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PROBING BEYOND STANDARD MODEL PHYSICS WITH ELELCTROWEAK PENGUIN B DECAYS

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ABSTRACT

Latest experimental progress is reviewed on the searches for physics beyond the Standard Model using the radiative and electroweak penguin decays of B mesons. This review covers inclusive and exclusive measurements of the $b \to s\gamma$, $b \to d\gamma$ and $b \to s\ell^+\ell^-$ processes, including the first observation of $B \to K\ell^+\ell^-$ and the first attempt to measure the inclusive $B \to X_s\ell^+\ell^-$ branching fraction.

1 Introduction

Since the first measurement of the inclusive $B \to X_s\gamma$ decay rate by CLEO in 1995 [1], rare B decays involving the penguin diagram have been a unique probe to search for new physics. The inclusive decay $B \to X_s\gamma$ corresponds to the quark level process $b \to s\gamma$, which is to date accurately calculated up to the next-to-leading order (NLO) QCD corrections. In the Standard Model (SM), the lowest order diagram for $b \to s\gamma$ is a loop (radiative penguin) diagram of top quark and W boson. In principle, new particles such as charged Higgs or SUSY partners can form the same loop diagram and may modify the SM amplitude. A comparison between the measured rate and the SM prediction has provided a stringent constraint on such new particles. As inclusive measurements have already been extensively performed, an exclusive measurement of $B \to K^*\gamma$ does not give a further constraint to new physics, because the model dependent form factor uncertainties in the SM predictions of the exclusive channels are too large.

Similar processes, $b \to d\gamma$ and $b \to s\ell^+\ell^-$, are also useful probes for new physics searches. Expected rates are two order of magnitude smaller than for $b \to s\gamma$, as $b \to d\gamma$ is suppressed by $|V_{td}/V_{ts}|^2$ and $b \to s\ell^+\ell^-$ is suppressed by an additional factor of α_{em}. At the lowest order, $b \to s\ell^+\ell^-$ process is described by an electroweak (Z) penguin diagram and a W-box diagram in addition to the radiative penguin. One can therefore expect some additional modifications to $b \to s\ell^+\ell^-$ that are not visible in $b \to s\gamma$, if there exist new particles that have large couplings with weak bosons. For these very rare decays, measurements of exclusive modes such as $B \to \rho\gamma$ and $B \to K^{(*)}\ell^+\ell^-$ also provide useful information even with the large uncertainties in the SM predictions, until the inclusive branching fraction for the corresponding process is known.

The SM amplitudes are calculated using an operator product expansion technique. The coefficients of the operators are called Wilson coefficients, C_i, that are theoretically calculated. At lowest order, $b \to s\gamma$ is described by the size of the coefficient C_7. For $b \to s\ell^+\ell^-$, the coefficients C_7, C_9 and C_{10} contribute. Higher order QCD corrections introduce other operators; however, one can absorb those contributions by modifying the lowest order coefficients into effective coefficients C_7^{eff}, C_9^{eff} and C_{10}^{eff}. The measured $b \to s\gamma$ rate provides a stringent limit on $|C_7^{\mathrm{eff}}|$, and then $b \to s\ell^+\ell^-$ results can be used to extract C_9^{eff} and C_{10}^{eff}, together with the sign of C_7^{eff}. In general, new physics can be modelled by introducing additional non-SM components C_i^{NP} to these Wilson coefficients that can be searched for by comparing the measured C_i and their SM predictions.

Other observables, such as the partial rate asymmetry (A_{cp}) between charge conjugate modes, are also useful to constrain new physics. For example, the SM predicts very small asymmetry, while there are several extensions of the SM that predict much larger A_{cp}. SM predictions for the A_{cp} of the exclusive channels are also reliable.

Studies of such rare decays have been pioneered by CLEO, which has accumulated about 13 fb^{-1} data. Now, two B-factory experiments, Belle and BaBar, have already superseded CLEO in the size of the collected data. All three detectors have similar experimental capabilities and comparable sensitivities for rare decays at a given integrated luminosity.

2 Radiative Decays $b \to s\gamma$

The decay $b \to s\gamma$ has a clear signature of an energetic photon in the range between 2 to 2.7 GeV due to its kinematics of two-body decay from the almost at-rest B meson (Figure 1). Underlying the signal, there are large backgrounds from continuum $q\bar{q}$ ($q = u, d, s, c$) productions, in which photons originate from initial state radiation or energetic π^0, η and other light mesons. In principle, this continuum background can be subtracted by using an off-resonance data sample taken below the $\Upsilon(4S)$ resonance. In addition, there are B decay backgrounds in the photon energy range below 2.2 GeV. For the subtraction of the B decay background, one has to rely on Monte Carlo (MC). The dominant part is from $B \to \pi^0 X$, for which MC is tuned by using the measured π^0 spectrum from B decays. Other B decay backgrounds are considerably smaller and reasonably modelled with MC. The recoil system X_s provides another useful background discrimination. By summing up the combinations of one kaon and 1 to 4 pions, one can perform a pseudo-reconstruction of the kinematic variables of B decays such as the beam-energy constrained (substituted) mass M_{bc} (M_{ES}) and the energy difference ΔE. These variables are explicitly used in the Belle analysis or included in the background suppression and candidate selection by CLEO.

The measured $B \to X_s\gamma$ branching fractions [2] are summarized in Table 1, together with SM predictions [3]. Until recently the theory error has been considered to be about 10%, but now there are arguments about the uncertainty of the charm quark mass included in the higher order loop calculation, which can be different from the pole mass as originally assumed. By taking into account this additional uncertainty, the overall uncertainty is about 15%. The measurement error of the world average is about 12%, and the branching fraction is in good agreement with

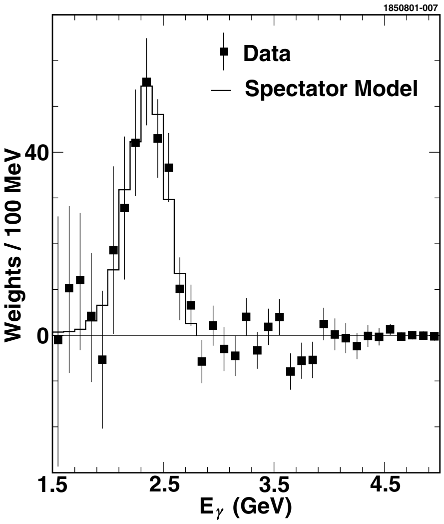

Figure 1: Photon energy spectrum of $B \to X_s\gamma$ by CLEO.

the SM expectation. In addition to the branching fraction, the measured photon energy spectrum provides information about B meson decay dynamics using the framework of heavy quark effective theory (HQET). This information has found to be quite useful to extrapolate the $b \to c\ell^-\bar{\nu}$ and $b \to u\ell^-\bar{\nu}$ measurements to the entire phase space in a less model dependent way, and to provide reliable values of $|V_{cb}|$ and $|V_{ub}|$ [4].

Table 1: Measured and predicted branching fractions for $B \to X_s\gamma$.

	Branching Fraction ($\times 10^{-4}$)
CLEO 2001	$3.21 \pm 0.43(\text{stat}) \pm 0.27(\text{syst})^{+0.18}_{-0.10}(\text{th})$
Belle 2001	$3.36 \pm 0.53(\text{stat}) \pm 0.42(\text{syst})^{+0.50}_{-0.54}(\text{th})$
ALEPH 1998	$3.11 \pm 0.80(\text{stat}) \pm 0.72(\text{syst})$
Average of measurements	3.22 ± 0.40
Chetyrkin et al. 1997, m_c(pole)	3.28 ± 0.33
Buras et al. 2002, $m_c(\overline{MS}(\mu))$	3.57 ± 0.30

The partial rate asymmetry between $b \to s\gamma$ and $\bar{b} \to \bar{s}\gamma$ is predicted to be less than 1% in the SM, and therefore any asymmetry beyond this will be a clear sign of new physics. This has been measured by CLEO [5], to be $A_{cp} = -0.079 \pm 0.108 \pm 0.022$, which is consistent with no asymmetry.

3 Exclusive Radiative Decays

In contrast to the inclusive measurement, reconstruction of exclusive channels such as $B \to K^*\gamma$ is fairly easy. Once the candidate is identified with M_{bc} (M_{ES}) and ΔE, the continuum background can be suppressed to a low level by using standard techniques such as cuts on R_2 or $\cos\theta_{\text{thrust}}$ (Figure 2). Backgrounds from other B decays are even smaller. The $B \to K^*\gamma$ branching fractions reported by CLEO, BaBar and Belle [6] are becoming very accurate as the data samples become large. However, corresponding theoretical predictions [7] suffer from large uncertainties, and as a result, exclusive modes are not as useful as the inclusive measurement to constrain new physics. The latest results are summarized in Table 2. The measured branching fractions are very precise, and the error may not shrink rapidly as the size of the statistical error has already reached that of the systematic error.

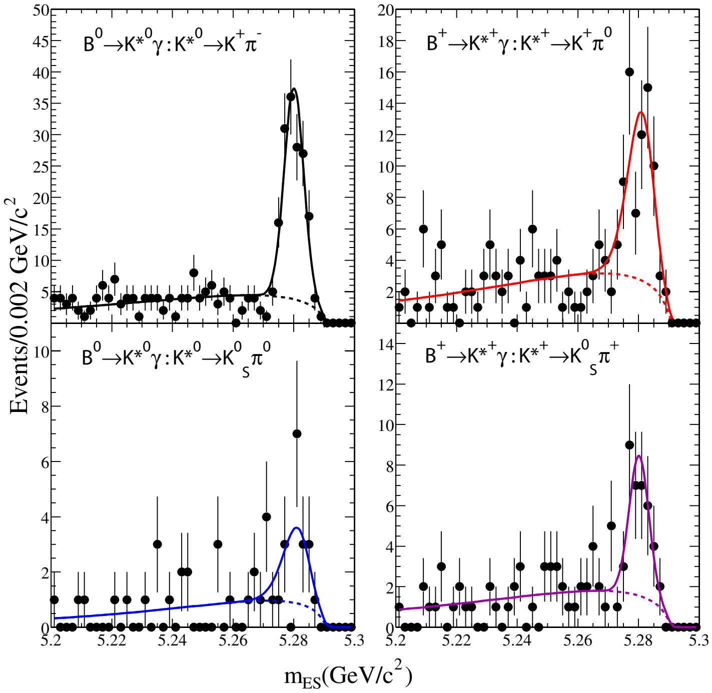

Figure 2: $B \to K^*\gamma$ signal by BaBar.

The rate difference between neutral and charged $B \to K^*\gamma$ also provides constraints on new physics. The latest results do not show such a difference.

The decay $B \to K^*\gamma$ accounts for 13% of total inclusive $b \to s\gamma$ decays. Exclusive decays through higher resonances provides additional information on the X_s system [8]. In the $K\pi\gamma$ final state, CLEO and Belle find evidence for $B \to$

Table 2: Measured and predicted branching fractions for $B \to K^*\gamma$.

	Branching Fraction ($\times 10^{-5}$)	
	$B^0 \to K^{*0}\gamma$	$B^+ \to K^{*+}\gamma$
CLEO 2000 (9 fb^{-1})	$4.55 \pm 0.70 \pm 0.34$	$3.76 \pm 0.86 \pm 0.28$
BaBar 2002 (21 fb^{-1})	$4.23 \pm 0.40 \pm 0.22$	$3.83 \pm 0.62 \pm 0.22$
Belle preliminary (29 fb^{-1})	$4.08 \pm 0.34 \pm 0.26$	$4.92 \pm 0.57 \pm 0.38$
Average of measurements	$4.21 \pm 0.25 \pm 0.26$	$4.32 \pm 0.38 \pm 0.30$
Ali, Parkhomenko 2002 (Large Effective Energy Theory)	7.2 ± 2.7	
Bosch, Buchalla 2002 (QCD factorization)	7.1 ± 2.5	

$K_2^*(1430)\gamma$. Belle searched for other exclusive channels in the $B^+ \to K^+\pi^-\pi^+\gamma$ final state. So far no particular resonant state is disentangled; however, $B^+ \to K^{*0}\pi^+\gamma$ and $B^+ \to K^+\rho^0\gamma$ branching fractions are measured separately. The results are summarized in Table 3. These results are used to estimate the decay rates into the unmeasured charge combinations of $K^*\pi\gamma$ and $K\rho\gamma$ assuming isospin. It is found that $35 \pm 8\%$ of inclusive rate is accounted for by the exclusive decays with $K\pi$ and $K\pi\pi$ final states. The remainder must be accounted for by the final states with η or η' mesons, more than 2 pions, more than 1 kaon, or final states with baryons.

Table 3: Branching fractions for exclusive radiative decays other than $B \to K^*\gamma$.

	Branching Fraction ($\times 10^{-5}$)
CLEO $B \to K_2^*(1430)\gamma$ (No $K^*(1410)$ is assumed)	$1.66 \pm 0.56 \pm 0.13$
Belle $B^0 \to K_2^*(1430)^0\gamma$	$1.5 \pm 0.6 \pm 0.1$
Belle $B^+ \to K^{*0}\pi^+\gamma$	$2.0^{+0.7}_{-0.6} \pm 0.2$
Belle $B^+ \to K^+\rho^0\gamma$	$1.0 \pm 0.5^{+0.2}_{-0.1}$
Belle $B^+ \to K^+\pi^-\pi^+\gamma$ (N.R.)	< 0.9 (90% CL)

The partial rate asymmetry between $\overline{B} \to \overline{K}^*\gamma$ and $B \to K^*\gamma$ in the SM is expected to be as small as in the inclusive case. The asymmetries measured by CLEO, BaBar and Belle are all consistent with no asymmetry, or in average, $A_{cp} = (+0.9 \pm 4.8 \pm 1.8) \times 10^{-2}$. Here, the statistical error is still dominant, and the error will be reduced to the level of 1–2% in the near future to provide a stringent constraint on new physics.

4 $b \to d\gamma$ Process

Similarly to the $b \to s\gamma$ process, $b \to d\gamma$ is sensitive to new physics. The expected branching ratio $\mathcal{B}(b \to d\gamma)/\mathcal{B}(b \to s\gamma)$ is approximately proportional to $|V_{td}/V_{ts}|^2$. As the size of $|V_{td}|$ is poorly known, $b \to d\gamma$ modes are useful for the determination of $|V_{td}/V_{ts}|$ until it is determined by the Tevatron experiments using the anticipated measurement of $\Delta m_s/\Delta m_d$.

No inclusive measurement of $b \to d\gamma$ has been attempted so far. An exclusive measurement of $B \to \rho\gamma$ or $B \to \omega\gamma$ is in principle a copy of the $B \to K^*\gamma$ measurement. The main issues are the more severe continuum background due to much lower branching fractions and the background from misidentified $B \to K^*\gamma$ in $B \to \rho\gamma$. Recently the BaBar group reported a significantly improved upper limit on $B \to \rho\gamma$ [9], by improving the pion selection algorithm. The reported results are, $\mathcal{B}(B^0 \to \rho^0\gamma) < 1.5 \times 10^{-6}$ and $\mathcal{B}(B^+ \to \rho^+\gamma) < 2.8 \times 10^{-6}$ at 90% confidence level. These limits are still slightly above the expected SM branching fractions, and do not provide an additional constraint on $|V_{td}|$.

5 Observation of $B \to K^{(*)}\ell^+\ell^-$

One of the recent highlights in B physics is the observation of the $b \to s\ell^+\ell^-$ process, which has only become possible in the B-factory era. CLEO, CDF and other experiments have previously searched for the decay $B \to K^{(*)}\ell^+\ell^-$ without success.

The first observation of the decay $B \to K\ell^+\ell^-$ has been made by Belle, using 29 fb^{-1} of data [10]. A lepton pair with an additional kaon is a very clear signal; however, there are a number of large sources of background. The largest background is due to the oppositely charged two leptons from semileptonic decays of both of the B meson pair or a $b \to c\ell\nu$ decay with a cascade $c \to s\ell\nu$ decay. The continuum background is suppressed by using shape variables. Electron pairs with small invariant masses are removed to reject $\pi^0 \to e^+e^-\gamma$ and $\gamma^* \to e^+e^-$ conversions. The charmonium decays $B \to J/\psi K$ and $B \to \psi' K$ have the same final states and interfere with the $B \to K\ell^+\ell^-$ signal. For this analysis, the $M_{\ell^+\ell^-}$ regions around the J/ψ and ψ' masses are removed. The removed area is much wider in the lower mass side, and especially for electrons, to account for energy loss due to the photon radiation from the electrons. When two pions are mis-identified as leptons, the copious $B \to K\pi\pi$ events from $B \to D\pi$ cannot be distinguished. The double mis-identification probability is very small. As a result the background from mis-identification is only 0.3 event for $K\mu^+\mu^-$ and much less for Ke^+e^-. These backgrounds are subtracted from the signal yield. Belle observed 13.6 $B \to K\ell^+\ell^-$ signal events with a 5.3σ significance (Figure 3-left) and obtained a branching fraction of $(7.5^{+2.5}_{-2.1} \pm 0.9) \times 10^{-7}$.

A similar analysis has been performed by the BaBar group. Initially BaBar did not observe the $B \to K\ell^+\ell^-$ signal using 20 fb^{-1} data, but the $B \to K\ell^+\ell^-$ signal is now observed with an updated dataset of 56 fb^{-1} [11] (Figure 3-right). Both results are consistent with the Belle results. Belle and BaBar have also searched for $B \to K^*\ell^+\ell^-$, but so far no significant signal is observed. The results are summarized in Table 4.

Table 4: Latest results for $B \to K^{(*)}\ell^+\ell^-$.

	significance	branching fraction ($\times 10^{-7}$)	upper limit ($\times 10^{-7}$, 90% C.L.)
Belle $B \to K\ell^+\ell^-$	5.3σ	$7.5^{+2.5}_{-2.1} \pm 0.9$	
BaBar $B \to K\ell^+\ell^-$	5.0σ	$8.4^{+3.0+1.0}_{-2.4-1.8}$	
BaBar $B \to K^*\ell^+\ell^-$	3.5σ	$18.9^{+8.4}_{-7.2} \pm 3.1$	< 35
Belle $B \to K^*e^+e^-$	2.5σ	$20.8^{+12.3+3.5}_{-10.0-3.7}$	< 56
Belle $B \to K^*\mu^+\mu^-$	—	—	< 31

The results for $B \to K^{(*)}\ell^+\ell^-$ have been used to constrain non-SM contributions C_9^{NP} and C_{10}^{NP} to the Wilson coefficients. The upper limit results have been excluding the outer part of a circular area on the C_9^{NP}–C_{10}^{NP} plane. The non-zero branching fraction results are now used to exclude the inner part of the C_9^{NP}–C_{10}^{NP} plane for the first time [12].

6 Inclusive $B \to X_s\ell^+\ell^-$

In order to reduce the theoretical error, it is desirable to have an inclusive measurement of $b \to s\ell^+\ell^-$. Belle has attempted a pseudo-reconstruction of $B \to X_s\ell^+\ell^-$, where X_s is reconstructed as one kaon and 0 to 4 pions, of which up to one π^0 is allowed. The background reduction conditions are tighter than in the exclusive analysis. In addition, the mass of X_s is required to be less than 2.1 GeV/c^2 to reduce the large combinatorial background. The mis-identification background is more severe, since $B \to X_s\pi^+\pi^-$ includes many decay channels of $B \to Dn(\pi)$ $(n \geq 1)$ with large branching fractions. The expected background yield is 2.4 ± 0.4 events, which is subtracted from the signal yield.

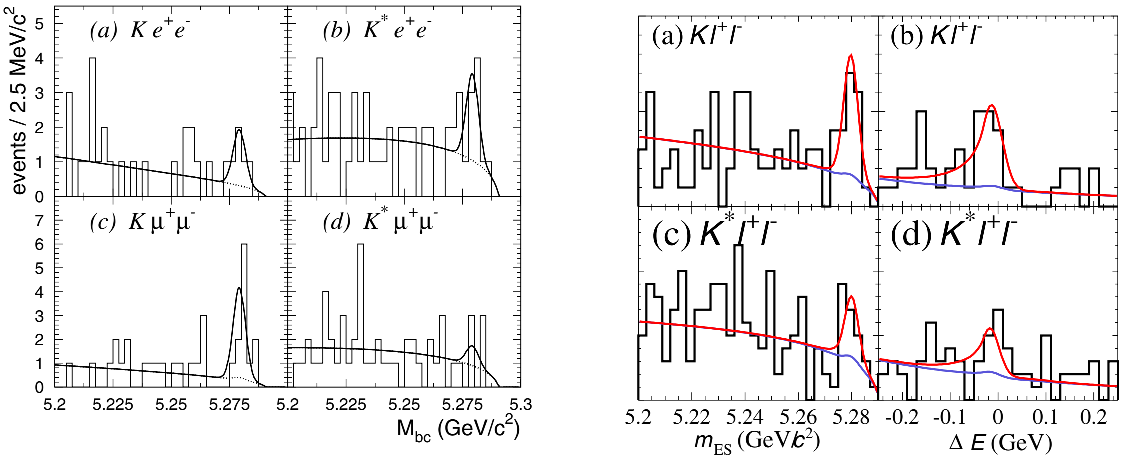

Figure 3: $B \to K\ell^+\ell^-$ signal and some hints for $B \to K^*\ell^+\ell^-$ by Belle (left) and BaBar (right).

The 42 fb^{-1} dataset has been analyzed, and a signal of 48 ± 11 events is found in the M_{bc} distribution (Figure 4). This corresponds to a 4.8σ significance and a branching fraction of $(7.1 \pm 1.6^{+1.4}_{-1.2}) \times 10^{-6}$. The result can be compared with a SM prediction, $(4.2 \pm 0.7) \times 10^{-6}$. The distributions of $M_{\ell^+\ell^-}$ and M_{X_s} are extracted from an analysis of the M_{bc} distributions for each bin of $M_{\ell^+\ell^-}$ and M_{X_s}. With the current statistics, it is too early to compare with the SM predictions. These results will provide a stringent constraint on new physics.

7 Conclusion

After the successful start of the Belle and BaBar experiments, $b \to s\gamma$ is now a mature topic; yet CLEO still provides the most advanced results on the inclusive measurements although B-factories which have a significantly larger datasets should catch up soon. For exclusive modes, results on both $b \to s\gamma$ and $b \to d\gamma$ by B-factories already superseded CLEO.

The long awaited $b \to s\ell^+\ell^-$ measurements are finally available. As observed by two groups, the $B \to K\ell^+\ell^-$ signal is firmly established, and $B \to K^*\ell^+\ell^-$ should be observed sooner or later. The first inclusive measurement of $B \to X_s\ell^+\ell^-$ was performed by Belle, and will hopefully become an important tool to find new physics in B decays in the coming years.

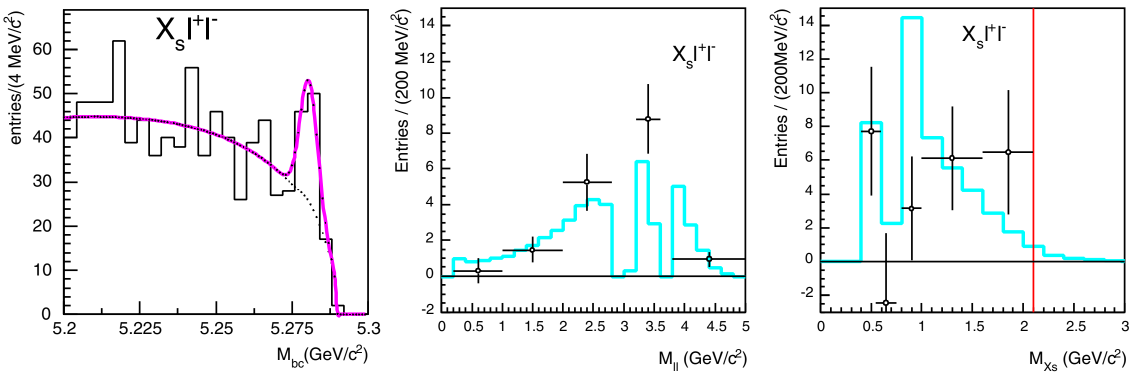

Figure 4: $B \to X_s \ell^+ \ell^-$ signal in M_{bc} (left) by Belle, and the $M_{\ell^+\ell^-}$ (middle) and M_{X_s} (right) distributions of the signal.

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