Radiative B Decays

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I discuss recent results in radiative B decays from the Belle and BaBar collaborations. I report new measurements of the decay rate and CP asymmetries in $b \to s\gamma$ and $b \to d\gamma$ decays, and measurements of the photon spectrum in $b \to s\gamma$.

1. Introduction

Radiative penguin decays are suppressed in the standard model (SM). They offer access to poorly-known SM parameters and are also a sensitive probe of new physics. The non-SM effects are potentially large in these decays which makes them thoeretically very interesting, but due to their small branching fractions they are typically eperimentally challenging.

Radiative penguin decays are flavour changing neutral currents which do not occur at tree level in the SM, but must proceed via one loop or higher diagrams. In the SM, the rate is dominated by the top quark contribution to the loop, but non-SM particles could also contribute with a size comparable to leading SM contributions (see Fig. 1).

2. $b \to s\gamma$

Considerable work has gone into the theoretical prediction for the $b \to s\gamma$ branching fraction (BF), which has now been calculated at the next-to-next-to leading order as $(3.15 \pm 0.23) \times 10^{-4}$ [1] and $(2.98 \pm 0.26) \times 10^{-4}$ [2]. A graphical comparison of the theoretical predictions with the experimental results is given in Fig. 2. Ther eis currently good agreement between theory and experiment, and work continues to reduce the errors on measurements to stringently test the predictions.

As well as the branching fraction, quantities such as the photon energy spectrum and various asymmetries in $b \to s\gamma$ decays can be measured. The photon energy distribution depends on the mass (m_b) and Fermi motion (μ_b) of the b quark - the spectrum peaks at half m_b as seen in Fig. 4. Measurements of the moments of the photon spectrum can be used to reduce the model-dependent error on the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{ub}|$ and $|V_{cb}|$. In the standard model the direct CP asymmetry is less than 1%, and new physics effects can enhance this to up to 15% [3]. The $B^0 B^+$ partial rate asymmetry, or isospin asymmetry, is predicted to be up to 10% in the SM [4]

2.1. Recoil Method

A number of different experimental techniques exist to measure the $b \to s\gamma$ transition. They are optimised to reduce the significant $q\overline{q}$ background (where $q = u, d, s, c$ quarks), also called continuum background.

In the recoil method, one B in the decay (the recoil or "tag" B) is fully reconstructed in a number of modes. The photon spectrum from other B (the signal B) is measured. In a recent BaBar analysis [5] using 210 $fb^{-}1$ over 1000 hadronic modes are used to reconstruct the tag B. The signal B is constructed from one high-energy photon, plus all tracks and neutral particles not used in the reconstruction of the tag B. This technique allows the photon spectrum to be measured in the signal B rest frame. The signal efficiency is low (around 0.3%) but continuum background is essentially eliminated. Using a photon energy cutoff of $E_\gamma > 1.9$ GeV the $b \to s\gamma$ branching fraction was found to be

$$BF(B \to X_s\gamma) = (3.65 \pm 0.85 \pm 0.60) \times 10^{-4} \quad (E_\gamma > 1.9 \text{ GeV})$$

where the first error is statistical and the second systematic. Extrapolating down to a photon energy limit of $E_\gamma > 1.6$ GeV gives:

$$BF(B \to X_s\gamma) = (3.91 \pm 1.11) \times 10^{-4} \quad (E_\gamma > 1.6 \text{ GeV}).$$

Using a more restricted photon spectrum of $E_\gamma > 2.2 GeV$ the CP and isospin asymmetries for $b \to (s,d)\gamma$ were found to be

$$A_{CP} = 0.10 \pm 0.18 \pm 0.05$$
$$\Delta_{0-} = -0.06 \pm 0.15 \pm 0.07$$

respectively. From the photon spectrum, shown in Fig. 3 the b quark mass and the Fermi energy can be caculated, giving

$$m_b = 4.46^{+0.21}_{-0.23} \text{ GeV}$$
$$\mu_\pi^2 = 0.64^{+0.39}_{-0.38} \text{ GeV}^2.$$

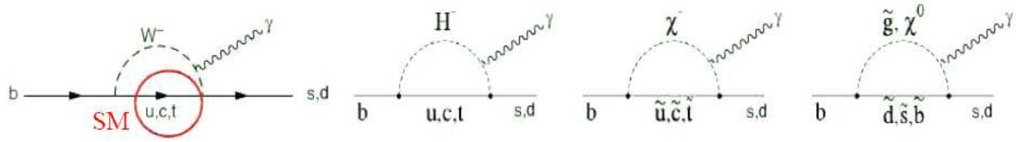

Figure 1: Feynman diagrams for radiative penguin decays, showing the stndard model loop and various new physics scenarios.

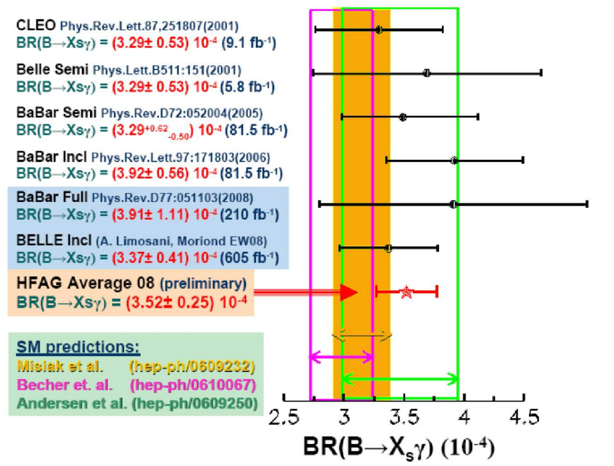

Figure 2: Summary of theoretical predications and experimental results for the $b \to s\gamma$ branching fraction.

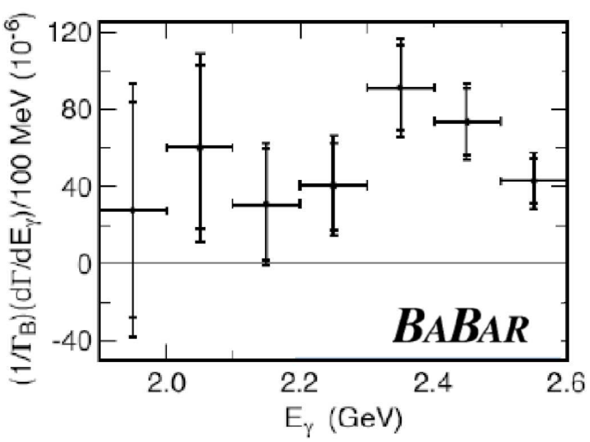

Figure 3: Photon energy spectrum for $b \to s\gamma$ decays measured by the BaBar collaboration using a recoil method [5].

2.2. Inclusive Method

Belle has recently made the first measurement of $b \to s\gamma$ to extend down to a photon energy of $E_\gamma > 1.7 GeV$, using $605 fb^{-1}$ of data. The technique used is a fully inclusive one, where only the signal photon is reconstructed and the background from non-B decays is reduced using lepton tags from the non-signal B. Vetoes are used to remove photons from π^0s and ηs by rejecting high energy photons if, when paired with any other photon in the event, they possess an invariant mass near that of a π^0 or η. Topological event information is used to suppress continuum backgrounds - $B\overline{B}$ decays tend to be spherical in shape in the centre-of-mass (CM) frame, whereas continuum events are more jet-like. After cuts have been made, there still remains significant background which is subtracted using off-resonance data for continuum background, and Monte Carlo simulated events for other B backgrounds. Figure 4 shows the photon energy spectrum after background subtraction.

The branching fraction for $b \to s\gamma$ was measured to be

$$BF(B \to X_s\gamma) = (3.31 \pm 0.19 \pm 0.37 \pm 0.001) \times 10^{-4} \quad (E_\gamma > 1.7 \text{ GeV})$$

where the first error is statistical, the second systematic and the third due to uncertainty in the boost. Extrapolating to photon energies above $E_\gamma > 1.6$ GeV

$$BF(B \to X_s\gamma) = (3.31 \pm 0.41) \times 10^{-4} \quad (E_\gamma > 1.6 \text{ GeV})$$

From the photon energy spectrum, shown in Fig. 4 the first and second moments are found to be

$$< E_\gamma >= 2.281 \pm 0.032 \pm 0.053 \pm 0.001 \text{ GeV}$$
$$< E_\gamma^2 > - < E_\gamma >^2 = 0.0396 \pm 0.0214 \pm 0.0012 \text{ GeV}^2$$

respectively.

2.3. Semi-inclusive method

BaBar recently presented an updated measurement of the CP asymmetry in $b \to s\gamma$ decays, made using a semi-inclusive method. In this type of analysis, the inclusive decay is approximated using a reconstruction of many exclusive final states. This analysis used 16 exclusive $B \to X_s\gamma$ final states which cover approximately 50% of the total width within the hadronic mass range of $0.6 < M(X_s) < 2.8 GeV/c^2$, which corresponds to a photon energy cutoff of $E_\gamma > 1.9 GeV$. Continuum background is reduced with a boosted decision tree multivariate tool and fake high energy photons from π^0 or η decays are removed using vetoes described above. The CP asymmetry is measured from a fit to the beam-constrained mass m_{ES} in the

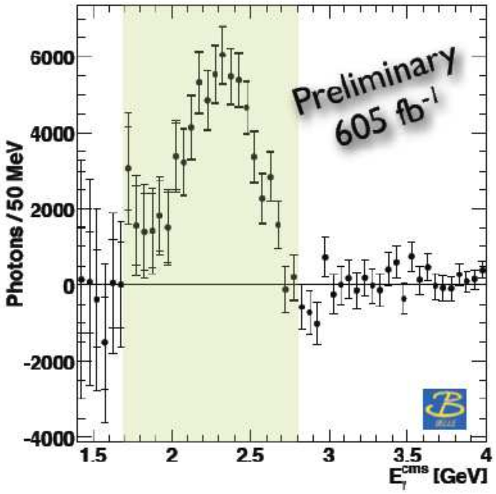

Figure 4: The photon energy spectrum in $b \rightarrow s\gamma$ measured by the Belle collaboration using a fully inclusive method, after background subtraction. The shaded area is the region used for the measurements described in the text. The absence of events outside this region indicates the the backgrounds have been successfully subtracted.

$b \rightarrow s\gamma$ and $\overline{s} \rightarrow \overline{s}\gamma$ channels, as shown in Fig. 5, where $m_{ES} = \sqrt{E^*_{beam} - p^*_B}$, where E^*_{beam} is the beam energy in the CM frame, and P^*_B is the B momentum in the CM frame. The result is the most accurate measurement to date of the direct CP violation in this decay:

$$A_{CP}(b \rightarrow s\gamma) = -0.012 \pm 0.030 \pm 0.018, \ [5]$$

where the first error is statistical and the second systematic. This is in good agreement with the standard model prediction of -1%.

3. $b \rightarrow d\gamma$

In the SM the rate for $b \rightarrow d\gamma$ is suppressed with respect to $b \rightarrow s\gamma$ by a factor of around 20, and is also sensitive to new physics. Direct CP asymmetries are expceted to be $O10\%$, but new physics effects could significantly enhance this. The ratio of CKM matrix elements V_{td}/V_{ts} can be obtained from the ratio of $b \rightarrow d\gamma$ and $b \rightarrow s\gamma$ BFs, for example in the ratio of exclusive decays using the formula:

$$\frac{BF(b \rightarrow \rho\gamma)}{BF(b \rightarrow K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{(1 - m^2_\rho/m^2_B)^3}{(1 - m^2_{K^*}/m^2_B)^3}\zeta^2[1 + \Delta R](1)$$

where ζ is the ratio of form factors for $B \rightarrow \rho\gamma$ and $B \rightarrow K^*\gamma$ and ΔR is a factor to account for the differences in decay dynamics.

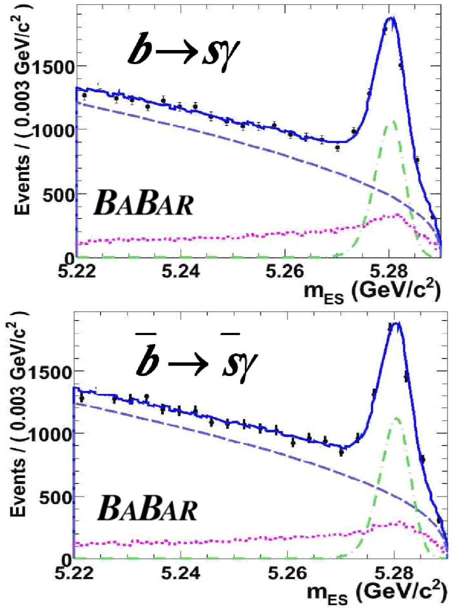

Figure 5: m_{ES} distribution for $b \rightarrow s\gamma$ decays (yop) and $\overline{b} \rightarrow \overline{s}\gamma$ decays (bottom). Data point with error bars, with signal contribution in green, $B\overline{B}$ in magenta, continuum background in blue dashed.

3.1. $B \rightarrow (\rho, \omega)\gamma$ Branching Fractions and V_{td}/V_{ts}

The exclusive $b \rightarrow d\gamma$ decays $B \rightarrow (\rho, \omega)\gamma$ have been extensively studied by both the Belle and BaBar collaborations. Background from continuum decays is more significant than for $b \rightarrow s\gamma$ analyses and cross-feed from mis-identified $b \rightarrow s\gamma$ decays is also a problem.

The BaBar analysis [8] uses a combination of lepton tags to suppress continuum background and constructed a neural net (NN) containing event shape variables which is used in the fit to a dataset of $347{\times}10^6$ $B\overline{B}$ pairs. Also included in the fit are m_{ES}, ΔE and the helicity angle, where ΔE is the energy difference between the beam and the reconstructed B meson $\Delta E = E^*_{beam} - E^*_B$, where E^*_B is the CM enery of the B. The Dalitz angle is also included in the fit to $B^0 \rightarrow \omega\gamma$. A fit is preformed in 4 dimensions (5 in $B \rightarrow \omega\gamma$) using m_{ES}, ΔE, the helicity angle and the neural net output (also the Dalitz angle in $B \rightarrow \omega\gamma$). The measured branching fractions are

$$BF(B \rightarrow \rho\gamma) = (1.36 \pm 0.28 \pm 0.10) \times 10^{-6}$$
$$BF(B \rightarrow (\rho, \omega)\gamma) = (1.25 \pm 0.25 \pm 0.09) \times 10^{-6}$$

where the first error is statistical and the second systematic.

The equivalent Belle analysis [9] uses $657{\times}10^6$ $B\overline{B}$ pairs, and also deals specifically with the backgrounds from $B \rightarrow K^*\gamma$ decays. The fit uses m_{ES}, ΔE and, in the channel $B \rightarrow \rho^0\gamma$, the invariant mass of the

$\pi\pi$ pair with Kaon mass assigned to one of the pions. The measured branching fractions are

$$BF(B \to \rho\gamma) = (1.21^{+0.24}_{-0.22} \pm 0.12) \times 10^{-6}$$
$$BF(B \to (\rho,\omega)\gamma) = (1.14 \pm 0.20^{+0.10}_{-0.12}) \times 10^{-6}.$$

To extract $|V_{td}/V_{ts}|$ we use the formula given in 1 and the theoretical quantities $\zeta = 0.85$ and $\Delta R = 0.1$. Using the world average branching fractions, we obtain:

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.206 \pm 0.018$$

This is represented graphically in the $\overline{\rho},\overline{\eta}$ plane for $B^0 \to \rho^0\gamma$ in Fig. 6 and for $B^+ \to \rho^+\gamma$ in Fig. 7.

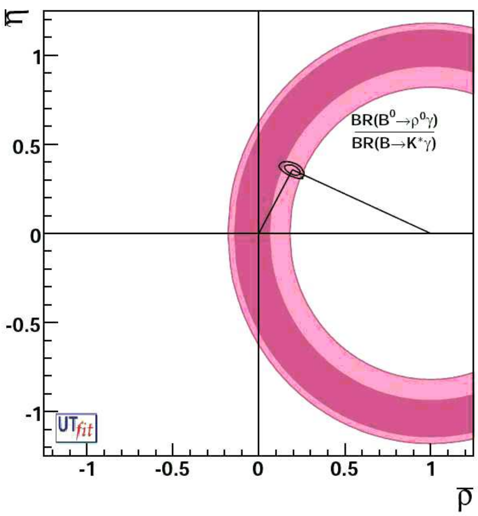

Figure 6: The limits on $|V_{td}/V_{ts}|$ for the ratio of branching fractions of the neutral ρ and K* decays, shown in the $\overline{\rho},\overline{\eta}$ plane.

3.2. CP asymmetry in $B \to \rho\gamma$

Belle recently presented a measurement of the direct CP asymmetry in $B^+ \to \rho^+\gamma$ using 657×10^6 $B\overline{B}$ pairs [10]. A simultaneous fit is performed to m_{Es} and ΔE for $B^+ \to \rho^+\gamma$ and $B^- \to \rho^-\gamma$ decays. Potential asymmetries from background sources are included in the systematic error, and a control sample of $B \to D\pi$ decays is used to understand bias in the detector. The direct CP asymmetry is measured as

$$A_{CP}(B^+ \to \rho^+\gamma) = 0.11 \pm 0.32 \pm 0.09,$$

where the first error is statistical and the second systematic. The result is not statistically significant, but it agrees with standard model predictions of 10%.

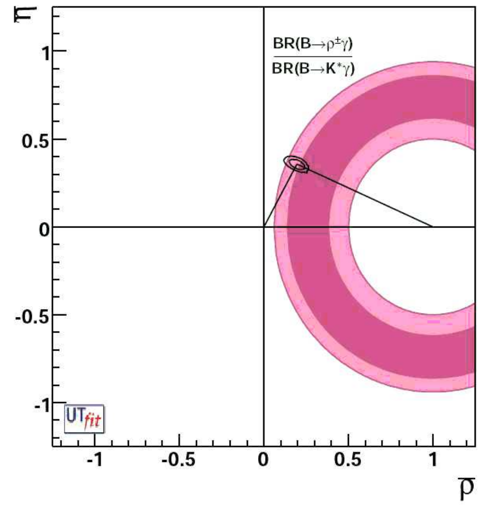

Figure 7: The limits on $|V_{td}/V_{ts}|$ for the ratio of branching fractions of the charged ρ and K* decays, shown in the $\overline{\rho},\overline{\eta}$ plane.

3.3. Inclusive $b \to d\gamma$

BaBar has recently made the first measurement of non-resonant $b \to d\gamma$ using 343×10^6 $B\overline{B}$ pairs, performing a semi-inclusive analysis to approximate the inclusive decay [11]. Seven exclusive final states were used, with up to four pions and up to one π^0 or η. The measurement was limited to the mass range $1.0 < M(X_d) < 1.8GeV/c^2$ to exclude the ρ and ω resonances and found

$$BF(B \to X_d\gamma) = (3.1 \pm 0.9 \pm 0.7) \times 10^{-6}$$

in this mass range. Work is on-going to convert this to a fully inclusive measurement and an determination of $|V_{td}/V_{ts}$.

4. Conclusion

Measurements of the $b \to s\gamma$ decay are becoming every more precise, in theory and experiment. Recent measurements have been made of the branching fractions with photon energy cutoffs at $E_\gamma < 1.7GeV$ and $E_\gamma < 1.9GeV$, and CP asymmetry in the mass range $0.6 < M(X_s) < 2.8GeV/c^2$.

New measurements of $b \to d\gamma$ have also been made, with the experimental error on the branching fractions continuously decreasing and the first measurement of the CP asymmetry in $B^+ \to \rho^+\gamma$. The first evidence for non-resonant $b \to d\gamma$ has been presented, and more results are promised in the near future.

Radiative penguin decays continue to be a rich source of information on SM parameters and offer a unique probe into physics beyond the standard model.

References

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