# Radiative Penguin Decays at the $B$ Factories

Karsten Köneke[1a] (for the BaBar and Belle Collaborations)

Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA

**Abstract.** In this article, I review the most recent results in radiative penguin decays from the $B$ factories Belle and BaBar. Most notably, I will talk about the recent new observations in the decays $B \to (\rho/\omega)\gamma$, a new analysis technique in $b \to s\gamma$, and first measurements of radiative penguin decays in the $B_s^0$ meson system. Finally, I will summarize the current status and future prospects of radiative penguin $B$ physics at the $B$ factories.

**PACS.** 11.30.Hv Flavor symmetries – 12.15.Hh Determination of Kobayashi-Maskawa matrix elements – 13.20.He Decays of bottom mesons – 14.40.Nd Bottom mesons

## 1 Introduction

Now, at the verge of the Large Hadron Collider (LHC) becoming operational, an exciting new era of discovery in high-energy particle physics is anticipated. There is a whole series of new physics models attempting to fix some of the shortcomings of the Standard Model (SM) of elementary particle physics, most notably the hierarchy problem of the Higgs sector. Low energy supersymmetry (SUSY) is probably the most popular extension of the SM. But all these new models introduce new free parameters. Current precision experiments can be used to constrain the allowed space of these additional new parameters and therefor guide the searches at the LHC.

One very interesting class of decays are so-called penguin decays where the leading order SM decay contribution is described by a one-loop Feynman diagram. Here, I will concentrate on penguin decays of $B$ mesons where a photon is radiated off.

Unknown particles that do not exist in the SM can contribute considerably to these decays, *e.g.* by appearing in this loop, and thus shift measurable observables. But if the measurements agree with SM based theoretical predictions, constraints on various beyond the SM physics scenarios can be extracted.

There is a large interest in $B$ meson decays since they provide an excellent window into the physics of quark mixing. In the SM, this is parameterized by four numbers that appear as the four independent parameters of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. A stringent test of the SM is performed by overconstraining these four parameters with independent measurements, of which many can be done by studying $B$ meson decays.

Hundreds of millions of $B$ mesons have been produced in the process $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ at the two energy-asymmetric $e^+e^-$ colliders KEKB and PEP-II. The measurements reviewed in this paper are performed with the Belle and BaBar detectors [1,2] situated at these two $B$ factories. In Sec. 2, I review common reconstruction techniques. In Sec. 3, I will talk about the decays $B \to (\rho/\omega)\gamma$. I introduce a new experimental approach to measuring the decay $b \to s\gamma$[1] in Sec. 4. In Sec. 5, I report on results of radiative penguin $B_s^0$ decays using a data sample collected at the $\Upsilon(5S)$ resonance. Finally, I conclude in Sec. 6.

## 2 Common reconstruction techniques

$B$ mesons[2] are reconstructed in two standard variables, $m_{ES}$ and $\Delta E$. The first is defined as $m_{ES} = \sqrt{\frac{s}{4} - |\boldsymbol{p}_B^*|^2}$, where $s$ is the center-of-momentum (CM) energy of the $e^+e^-$ collision and $\boldsymbol{p}_B^*$ is the measured three-vector of the reconstructed $B$ meson, also in the CM frame. The second important variable is defined as $\Delta E = E_B^* - \sqrt{s}/2$, where $E_B^*$ is the measured CM energy of the reconstructed $B$ meson.

Due to the small mass difference between $m_{\Upsilon(4S)} - 2m_B$, the two $B$ mesons are almost at rest in the CM frame. They decay thus rather spherically symmetric in that frame. This is different for the so-called light-quark continuum background ($e^+e^- \to f\overline{f}$, where $f = u, d, s, c, \tau$) where the light quarks (or leptons) have a large momentum in the CM frame. Their hadronization and decay is thus relatively collimated along the decay axis. These event shape differences are used in various ways in all analysis described below.

[1] Charge conjugation is implied throughout this article.

[2] All particles mentioned in the experimental part of this paper are actually “candidates” in the sense that their true identity is only assumed.

[a] *Email:* kkoeneke@alum.mit.edu

## 3 The Unitarity Triangle and $B \to (\rho/\omega)\,\gamma$

Besides the generic interests in radiative penguin decays mentioned in the introduction, this decay is also interesting due to its implications to measuring CKM matrix elements. If the experimental branching fraction of $B \to (\rho/\omega)\,\gamma$ is known, the ratio with that of $B \to K^*\gamma$ is proportional to $|V_{td}/V_{ts}|^2$ [3,4]

$$\frac{\mathcal{B}(B\to\rho\gamma)}{\mathcal{B}(B\to K^*\gamma)} = S_\rho \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{\left(1-m_\rho^2/M^2\right)^3}{\left(1-m_{K^*}^2/M^2\right)^3}\zeta^2 \cdot \left[1+\Delta R(\rho/K^*)\right] \ . \qquad (1)$$

Here, $\zeta = \xi_\perp^\rho(0)/\xi_\perp^{K^*}(0)$ is the ratio of form factors computed in Heavy Quark Effective Theory (HQET), $S_\rho = 1(1/2)$ are isospin weights for the charged (neutral) $\rho$ meson and $\Delta R(\rho/K^*)$ is a dynamical function calculated for example in [4] which accounts for different dynamics in the three decays like vertex, hard-spectator, weak annihilation or exchange contributions.

A recent calculation based on Light-Cone Sum Rules determines $\xi_\rho = 1.17 \pm 0.09$ and $\xi_\omega = 1.30 \pm 0.10$ [5]. $\Delta R(\rho/K^*)$ is usually computed to be in the neighborhood of 0.1 $\pm$ 0.1. A new calculation that also accounts for the additional $W$ annihilation diagram of the $B^+ \to \rho^+\gamma$ decay is also available [6].

The same ratio of CKM matrix elements is also measured by a physically very different process, $B$ mixing. The frequency of the oscillation of a $B$ meson turning into a $\bar{B}$ meson is related to the mass difference of the light and heavy $B$ meson eigenstates $\Delta m$. The ratio of these mass differences between the $B_d^0$ and the $B_s^0$ is proportional to $|V_{td}/V_{ts}|^2$. The $B$ factories have measured $\Delta m_d$ very precisely [7] and $\Delta m_s$ has recently been measured by the CDF collaboration [8].

The first observation of $B \to (\rho/\omega)\,\gamma$ decays was reported by Belle regarding the $B^0 \to \rho^0\gamma$ channel and the combined $B \to (\rho/\omega)\,\gamma$ channel [9]. *BaBar* also reported recently the observation of the combined $B \to (\rho/\omega)\,\gamma$ and $B \to \rho\gamma$ modes and also evidence for $B^0 \to \rho^0\gamma$ and first evidence for $B^+ \to \rho^+\gamma$. This result is based on a dataset of 347 million $B\overline{B}$ events [10].

The high-energy photon is enforced to not originate from a $\pi^0$ or $\eta$ decay by means of a two-dimensional likelihood comprised of the energy of any other photon found in the event and the two-photon invariant mass. Continuum background is rejected with a high-dimensional neural network, optimized for each mode individually. These neural networks combine event shape information, separation of the decay vertices of the two $B$ mesons in the event along the $z$ axis, decay angular information, information related to tagging of the flavor of the other $B$ meson in the event, and other quantities. The signal extraction is performed with an unbinned maximum likelihood fit in four (five) dimension for the individual $B \to \rho\gamma$ ($B^0 \to \omega\gamma$) channels, where the dimensions used are $m_{ES}$, $\Delta E$, a transformation of the neural network output, and the cosine of the helicity angle of the vector meson (and the sine of the second independent angle in the three body $\omega \to \pi^+\pi^-\pi^0$ decay). For the extraction of the combined results a simultaneous fit is used with the additional constraint on the decay widths $\Gamma_{B\to\rho^+\gamma} = 2\Gamma_{B\to\rho^0\gamma} = 2\Gamma_{B\to\omega\gamma}$.

**Table 1.** The branching fraction ($\mathcal{B}$) for each $B \to (\rho/\omega)\,\gamma$ mode is shown for the results from *BaBar* [10] and the new preliminary results from Belle [11], including their significance ($\Sigma$) in standard deviations (systematics included).

| Mode | $\mathcal{B} \pm \sigma_{\rm stat} \pm \sigma_{\rm sys}(10^{-6})$ ($\Sigma$) *BaBar* | Belle |
|---|---|---|
| $\rho^+\gamma$ | $1.10^{+0.37}_{-0.33} \pm 0.09$ (3.8) | $0.86^{+0.30+0.07}_{-0.28-0.08}$ (3.2) |
| $\rho^0\gamma$ | $0.79^{+0.22}_{-0.20} \pm 0.06$ (4.9) | $0.76 \pm 0.17 \pm 0.06$ (4.9) |
| $\omega\gamma$ | $0.40^{+0.24}_{-0.20} \pm 0.05$ (2.2) | $0.42^{+0.20}_{-0.18} \pm 0.04$ (2.6) |
| $(\rho/\omega)\gamma$ | $1.25^{+0.25}_{-0.24} \pm 0.09$ (6.4) | $1.13 \pm 0.20 \pm 0.11$ (5.9) |
| $\rho\gamma$ | $1.36^{+0.29}_{-0.27} \pm 0.10$ (6.0) | $1.19 \pm 0.24 \pm 0.12$ (5.5) |

The resulting branching fractions are listed in Table 1. While writing these conference proceedings, the Belle collaboration presented an updated preliminary analysis of these decays at the Lepton-Photon 2007 conference performed with a data sample of 657 million $B\overline{B}$ events [11]. Evidence is found for the two $\rho\gamma$ modes and both combined modes are observed, but the $B^0 \to \omega\gamma$ mode still eludes detection. These preliminary branching fractions are also listed in Table 1.

Combining both measurements to a new preliminary world average and using the measured results of the $B \to K^*\gamma$ decay [7], which includes the latest *BaBar* measurement [12], and applying Eq. 1 with input from [5,6] yields the results

$$\begin{aligned} |V_{td}/V_{ts}|^{\rm WA}_{\rho/\omega} &= 0.194^{+0.015}_{-0.014}({\rm exp.}) \pm 0.014({\rm th.}) \\ |V_{td}/V_{ts}|^{\rm WA}_{\rho} &= 0.201 \pm 0.016({\rm exp.}) \pm 0.015({\rm th.}) \end{aligned} \qquad (2)$$

for the $\rho/\omega$ mode and $\rho^+/\rho^0$ mode, respectively.

Both of these results are in excellent agreement with the result extracted from $B_d^0/B_s^0$ oscillations recently reported by the CDF collaboration [8]

$$|V_{td}/V_{ts}|^{\rm CDF}_{\Delta m_d/\Delta m_s} = 0.208^{+0.001}_{-0.002}({\rm exp.})^{+0.008}_{-0.006}({\rm th.}). \qquad (3)$$

The implications of the $|V_{td}/V_{ts}|$ measurement using the two $\rho$ modes only is shown in Fig. 1, compared with the CDF result. It is a remarkable success of the Standard Model that these two very different physics processes agree that beautifully.

## 4 A new approach to $b \to s\gamma$

Besides the possibility of constraining extensions of the SM, this decay is interesting because the high-energy photon carries information about the $b$ quark inside the $B$ meson. If we consider for a moment the decay of a free $b$ quark to a free $s$ quark and the high-energy photon, then this photon has a specific energy since this would be a two-body decay. As quarks are not free, the energy of the photon is smeared. But still, its first moment is related to the mass of the $b$ quark and its second moment to the Fermi motion of the $b$

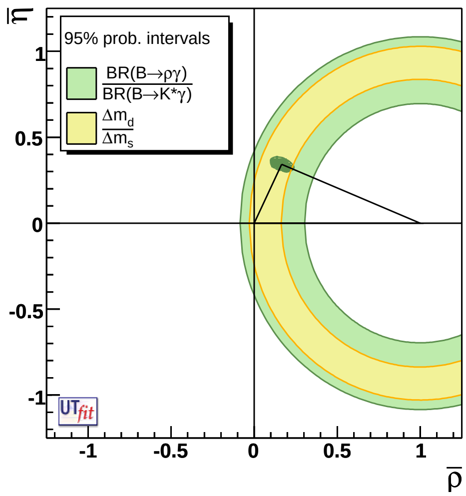


**Fig. 1.** Constraints on the far side of the unitarity triangle extracted from the $B \to \rho\gamma$ measurements reported in this paper (green) compared to $B$ oscillation measurements (yellow), computed with the UTFit code [13,14].

quark inside the $B$ meson. Extracting these quantities from the high-energy photon energy spectrum feeds into the determination of the CKM matrix element $V_{ub}$ since the extracted parameters are universal for the $B$ meson and are needed for the determination of this CKM matrix element from semi-leptonic $B$ decays.

The three recently published theoretical SM branching fraction predictions at NNLO [15,16,17] show the big interest of the physics community in this decay. These precise calculations (up to 7% uncertainty) allow for a very good comparison with the measurement and thus a stringent test of the SM can be performed.

Traditionally there are two experimental approaches to this measurement, a fully inclusive and a sum-of-exclusive. In the fully inclusive approach only the high-energy photon of the signal $B$ decay is reconstructed and the event is tagged as a $\Upsilon(4S) \to B\overline{B}$ event by requiring the existence of a lepton ($e$ or $\mu$) coming from a semi-leptonic decay of the other $B$ meson (the "tag $B$") in the event. This method is theoretically very clean but has two experimental drawbacks: high background and the measurement of the high-energy photon energy spectrum in the $\Upsilon$(4S) rest frame instead of the $B$ rest frame. The sum-of-exclusive approach reconstructs the decay in as many final state modes of the $s$ quark fragmentation as possible. Thus the photon energy is measured in the $B$ rest frame and the background is much reduced *w.r.t.* the fully inclusive method. However the theoretical interpretation is more difficult due to the uncertainty of the missing fraction of the $s$ quark hadronization.

A new experimental approach presented by BaBar is combining the advantages of both analysis. The tag $B$ meson is fully reconstructed in an all-hadronic final state, *e.g.* $B \to D\pi$. Only the photon is reconstructed from the signal side $B$ meson. Due to the knowledge of the initial beam conditions and the full reconstruction of the tag $B$ meson, the four momentum of the signal side $B$ meson is known and thus, the photon energy can be measured in the $B$ meson rest frame. The fully tagged event also reduces the background considerably. No uncertainty from the $s$ quark hadronization is present since only the high-energy photon is reconstructed and not the hadronization products of the signal side $s$ quark. The drawback of this new method is the small reconstruction efficiency of only about 0.3%.

**Table 2.** Measurements of the first and second moment of the photon energy spectrum in the $b \to s\gamma$ decay, depending on the low cut on the photon energy $E_\gamma^{\text{cut}}$.

| $E_\gamma^{\text{cut}}$ (GeV) | First moment Value $\pm\sigma_{\text{stat}} \pm \sigma_{\text{sys}}$ | Second moment Value $\pm\sigma_{\text{stat}} \pm \sigma_{\text{sys}}$ |
|---|---|---|
| 1.9 | 2.289 ±0.058 ±0.026 | 0.0334 ±0.0124 ±0.0065 |
| 2.0 | 2.315 ±0.036 ±0.020 | 0.0265 ±0.0057 ±0.0024 |
| 2.1 | 2.371 ±0.025 ±0.011 | 0.0142 ±0.0037 ±0.0013 |
| 2.2 | 2.398 ±0.016 ±0.006 | 0.0092 ±0.0015 ±0.0010 |
| 2.3 | 2.427 ±0.010 ±0.007 | 0.0059 ±0.0007 ±0.0003 |

After the tag $B$ meson reconstruction, the signal side high-energy photon is required to not be a product of a $\pi^0$, $\eta$, or $\rho$ decay. The continuum background is suppressed by means of a Fisher discriminant which is built with 12 inputs, mostly based on event shapes. The remaining continuum background does not peak in $m_{ES}$ and can thus be subtracted. The left over $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ background is mostly due to a $\pi^0$ or $\eta$ decay where the signal high-energy photon is not identified as a decay product of these particles. The signal yield is determined from an individual fit to $m_{ES}$ for each 100 MeV photon energy bin.

The branching fraction for a minimum energy of the photon of 1.9 GeV is determined on a BaBar dataset with an integrated luminosity of 210 fb$^{-1}$ as

$$\mathcal{B}(b \to s\gamma)\,[E_\gamma > 1.9\,\text{GeV}] = (3.66 \pm 0.85 \pm 0.59)\times 10^{-4}. \quad (4)$$

Extrapolating this to the theoretically preferred photon-energy cut of 1.6 GeV using [18] gives

$$\mathcal{B}(b \to s\gamma)\,[E_\gamma > 1.6\,\text{GeV}] = (3.91 \pm 0.91 \pm 0.63)\times 10^{-4}. \quad (5)$$

The systematic uncertainties can be reduced with higher statistics. The resulting first and and second moments for different photon energy cuts are shown in Table 2.

With this new preliminary BaBar measurement, a third independent approach to measure $b \to s\gamma$ is explored. Since the data samples of the three measurements are independent, they can be combined to one result. Currently, this new method does not reach the precision of the other two. But I expect that unlike the other two, this approach will benefit from more statistics, especially from very large datasets in the multi inverse attobarn era expected at super-$B$ factories.

## 5 Results from the $\Upsilon$(5S) run

KEKB ran also at a higher CM energy equivalent to the mass of the $\Upsilon$(5S) meson. The Belle detector collected 23.6 $\text{fb}^{-1}$ at this configuration, corresponding to about 2.6 million $B_s^0$ mesons produced. The number of produced $B_s^0$ mesons per inverse femtobarn is small for two reasons. First the production cross-section of the $\Upsilon(5\text{S})$ resonance is with 0.3 nb about three times smaller as that of the $\Upsilon(4\text{S})$ resonance. And only about 20% of the $\Upsilon(5\text{S})$ mesons decay into $B_s^{0(*)}$ pairs. The majority of strange $B$ mesons are actually created as $B_s^{0*}$ mesons and they decay via $B_s^{0*} \to B_s^0\gamma$ with a soft photon. Besides this soft photon, $B_s^0$ reconstruction is performed as in the $\Upsilon(4S) \to B\overline{B}$ case. The photon is too soft to be reliably reconstructed, so it is ignored and only visible in a $\approx 50\,\text{MeV}$ downward shift in $\Delta E$.

### 5.1 $B_s^0 \to \phi\gamma$

This decay mode is the brother of $B^0 \to K^{*0}\gamma$, just the spectator quark is different. The SM theory prediction for the branching fraction is $(4 \pm 1) \times 10^{-5}$ [6]. A recent NNLO calculation gives $(4.3 \pm 1.4) \times 10^{-5}$ [19].

Two oppositely charged kaons are reconstructed and combined to form the $\phi$ candidate. A cut on the invariant mass of the two kaons is applied with a $2.5\sigma$ window around the nominal $\phi$ mass. The light quark continuum background is suppressed utilizing event shape information in the form of modified Fox-Wolfram moments. The photon is required to not originate from a $\pi^0$ or an $\eta$ decay. The final signal yield is extracted with a three-dimensional unbinned maximum likelihood fit. The three variables entering in this fit are $m_{ES}$, $\Delta E$, and the cosine of the helicity angle of the $\phi$ meson. 18 signal events are found which yields

$$\mathcal{B}\left(B_s^0 \to \phi\gamma\right) = \left(5.7^{+1.8+1.2}_{-1.5-1.7}\right) \times 10^{-5}. \qquad (6)$$

The significance of this result, including systematic uncertainties, is $5.5\sigma$. This is the first observation of a radiative penguin decay of the $B_s^0$ meson.

### 5.2 $B_s^0 \to \gamma\gamma$

This decay proceeds in the SM at leading order via a penguin fusion diagram between the $\bar{b}$ quark and the $s$ quark. It is like the Feynman diagram of the $b \to s\gamma$ decay turned by 90° with an additional photon attached. The SM theory predictions are in the range $(0.5 - 1.0) \times 10^{-6}$ [20,21]. This low branching fraction can be enhanced by up to one order of magnitude in several models extending the SM, *e.g.* in $4^{th}$ quark generation models [22] or in supersymmetric models with broken R-parity [23]. No discovery of this decay has been reported as of today.

The reconstruction is performed similar to the above case. Especially the two photons are required to not be consistent with the decay of a $\pi^0$ or $\eta$ meson. The signal is extracted with a two-dimensional unbinned maximum likelihood fit where the two variables are $m_{ES}$ and $\Delta E$. No signal is seen and an upper limit is set at a 90% confidence level of

$$\mathcal{B}\left(B_s^0 \to \gamma\gamma\right) < 8.6 \times 10^{-6} \text{ at } 90\%. \qquad (7)$$

This is as of today the best limit for this decay mode.

## 6 Conclusions

New measurements of $B \to (\rho/\omega)\,\gamma$ are available. The agreement with $B_s^0$ oscillation measurements is excellent and a non-trivial test of the SM succeeds. The experimental precision will improve with larger datasets. A new reconstruction method for the $b \to s\gamma$ decay is presented. This method will fully benefit from datasets from super $B$ factories unlike previous reconstruction methods. The first radiative penguin $B$ decay of the $B_s^0$ meson, $B_s^0 \to \phi\gamma$, has been observed by Belle using data collected at the $\Upsilon(5\text{S})$ resonance. All measurements presented have a large impact on SM tests and constraints of beyond the SM physics. The rich field of radiative penguin $B$ decays will provide more input to constraining the physics beyond the SM.

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