Physics in Collision - Zeuthen, Germany, June 26-28, 2003

PROBING THE STANDARD MODEL WITH ELECTROWEAK PENGUIN B DECAYS

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ABSTRACT

Recent branching fraction and asymmetry results of Electroweak Penguin B decays from BaBar, Belle and CLEO experiments are reviewed. While these branching fractions are consistent with the Standard Model expectations and are being used to extract heavy quark model parameters and CKM matrix elements, the asymmetry results are just becoming sensitive to observe any new physics effects.

1 Introduction

It has long been observed that flavor changing neutral current (FCNC) transitions, e.g., $b \to s\gamma$, $b \to d\gamma$ and $b \to sl^+l^-$, are suppressed in nature. In particular the exclusive electroweak decays, $B \to K^*\gamma$ and $B \to K^{(*)}l^+l^-$ are known to have branching fractions at or below 10^{-5}. The Standard Model, by its very construction, does not allow tree level FCNC. The rarity of these decays is naturally explained due to the requirement of higher order loop (penguin and box) diagrams . New physics models must also contend with stringent restrictions on FCNC. However, new particles, e.g., charged higgs bosons of models with two higgs doublets, and charged scalars of the super symmetric (SUSY) models do enter these loop diagrams modifying the $b \to sX$ and $b \to dX$ amplitudes. Interference between the Standard model amplitude and these new amplitudes can manifest as an increase in the branching fractions or more subtly in increased direct CP violating or isospin violating asymmetries.

The CLEO experiment, which collected 9.1 fb^{-1} on Υ(4S) resonance and 4.4 fb^{-1} 60 MeV below it, was first to measure many of these decays. The new B-Factory experiments BaBar and Belle are now producing results using new techniques with much larger luminosities, up to 113 (140) fb^{-1} on resonance and 12 (18) fb^{-1} off resonance for BaBar (Belle). In this paper we review the status and examine the prospects of electroweak penguin B decay measurements. We also discuss the extraction of heavy quark model parameters and CKM matrix elements from these measurements.

2 Experimental Techniques

The radiative electroweak penguin B decay signals are difficult to extract due to large continuum and combinatorial background in $B\overline{B}$ events. The background is composed of initial state radiation photons, and photons from neutral meson $(\pi^0, \eta, ...)$ that have been misidentified as single photons. The leptonic electroweak penguin decays are mainly combinatorial arising from double semileptonic decays of heavy mesons. Although the backgrounds in this case are lower, the signals are also expected to be suppressed compared to the radiative decays making these measurements challenging.

The Standard Model expectations for the quark level decays are calculated to high accuracy. However, it is necessary to use approximate theoretical models that take into account the non-perturbative hadronic effects to calculate B meson decay processes that we measure in the laboratory. These calculations are most reliable when inclusive measurements are made. Unfortunately, making inclusive measurements is experimentally more difficult. In order to suppress the backgrounds three different techniques have been used thus far. The CLEO experiment collected substantial continuum data to make statistical subtraction of non-B background. All experiments are measuring radiative B-meson decays in as many exclusive hadronic states as possible. The higher statistics BaBar and Belle experiments are able to use a partially reconstructed second B meson in the event, e.g., a semi-leptonic B decay, to suppress the continuum background.

3 $b \to s\gamma$ measurements

The SM $b \to s\gamma$ branching fraction is predicted to be $\mathcal{B}(b \to s\gamma) = (3.73 \pm 0.3) \times 10^{-4}$ [1] at the next–to–leading order (NLO). The present theoretical uncertainty of $\sim 10\%$ is dominated by the mass ratio of the c–quark and b–quark and the choice of the renormalization scale. New Physics contributions with e.g. charged Higgs exchanges or chargino–squark loops are expected to be at the same level as the SM ones. Unfortunately, initial measurements have already ruled out possibility of discovering any dramatic new physics effects here. However, *CP* asymmetries do provide a stringent test of the SM. While small in the SM ($\leq 1\%$) [2] the *CP* asymmetries can reach 10–50% in models beyond the SM [3].

The photon energy spectrum in $b \to s\gamma$ is used to understand the hadronic effects as it only depends on the parameters defining the structure of the B mesons. For instance, the moments of the photon energy spectrum are used to measure the Heavy Quark Effective Theory (HQET) parameters which determine the b–quark pole mass ($\overline{\Lambda}$) and the kinetic energy (λ_1) [4]. These parameters are needed to obtain a precision value of $|V_{cb}|$ from the $b \to c\ell\nu$ inclusive rate, and V_{ub} from $B \to X_u\ell\nu$.

At the lowest order in Λ_{QCD}/M_B, the $B \to X_s\gamma$ photon energy spectrum, where X_s refers to inclusive strange hadronic states, is given by a convolution of the parton level $b \to s\gamma$ photon energy spectrum with the light–cone shape function of the B meson, which describes all b to light–quark transitions. At the same order in Λ_{QCD}/M_B, the $B \to X_u\ell\nu$ lepton energy spectrum is given by a convolution of the parton level $b \to u\ell\nu$ lepton energy spectrum with the same shape function [5]. Corrections up to the next order of Λ_{QCD}/M_B are currently the subject of active investigation [6].

3.1 Inclusive $b \rightarrow s\gamma$

Two experimental approaches have been used to measure the inclusive rate for the $b \rightarrow s\gamma$ process.

The "fully inclusive" method measures the high energy photon spectrum without identifying the hadronic system X_s. Continuum backgrounds are suppressed with event shape information, and then subtracted using off–resonance data. B decay backgrounds are subtracted using a generic Monte Carlo prediction, which is cross–checked with a $b \rightarrow s\pi^0$ analysis. BaBar [7] has presented a preliminary result from a fully inclusive analysis in which the "other" B is leptonically tagged to almost completely suppress the continuum background reducing the need for large off-resonance data, and exploiting its high statistics on-resonance data. These methods do need to tackle the B decay background.

A "semi–inclusive" method, which measures a sum of exclusive $B \rightarrow X_s\gamma$ decays, has been used by both BaBar [8] and Belle [9]. The hadronic X_s system is reconstructed by BaBar (Belle) in 12 (16) final states with a mass range up to 2.40 (2.05) GeV. This includes about 50 % of all $b \rightarrow s\gamma$ final states. Continuum and B decay backgrounds are subtracted by a fit to the beam–constrained B mass in the same way as in an exclusive analysis. The result is extrapolated to obtain inclusive branching fraction using Monte Carlo simulations.

CLEO [10] has published a measurement combining several methods each with a different technique to reduce the background. This measurement is still the best single result. Figure 1 summarizes the measurements of the $b \rightarrow s\gamma$ branching fraction. The theoretical error from the extrapolation of the inclusive rate from the measured energy range to the full photon spectrum is quoted. CLEO has a lower threshold (2.0 GeV) than BaBar (2.1 GeV) and Belle (2.25 GeV). Presently, experimental errors are only slightly larger than the theoretical uncertainty. Computing a world average is complicated by the correlated systematic and theoretical errors. The dominant systematic error for the fully inclusive method is from the B decay background subtraction. The a dominant systematic error for the semi–inclusive method is from the efficiencies of reconstructing the final states, including a correction for final states not considered in the analysis. This error is expected to be reduced significantly in the next round of analyses. The average branching fraction reported, $\mathcal{B} = (3.40 \pm 0.39) \times 10^{-4}$, is computed assuming that the systematic errors are uncorrelated, for simplicity.

The present $\mathcal{B}(B \rightarrow X_s\gamma)$ measurements already provide a significant constraint on the SUSY parameter space. For example limits on new physics contributions to $B \to X_s\gamma$ have been calculated using the minimal supergravity model (SUGRA) [11] and charged Higgs bosons [1].

So far, only CLEO [12] has measured the direct *CP* asymmetry. Their technique does not suppress the background coming from $b \to d\gamma$ decays (which is expected to have a large *CP* asymmetry). The measured direct *CP* asymmetry is $0.965 \times \mathcal{A}_{CP}(B \to X_s\gamma) + 0.02 \times \mathcal{A}_{CP}(B \to X_d\gamma) = (-0.079 \pm 0.108 \pm 0.022) \times (1.0 \pm 0.03)$. The first error is statistical, while the second and third errors represent additive and multiplicative systematic uncertainties, respectively. The theoretical expectation of $\mathcal{B}(B \to X_d\gamma)$ is used. Results are consistent with no asymmetry.

BaBar [8] and CLEO [10] have published a measurement of the photon energy spectrum down to a threshold $E^*_\gamma > 2.1$ and 2.0 GeV, respectively, where E^*_γ is measured in the B and in the laboratory rest frame, respectively (see Figure 2). For the semi–inclusive analysis the E_γ spectrum is obtained from the mass of the hadronic system X_s because E_γ, because $E_\gamma = \frac{M_B^2 - M_{X_s}^2}{2M_B}$ in the B rest frame.

From the measured spectrum, BaBar and CLEO have extracted the first moment in the B rest frame, $\langle E_\gamma \rangle$, finding $\langle E_\gamma \rangle = 2.35 \pm 0.04 \pm 0.04$ GeV and $\langle E_\gamma \rangle = 2.346 \pm 0.032 \pm 0.011$ GeV, respectively. Using expressions in the $\overline{MS}$ renormalization scheme, to order $1/M_B^3$ and order $\alpha_s^2\beta_0$ [4], BaBar and CLEO obtain $\overline{\Lambda} = 0.37 \pm 0.09 \pm 0.07 \pm 0.10$ GeV and $\overline{\Lambda} = 0.35 \pm 0.08 \pm 0.10$ GeV from the first moment. The errors are statistical, systematic (combined in the CLEO measurement) and theoretical, respectively. Moreover, CLEO has used their measured $B \to X_s\gamma$ photon energy spectrum to determine the light–cone shape function. Using this information, CLEO extracts $|V_{ub}| = (4.08 \pm 0.34 \pm 0.44 \pm 0.16 \pm 0.24) \times 10^{-3}$ [13], where the first two uncertainties are experimental and the last two are from theory.

3.2 The Exclusive Process $B \to K^*\gamma$

For the exclusive decay, $B \to K^*\gamma$, two recent NLO calculations predict SM branching fractions of $\mathcal{B}(B \to K^*\gamma) = (7.1^{+2.5}_{-2.3}) \times 10^{-5}$ [14] and $\mathcal{B}(B \to K^*\gamma) = (7.9^{+3.5}_{-3.0}) \times 10^{-5}$ [15]. The errors are still dominated by the uncertainties in the form factors.

The exclusive $B \to K^*\gamma$ modes have been studied by BaBar [16], Belle [17] and CLEO [18], where Belle used the highest statistics sample. Utilizing kinematic constraints resulting from a full reconstruction of the B decay, substantial reduction of the $q\overline{q}$ (continuum) background is seen. The Belle *beam–constrained* [1] mass distri-

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[1] Results for exclusive B decays are typically presented using the following kinematic variables. If $(E^*_B, \vec{p}^*_B)$ is the four–momentum of a reconstructed B candidate in the overall CM ($\Upsilon(4S)$) frame, we define

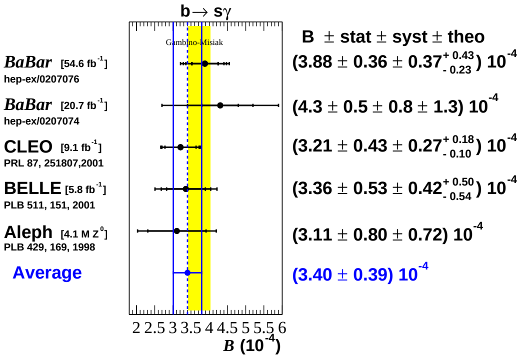

Figure 1: Summary of $b \rightarrow s\gamma$ branching fractions. The shaded band shows the theoretical prediction described in Ref. [1].

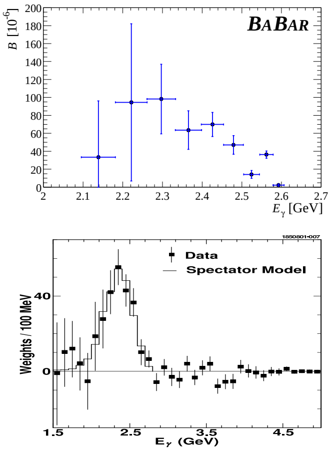

Figure 2: BaBar [8] (upper plot) and CLEO [10] (lower plot) photon energy spectrum in $b \rightarrow s\gamma$ decays.

bution is shown in Figure 3 for all the K^* decay channels. The measured branching fractions from all the experiments and the corresponding average are summarized in Table 1. The average branching fraction measurement is consistent with the NLO SM predictions and is known to higher accuracy than the theoretical uncertainty of 35–40%.

The direct CP asymmetry is defined, at the quark level, as:

$$A_{CP} = \frac{\Gamma(b \rightarrow s\gamma) - \Gamma(\bar{b} \rightarrow \bar{s}\gamma)}{\Gamma(b \rightarrow s\gamma) + \Gamma(\bar{b} \rightarrow \bar{s}\gamma)}.$$

Table 1 also summarizes the measurements of the direct CP asymmetry in $B \rightarrow K^*\gamma$. These are consistent with zero and are statistics limited.

Isospin asymmetry, Δ_{0+}, is calculated by Belle using the world average value $\tau_{B+}/\tau_{B^0} = 1.083 \pm 0.017$ [19]. The result is: $\Delta_{0+} = +0.003 \pm 0.045 \pm 0.018$, where the first error is statistical and the second systematic. It is consistent with no asymmetry, having assumed equal production of charged and neutral B's at the $\Upsilon(4S)$ resonance. The isospin asymmetry can be used to set limits on Wilson coefficients [20].

$$\Delta E^* \equiv E^*_B - E^*_{\text{beam}} \ ,$$

$$m_{\text{ES}} \ (\text{or } M_{bc}) \equiv \sqrt{{E^*_{\text{beam}}}^2 - p^{*2}_B} \ .$$

The latter is called the *energy–substituted* (BaBar) or *beam–constrained* (Belle, CLEO) mass. Signal events peak at ΔE^* near 0 GeV and m_{ES} (M_{bc}) near B meson mass; whereas continuum background lacks peaks.

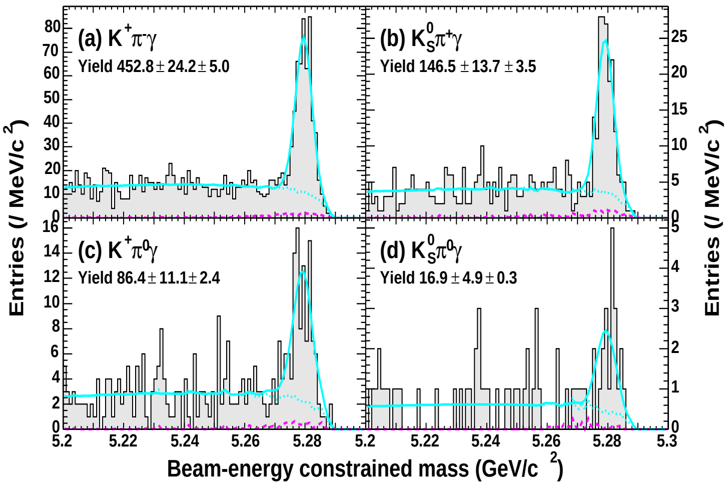

Figure 3: Belle [17] *beam–constrained* mass distribution for the exclusive $B \to K^*\gamma$ for the four K^* final states.

	$B^0 \to K^{*0}\gamma \times 10^{-5}$	$B^+ \to K^{*+}\gamma \times 10^{-5}$	A_{CP}
BaBar[16](21 fb^{-1})	$4.23 \pm 0.40 \pm 0.22$	$3.83 \pm 0.62 \pm 0.22$	$-0.04 \pm 0.08 \pm 0.01$
Belle[17] (78 fb^{-1})	$4.09 \pm 0.21 \pm 0.19$	$4.40 \pm 0.33 \pm 0.24$	$-0.00 \pm 0.04 \pm 0.01$
CLEO[18] (9 fb^{-1})	$4.55\,^{+0.72}_{-0.68} \pm 0.34$	$3.76\,^{+0.89}_{-0.83} \pm 0.28$	$+0.08 \pm 0.13 \pm 0.03$
Average	4.18 ± 0.23	4.14 ± 0.33	-0.01 ± 0.04

Table 1: $B \to K^*\gamma$ branching fraction and direct CP asymmetry measurements.

In addition to the already established $B \to K^*\gamma$ decay, there are several known resonances that can contribute to the X_s final state. Current measurements of higher than $K^*(892)$ mass systems are from Belle [21] and CLEO [18]. Note that the decay $B \to \phi K\gamma$ was observed recently by Belle [22] for the first time. CLEO also observed radiative B decays with baryons [23]. Theoretical predictions cover a wide range; results so far are consistent with those from a relativistic form factor model as in Ref. [24].

4 $b \to d\gamma$ final states

Both inclusive and exclusive $b \to d\gamma$ decays, which are suppressed by $\mid V_{td}/V_{ts} \mid^2 \sim 1/20$ with respect to corresponding $b \to s\gamma$ modes, have not been seen yet. An NLO calculation, which includes long–distance effects of u–quarks in the penguin loop, predicts a range of $6.0 \times 10^{-6} \leq \mathcal{B}(B \to X_d\gamma) \leq 2.6 \times 10^{-5}$ [25] for the inclusive branching fraction. The uncertainty is dominated by imprecisely known CKM parameters.

A measurement branching fraction ratio of $\mathcal{B}(B \to X_d\gamma)/\mathcal{B}(B \to X_s\gamma)$ provides a determination of $\mid V_{td}/V_{ts} \mid$ with small theoretical uncertainties. A determination of $\mid V_{td}/V_{ts} \mid$ in the exclusive modes $B \to \rho(\omega)\gamma$ has somewhat enhanced model uncertainties, since form factors are not precisely known. The *CP* asymmetry predicted in the SM for the inclusive process is foreseen between ~ 7 % and ~ 35 % [25].

Studies of the $b \to d\gamma$ decays presently focus on searching for the exclusive process $B \to \rho/\omega\gamma$. The corresponding branching fraction is predicted to be $\mathcal{B}(B \to \rho\gamma) = (1.6^{+0.8}_{-0.5}) \times 10^{-5}$ [14], while the *CP* asymmetry is of the order of 10% [14].

From the experimental point of view, the $B \to \rho(\omega)\gamma$ is more difficult than $B \to K^*\gamma$ because the backgrounds are bigger since this mode is CKM suppressed and $u\overline{u}, d\overline{d}$ continuum processes are enhanced compared to $s\overline{s}$ continuum processes.

The smallest upper limits on the exclusive decays $B \to \rho(\omega)\gamma$ come from BaBar [26], which uses a neural network to suppress most of the continuum background. The $B \to K^*\gamma$ events are removed using particle identification to veto kaons, with a $K \to \pi$ fake rate of ≈1%. A multi–dimensional likelihood fit is made to the remaining events to give 90 % C.L. upper limits of 1.2, 2.1 and 1.0×10^{-6} on $\rho^0\gamma$, $\rho^+\gamma$ and $\omega\gamma$, respectively. Assuming isospin symmetry, this gives a combined limit $\mathcal{B}(B \to \rho\gamma) < 1.9 \times 10^{-6}$ (90 % C.L.). Limits from Belle and CLEO can be found in Refs. [27] and [18], respectively.

Of particular theoretical interest is the ratio $\mathcal{B}(B \to \rho\gamma)$ to $\mathcal{B}(B \to K^*\gamma)$

as most of the theoretical uncertainty cancels and so it can be used to determine the ratio $| V_{td}/V_{ts} |$. [28] The present limit is $| V_{td}/V_{ts} | < 0.36$ at 90% confidence level, and is not as tight as the constraint from B_s/B_d mixing. However, New Physics may appear in different ways in penguin and mixing diagrams, so it is important to measure it in both processes.

5 $b \to sl^+l^-$

In the SM, three amplitudes contribute at leading order to the $b \to sl^+l^-$ decay: an electromagnetic penguin, a Z penguin, and a W^+W^- box diagram. The presence of three SM electroweak amplitudes makes $b \to sl^+l^-$ more complex than $b \to s\gamma$, which proceeds solely through the EM penguin. The branching fraction for $B \to Kl^+l^-$ is predicted to be 0.5×10^{-6}, and three times that for $B \to K^*l^+l^-$.[29]

Although the $B \to Kl^+l^-$ has lower branching fraction than $B \to K^*\gamma$, there are several experimental advantages that can be exploited. Tracking of leptons is more accurate than measuring photons in the calorimeter. A control sample is provided by $B \to J/\Psi(\to l^+l^-)K$ events which are used by both experiments to understand efficiencies and systematics.

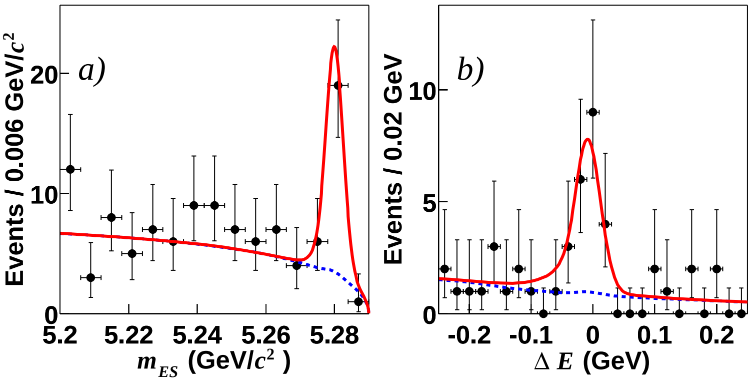

Figure 4: BaBar [32] energy-substituted mass and ΔE distributions (points) and projections (curves) of the simultaneous fit used to extract the branching fraction results for the exclusive $B \to Kl^+l^-$ process are shown. (a) m_{ES} for $-0.11 < \Delta E < 0.05$ GeV (b) ΔE for $|m_{ES} - m_B| < 6.6$ MeV/c^2. The solid curve is the sum of signal and all background fit components, whereas the dashed curve is just the sum of all background fit components.

The Belle collaboration has observed $B \to Kl^+l^-$, as well as the inclusive $B \to X_sl^+l^-$ decay[30, 31], which follows the "semi-inclusive" $b \to s\gamma$ analysis strategies. The BaBar collaboration has also observed $B \to Kl^+l^-$ and $B \to X_sl^+l^-$

decays[32, 33]. Figure 5 shows the BaBar distributions of M_{ES} and ΔE along with the projections of the simultaneous fit used to extract the branching fractions. For $K^*l^+l^-$, the reconstructed mass of K^* is also used in the multidimensional fit.

The electron and muon modes are separately analysed. The lepton result is defined using $\mathcal{B}(B \to Kl^+l^-) = \mathcal{B}(K\mu^+\mu^-) = 0.75 \times \mathcal{B}(B \to Ke^+e^-)$, which accounts for larger electron $q^2 = 0$ pole. The measurements of the branching fractions are shown in Table 2. With more statistics, theoretically interesting M_{ll} spectrum can be measured.

	$B^0 \to Kl^+l^-$	$B^+ \to K^*l^+l^-$	$B \to X_sl^+l^-$
Belle [30, 31] (130 fb^{-1})	$0.48^{+0.10}_{-0.09} \pm 0.03$	$0.12^{+0.26}_{-0.24} \pm 0.08$	$6.1 \pm 1.4^{+1.4}_{-1.1}$
BaBar [32, 33] (113 fb^{-1})	$0.65^{+0.14}_{-0.13} \pm 0.04$	$0.88^{+0.33}_{-0.29} \pm 0.10$	$6.3 \pm 1.6^{+1.8}_{-1.5}$

Table 2: Branching fractions in units of $(\times 10^{-6})$ for $B \to Kl^+l^-$, $B \to K^*l^+l^-$ and inclusive $B \to X_sl^+l^-$.

6 Conclusions and Outlook

A review of recent experimental results of radiative penguin decays $b \to s(d)\gamma$ and $b \to sl^+l^-$ is presented. The $b \to s\gamma$ process both in the inclusive and exclusive final states is well established. More statistics can be used to improve the limits or indirectly find evidence of new physics in *CP* and isospin asymmetries. Higher statistics can also improve the measurement of the photon energy spectrum, which is necessary to make better determination of the CKM matrix elements.

There is not yet any evidence of $b \to d\gamma$ decays but BaBar and Belle expect to collect ≈ 500 fb^{-1} by 2006. This should be sufficient to observe $B \to \rho\gamma$ enabling an important alternate method for the determination of $|V_{td}/V_{ts}|$. It may also be feasible to measure the inclusive $b \to d\gamma$ rate. For the measurement of $|V_{td}/V_{ts}|$, the ratio of $b \to d\gamma$ to $b \to s\gamma$ has much smaller theoretical uncertainties than the ratio of the exclusive decays.

The signals for $B \to Kl^+l^-$ are observed at 8σ level, and evidence for $B \to K^*l^+l^-$ is seen by both Belle and BaBar. So far these results are in agreement with the Standard Model expectations.

7 Acknowledgements

I would like to thank BaBar, Belle and CLEO collaborations for making the measurements available. I would also like to acknowledge the help of Dr. F. Di Lodovico, University of Wisconsin, in preparing this paper. This work is supported in part by grants from the U.S. Department of Energy and the University of Wisconsin, WARF.

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