamma$, $\omega\gamma$, or $\rho^\pm\gamma$. We find $\Gamma(B \to \rho/\omega\gamma)/\Gamma(B \to K^*\gamma) < 0.34$, at 90% c.l. Allowing for SU(3) breaking, but otherwise throwing theoretical cautions to the winds, we obtain $|V_{td}/V_{ts}| < 0.64 - 0.76$, depending on SU(3)-breaking parameter. This limit is less restrictive than that from unitarity.

6. $b \to s\gamma$

The final, and principal analysis that I will present is a measurement of the branching ratio for the inclusive process $b \to s\gamma$. Theoretical interest in this process began in 1982[4]. Thereafter, it was recognized that there were large QCD corrections to the basic penguin diagram, and progressively more complete calculations, based on the method of renormalization-group-improved perturbation theory, were applied to the problem[5]. There is now general agreement among theorists on the full leading log calculation[6], and some, but not all, of the next-to-leading logarithmic QCD correctons have been calculated[7]. The QCD corrections increase the rate a factor of 2-3 over the basic penguin diagram. The Standard Model branching ratio for a leading-log calculation is $(2.75 \pm 0.80) \times 10^{-4}$[8], where the error is dominated by the uncertainty in the renormalization scale $m_b/2 < \mu < 2m_b$. If those next-to-leading log terms that have been calculated are included, the branching ratio falls to 1.9×10^{-4}[9]. The branching ratio is sensitive to non-standard-model physics, such as charged Higgs[10], anomalous $WW\gamma$ coupling[11], and many others[12].

Last year CLEO observed the decay $B \rightarrow K^*(892)\gamma$[3], a hadron-level example of the parton-level process $b \rightarrow s\gamma$. This was the first conclusive observation of a penguin, and established the existence of penguins generally and $b \rightarrow s\gamma$ in particular. However, there are large theoretical uncertainties in the hadronization process, and so $\Gamma(B \rightarrow K^*\gamma)$ gives only a very rough indication of $\Gamma(b \rightarrow s\gamma)$, the quantity of theoretical interest.

Our signature for the inclusive $b \rightarrow s\gamma$ process is a photon from B meson decay with energy between 2.2 and 2.7 GeV. There are small, calculable backgrounds from other B decay processes. There are *large* backgrounds from the continuum, both from the initial state radiation (ISR) process $e^+e^- \rightarrow q\bar{q}\gamma$, and from the normal $(q\bar{q})$ continuum reaction $e^+e^- \rightarrow q\bar{q}$, with the high energy photon arising from the hadronic debris (π^0, η, $\omega \rightarrow \pi^0\gamma$, etc). We suppress the continuum, two ways, and then subtract what is left, using data taken at E_{cm} just below the $\Upsilon(4S)$ resonance.

In the first method for suppressing the continuum, we take 8 carefully chosen event-shape variables: R_2, $S_\perp$, R_2', $\cos\theta'$ as defined in Ref[3], and the energies in 20° and 30° cones, parallel and antiparallel to the high energy photon direction. We combine the 8 variables into a single variable r which tends towards +1 for $b \rightarrow s\gamma$ and tends towards -1 for ISR and $q\bar{q}$, using a neural network. Distributions in r are shown in Fig. 1, for MC signal, MC background, and off-resonance data. There is substantial discrimination between signal and background, and good agreement between MC background and off-resonance data. Given r, we perform a weighted sum of candidate high energy photon events, with an r-dependent weighting, large near $r = +1$, small near $r = -1$, optimized based on Monte Carlo samples of signal and background. This weighting procedure is equivalent to performing a 1-parameter fit to the r distribution.

In the second method for suppressing the continuum, we search each event containing a high energy γ for combinations of particles which fit the $B \rightarrow X_s\gamma$ decay hypothesis. We use: the γ; $K^\pm$ or $K_s^0 \rightarrow \pi^+\pi^-$; 1-4 π's, which may include 0 or 1 π^0. We do not concern ourselves with cross-feed, combinatoric

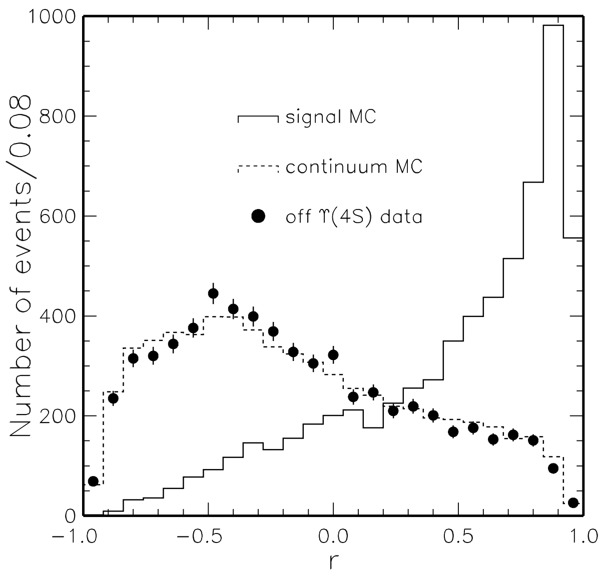

Figure 1. Distributions in the neural net variable r, for Monte Carlo samples of $b \rightarrow s\gamma$ signal (solid histogram) and continuum background (dashed histogram), and for the off-resonance data sample (points).

background, or reconstruction ambiguities, as we are using reconstruction to suppress the continuum, and *not attempting a mode-by-mode B reconstruction analysis.* In each event, we pick the best combination of particles, and for that combination consider

$$\chi_B^2 = \left(\frac{M_B - 5.279}{\sigma_M}\right)^2 + \left(\frac{E_B - E_{beam}}{\sigma_E}\right)^2. \quad (1)$$

We also calculate $\cos\theta_{tt}$, where θ_{tt} is the angle between the thrust axis of the candidate B and the thrust axis of the rest of the event. Both χ_B^2 and $\cos\theta_{tt}$ give good discrimination between signal and background. We make cuts $|\cos\theta_{tt}| < 0.6$ and $\chi_B^2 < 6.0$.

There are backgrounds from B decay processes other than $b \rightarrow s\gamma$, in particular from $b \rightarrow cW^-$, $b \rightarrow uW^-$, and $b \rightarrow sg$. As a first approximation, we take these from Monte Carlo. We then correct for any difference between the π^0 momentum spectra from data and Monte Carlo, and similarly for the η momentum spectra. Thus, in a very real sense, these backgrounds are determined from data. It is only for those small B-decay backgrounds *not* from π^0 or η that we rely on Monte Carlo.

The photon energy spectra from the event-shape

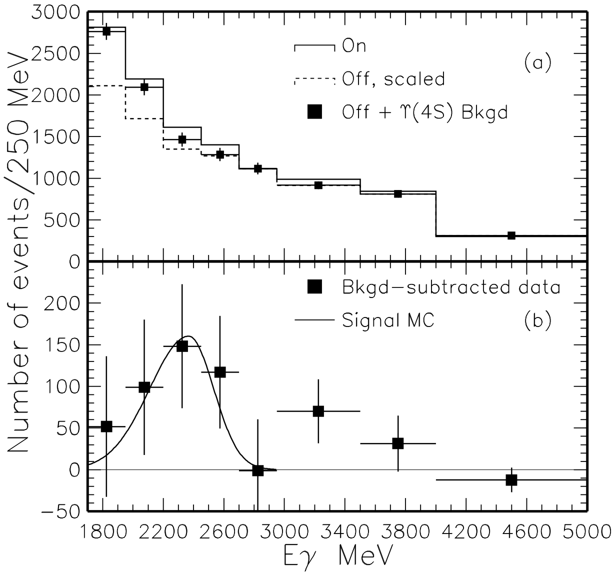

Figure 2. Photon energy spectra from the event-shape analysis. (a) On-resonance (solid histogram), scaled off-resonance (dashed histogram), and sum of off-resonance and background from Υ(4S) (squares). (b) Background-subtracted data (points) and Monte Carlo prediction for the shape of the $b \to s\gamma$ signal (solid curve).

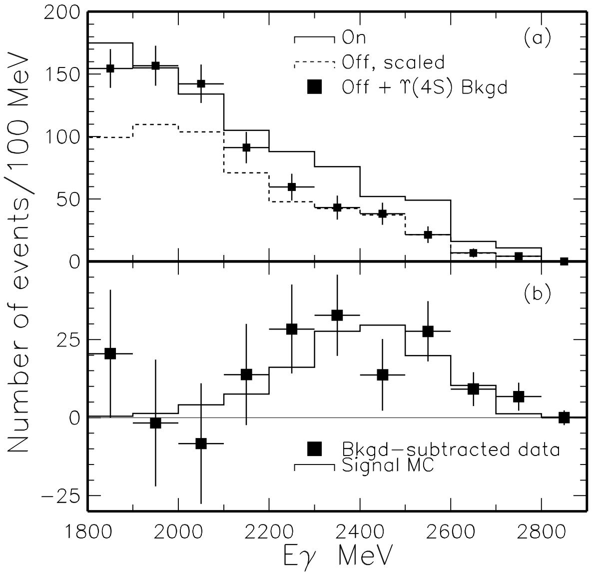

Figure 3. Photon energy spectra from the B reconstruction analysis. (a) On-resonance (solid histogram), scaled off-resonance (dashed histogram), and sum of off-resonance and background from Υ(4S) (squares). (b) Background-subtracted data (points) and Monte Carlo prediction for the shape of the $b \to s\gamma$ signal (solid curve).

analysis are shown in Fig. 2a, while those from the B reconstruction analysis are shown in Fig. 3a. In both cases, the on-resonance spectrum exceeds the sum of off-resonance plus Υ(4S) backgrounds in the energy interval 2.2 - 2.7 GeV, demonstrating the presence of $b \to s\gamma$. The subtracted spectra are shown in Figs. 2b and 3b, along with a Monte Carlo prediction of the shape of the $b \to s\gamma$ photon spectrum. A signal of the expected shape is apparent. Yields between 2.2 and 2.7 GeV for the two analysis procedures are given in Table 2.

To calculate the detection efficiency, we model $b \to s\gamma$ with the spectator model of Ali and Greub[13], which includes gluon bremsstrahlung and higher order radiative effects. It gives us the X_s mass distribution. We hadronize X_s with conventional models of quark hadronization. In the Ali-Greub model, we vary P_F and $m_{\rm spectator}$ simultaneously such that the b quark average mass $< m_b >$ is constant at 4.87 ± 0.10 GeV, a value suggested by recent theoretical work[14]. We take $P_F = 270 \pm 40$ MeV/c, based on fits to our $B \to X\ell\nu$ data with the same $< m_b >$.

We find $Br(b \to s\gamma) = (1.88 \pm 0.67) \times 10^{-4}$ with the event-shape analysis, and $(2.75 \pm 0.63) \times 10^{-4}$ with the

Table 2. Yields of events with 2.2 - 2.7 GeV photons, for the two $b \to s\gamma$ analysis procedures.

	Event Shape	B Reconstruction
On	3013 ± 59	281 ± 17
Off(scaled)	2618 ± 73	155 ± 18
$\Upsilon(4S)$ background		
$b \to c$	50.7 ± 5.1	12 ± 2
$b \to u$	11.9 ± 4.0	2 ± 1
π^0 correction	50.2 ± 27.7	−0.7 ± 2.3
η correction	16.5 ± 33.7	2.0 ± 8.5
Non-$B\bar{B}$	2.3	
$\Upsilon(4S)$ total	132 ± 44	15 ± 9
On$-$Off$-\Upsilon(4S)$	263 ± 94 ± 49	110 ± 25 ± 10

B reconstruction analysis. Allowing for correlations, the difference is 1.1 σ. We combine the two results, allowing for correlations, obtaining

$$Br(b \to s\gamma) = (2.32 \pm 0.51 \pm 0.29 \pm 0.32) \times 10^{-4}, \quad (2)$$

where the first error is statistical, the second error is the additive systematic error from uncertainty in yield,

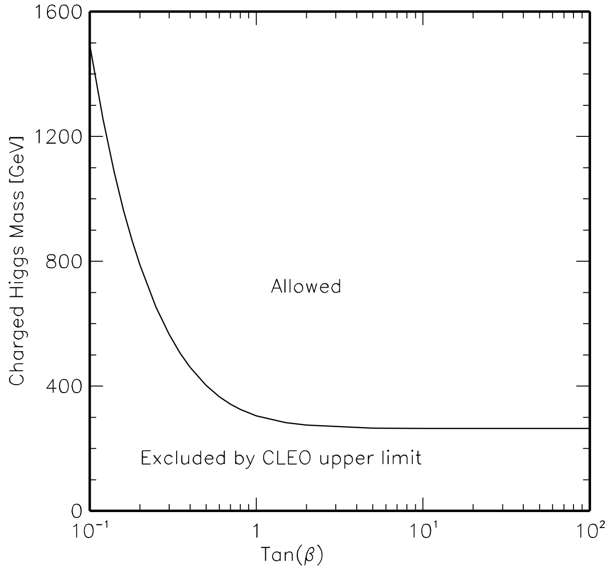

Figure 4. Lower limit on Two-Higgs-Doublet-Model-II Higgs mass as a function of $\tan(\beta)$. The region below the curve is ruled out by the upper limit on the $b \to s\gamma$ branching ratio reported here.

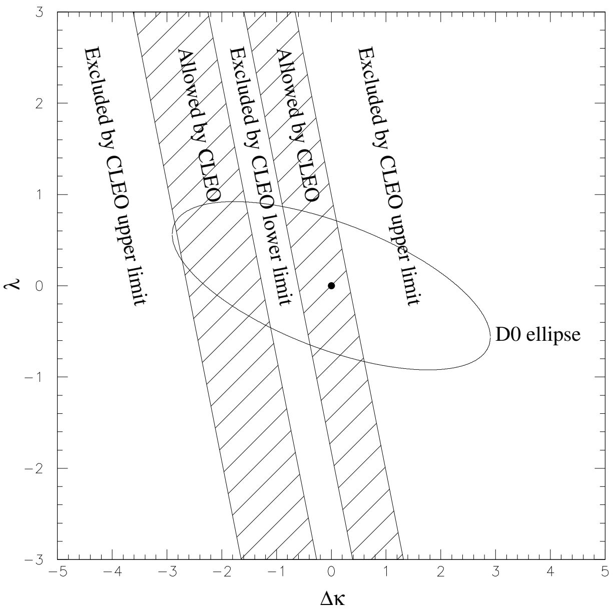

Figure 5. Limits on anomalous $WW\gamma$ coupling parameters λ and $\Delta\kappa$. The shaded regions are consistent with the $b \to s\gamma$ branching ratio reported here. The space between the shaded regions is ruled out by CLEO's lower limit, while the spaces outside the shaded regions are ruled out by CLEO's upper limit. D0's yield of $p\bar{p} \to W\gamma X$ limits the allowed range to the interior of the ellipse (the CDF $p\bar{p} \to W\gamma X$ limit gives a similar ellipse)[15]. The Standard Model value is shown as the dot at $\Delta\kappa = \lambda = 0$.

and the third error is the multiplicative systematic error from uncertainty in efficiency, including model dependence. We further obtain 95% c.l. lower and upper limits on the branching ratio

$$1 \times 10^{-4} < Br(b \to s\gamma) < 4 \times 10^{-4}. \qquad (3)$$

Our measurement, $(2.3 \pm 0.7) \times 10^{-4}$ is in good agreement with the Standard Model expectation $(2.8 \pm 0.8) \times 10^{-4}$. (For theory, we use $m_t = 175$ GeV, leading log terms only, and a renormalization scale $m_b/2 < \mu < 2m_b$. We assume a 10% theoretical uncertainty in addition to the renormalization scale uncertainty.) We illustrate the implications of our result for non-standard models with two examples.

A charged Higgs, with Model II coupling, would increase the $b \to s\gamma$ branching ratio, and by larger amounts for lower Higgs masses[10], so our upper limit on $b \to s\gamma$ provides a lower limit on charged Higgs mass. This limit is shown in Fig. 4. (With additional SUSY particles, this limit can be circumvented.)

Anomalous $WW\gamma$ couplings could either increase or decrease the $b \to s\gamma$ branching ratio[11], and so both our upper and lower limits rule out portions of the $\Delta\kappa - \lambda$ space that describes these anomalous couplings. In Fig. 5 we show the regions of the $\Delta\kappa - \lambda$ plane allowed and excluded by our limits, and also the regions allowed and excluded by $\bar{p}p \to W\gamma X$ measurements[15]. One notes a complementarity of the two types of measurements. The Standard Model gives $\Delta\kappa = \lambda = 0$.

7. Conclusion

I have presented five searches for rare B decays by CLEO. Upper limits on hadronic charmless decays are approaching Standard Model predictions. The measurement of branching ratio for $b \to s\gamma$ is in good agreement with Standard Model predictions, and places constraints on non-standard models. Further progress here requires completion of a next-to-leading log calculation, to reduce the theoretical uncertainty from renormalization scale.

8. Acknowledgements

I thank Ahmed Ali and Christoph Greub for performing several spectator model calculations for us, and for many interesting conversations. JoAnne Hewett and Tom Rizzo have helped me understand the implications of $b \to s\gamma$ for non-standard models. I thank Jesse Ernst and Peter Kim for help in preparing this paper, and for many interesting discussions. This work was supported by the National Science Foundation, the U.S. Dept. of Energy, the Heisenberg Foundation, the SSC Fellowship program of TNRLC, Natural Sciences and Engineering Research Council of Canada, and the A.P. Sloan Foundation.

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