Radiative Penguin Decays at the B Factories

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An overview of the measurements of $b \to s\gamma$, $b \to d\gamma$ and $b \to s\ell\ell$ penguin transitions at the B Factories is presented.

1. Introduction

The flavor-changing neutral current transitions $b \to s$ and $b \to d$ cannot proceed at the tree level in the Standard Model (SM). Radiative decays such as $B \to X_s\gamma$, $B \to X_d\gamma$ and $B \to X_s\ell\ell$ hence proceed primarily via one-loop diagrams known as penguin and box diagrams. Because of this, these processes are rare in the SM, with branching ratios on the order of 10^{-4} to 10^{-6}. However, for the same reason, these channels are very sensitive to new physics beyond the SM.

In the past few years, the B Factory detectors, Belle at the KEKB collider at KEK, Japan and *BABAR* at the PEP-II collider at SLAC, U.S.A., have recorded a total of more than $0.9\,\mathrm{ab}^{-1}$ of data, making it possible to study these decays extensively. Both experiments benefit from high-granularity electromagnetic calorimetry with excellent angular and energy resolution ($\sim 3\%$ for $1\,\mathrm{GeV}$ photons), silicon vertex detectors providing position resolution on the order of $100\,\mu\mathrm{m}$ along the beam axis and K/π separation for momenta up to 3-4 GeV. Details of the detectors can be found in references [1].

The relevant theoretical framework for all the decays reviewed in this paper is the operator product expansion (OPE) [2], with which the heavy particles (the gauge bosons and the top quark in the SM) are integrated out to obtain an effective low-energy theory with five quarks. The long-distance contributions are captured in operator matrix elements, whereas the short-distance physics is described by the effective coupling constants, known as Wilson coefficients. Physics beyond the SM can manifest in new operators, or in vastly different values for the Wilson coefficients of the existing operators, compared to the SM predictions.

The OPE framework provides parton-level predictions, so the connection to the experimental observables require further non-perturbative corrections. Form factors, calculations of which introduce significant theoretical uncertainties, are needed to study exclusive final states ($B \to K^*\gamma$, $B \to K\ell\ell$, etc.). On the other hand, for inclusive decays, heavy-quark expansion (HQE) and quark-hadron duality keep non-perturbative corrections under control. This allows more direct interpretations of the measurements of the inclusive decay rates. However, exclusive decays, being experimentally cleaner, are observed earlier and measured with better precision. Ratios of exclusive-decay observables, in which the form-factor corrections partially or completely cancel, can also provide complimentary information to that obtained from inclusive decays.

2. $b \to s\gamma$

2.1. Exclusive $b \to s\gamma$

Since its first observation in the exclusive mode $B \to K^*(892)\gamma$ in 1993 [3], $b \to s\gamma$ has been the most extensively studied radiative penguin process. With the large data samples of the B Factories, many other exclusive modes have since become accessible and so far the branching fractions of nine charged and six neutral final states have been measured at 3σ or better significance (Fig. 1) [4]. For some of these modes, measurements of the charge asymmetry and the time-dependent CP violation have also been done [5]; the results are so far consistent with the predictions from the SM.

It is worth highligthing a few of the most recent results. The evidence for the first baryonic final state, $B^+ \to p\overline{\Lambda}\gamma$, has been reported by the Belle collaboration in 2004 [6]. While this decay has currently the smallest branching fraction ($(2.16^{+0.58}_{-0.53} \pm 0.20) \times 10^{-6}$) among all the $b \to s\gamma$ final states measured at 3σ or better significance, its penguin nature becomes apparent due to the stringent upper limit on the two-body decay $B^+ \to p\overline{\Lambda}$ [7].

More recently, the observation by the Belle Collaboration of $B^+ \to K_1^+(1270)\gamma$, the first radiative B-meson decay involving an axial-vector resonance, with an unexpectedly high branching fraction ($(43 \pm 9 \pm 9) \times 10^{-6}$) has attracted some interest [8]. Inclusive measurements of four different $K\pi\pi\gamma$ final states by the *BABAR* Collaboration yield similarly high branching fractions [9]. With more statistics, the decays $B \to K\pi^+\pi^0\gamma$ will permit the measurement of the photon polarization, which is almost completely left-handed in the SM [10].

Finally, the most recent development in the exclusive $b \to s\gamma$ front is the confirmation by *BABAR* of Belle's earlier measurement of the $B \to K\eta\gamma$ decay [11]. Both charged and neutral modes are now established at better than 5σ significance. Additionally *BABAR* has also obtained the first upper limits on the decay $B \to K\eta'\gamma$. These upper limits (at 90% C.L.) and the new combined averages for the $K\eta\gamma$ final states by the Heavy Flavor Averaging Group (HFAG) are given in Eq. 1:

$$\begin{aligned} \mathcal{B}(B^+ \to K^+\eta\gamma) &= (9.3 \pm 1.1) \times 10^{-6}, \\ \mathcal{B}(B^0 \to K^0\eta\gamma) &= (10.3^{+2.3}_{-2.1}) \times 10^{-6}, \\ \mathcal{B}(B^+ \to K^+\eta'\gamma) &< 4.2 \times 10^{-6}, \\ \mathcal{B}(B^0 \to K^0\eta'\gamma) &< 6.6 \times 10^{-6}. \end{aligned} \quad (1)$$

These measurements will be useful in reducing the systematic uncertainties in the inclusive measurements of $B \to X_s\gamma$, and in searches for higher-mass K^* resonances. Moreover, it is possible to measure time-dependent CP asymmetry in the neutral final states.

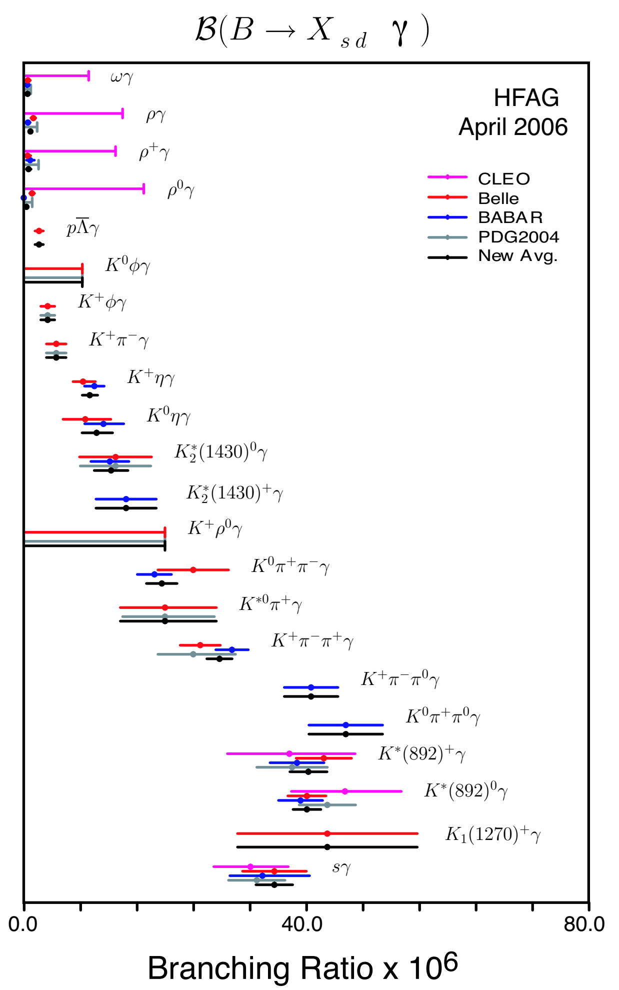

Figure 1: Branching fractions for $b \to s/d$ photon penguins [4]. The value for inclusive $s\gamma$ has been reduced by an order of magnitude to fit it in the figure.

2.2. Inclusive $b \to s\gamma$

Inclusive measurement of the $B \to X_s\gamma$ total rate,[1] where X_s refers to any hadronic system with unit strangeness, gives one of the most widely quoted constraints on physics beyond the SM. Additionally, the shape of the photon energy spectrum, which is mostly insensitive to new physics, provides essential input for measuring Cabibbo-Kobayashi-Maskawa (CKM) matrix elements V_{cb} and V_{ub} from semileptonic B-meson decays. Therefore, this decay has been measured multiple times using independent techniques.

The current experimental world average reported by HFAG, $(3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$, where the errors are combined statistical and systematic, systematic due to the shape function, and systematic due to the subtraction of $d\gamma$ contribution, incorporates five branching fraction measurements from CLEO, Belle and *BABAR* Collaborations [4]. All five measurements are in very good agreement with each other and with the SM prediction of $(3.61^{+0.37}_{-0.49}) \times 10^{-4}$, computed at the next-to-leading-log precision [13]. This remarkable agreement implies strong constraints on various models of new physics. For example, in type-II two-Higgs-doublet model, which represents a good approximation for gauge-mediated supersymmetric models with large $\tan\beta$, where the charged Higgs contribution dominates the chargino contribution, the current experimental value implies a minimum charged-Higgs-boson mass of 350 GeV [14].

The moments obtained from the photon energy spectra are consistent among the different measurements and with the HQE predictions based on inputs from the hadron-mass and lepton-energy spectra measured in $B \to X_c\ell\nu$ decays. A fit to all the available data from $B \to X_s\gamma$ and $B \to X_c\ell\nu$ decays has yielded precise values for the HQE parameters m_b and μ_π^2, as shown in Table I. Further details on the derivation of these parameters and the extraction of $|V_{cb}|$ and $|V_{ub}|$ can be found elsewhere in the FPCP conference proceedings [16].

Table I Heavy-quark expansion parameters m_b and μ_π^2, and their correlation ρ, obtained from the combined fit to $B \to X_s\gamma$ and $B \to X_c\ell\nu$ data in two HQE schemes [15].

Scheme	m_b(GeV)	μ_π^2(GeV^2)	ρ
Kinetic	4.590 ± 0.039	0.401 ± 0.040	-0.39
Shape Function	4.604 ± 0.038	0.189 ± 0.038	-0.23

[1]Both within the theory community and among the experimentalists, the $B \to X_s\gamma$ total rate usually refers to the decay rate for photon energy above 1.6 GeV [12].

3. $b \to d\gamma$

Compared to $b \to s\gamma$, the amplitude for the process $b \to d\gamma$ is suppressed by the ratio of the CKM matrix elements $|V_{td}|/|V_{ts}|$. Therefore it is experimentally more difficult to observe than $b \to s\gamma$: the branching fractions for even the most prominant exclusive final states are expected to be on the order of 10^{-6}. Furthermore, misidentified $b \to s\gamma$ decays add up to the other substantial backgrounds (mostly high-energy photons produced through $\pi^0/\eta \to \gamma\gamma$ decays or via initial-state radiation in $e^+e^- \to q\bar{q}$ continuum events, where $q = u, d, s, c$) that are common to the measurements of all the radiative penguin decays.

The search for $b \to d\gamma$ has been carried out by CLEO, *BABAR* and Belle collaborations in one charged ($B^+ \to \rho^+\gamma$) and three neutral ($B^0 \to \rho^0/\omega/\phi\,\gamma$) exclusive decays. It is customary to combine the charged and neutral ρ and ω modes using isospin relations to obtain an average branching fraction defined by: $\mathcal{B}(B \to (\rho/\omega)\gamma) = \frac{1}{2}\{\mathcal{B}(B^+ \to \rho^+\gamma) + \frac{\tau_{B^+}}{\tau_{B^0}}[\mathcal{B}(B^0 \to \rho^0\gamma) + \mathcal{B}(B^0 \to \omega\gamma)]\}$, where $\frac{\tau_{B^+}}{\tau_{B^0}}$ is the ratio of the B-meson lifetimes. The branching fractions for each mode from Belle and *BABAR* are listed in Table II. For the ρ and ω modes, center values are given for comparison, even in the absence of any significant signal. While Belle and *BABAR* results do not agree well with each other for the decay $B^0 \to \rho^0\gamma$, the clear signal in Belle measurement of this mode gives the first observation of the $b \to d\gamma$ process. Figure 2 shows the beam-energy constrained mass $M_{bc} = \sqrt{(E^*_{beam}/c^2)^2 - |\vec{p}^*_B/c|^2}$, and the energy difference $\Delta E = E^*_B - E^*_{beam}$ distributions for the reconstructed B-meson candidates. Here, $\vec{p}^*_B$ and E^*_B are the c.m. momentum and energy of the B candidate, and E^*_{beam} is the c.m. beam energy. The simultaneous fit to all three decay modes, assuming isospin symmetry[2] yields the final Belle result:

$$\mathcal{B}(B \to (\rho/\omega)\gamma) = 1.32^{+0.34+0.10}_{-0.31-0.09}\,. \qquad (2)$$

Table II Branching fraction and significance for each $b \to d\gamma$ mode from Belle [17] and *BABAR* [18].

Mode	$\mathcal{B}\,(10^{-6})$	Sig.	$\mathcal{B}\,(10^{-6})$	Sig.
$B^+ \to \rho^+\gamma$	$0.55^{+0.42+0.09}_{-0.36-0.08}$	1.6	$0.9^{+0.6}_{-0.5} \pm 0.1$	1.9
$B^0 \to \rho^0\gamma$	$1.25^{+0.37+0.07}_{-0.33-0.06}$	5.2	$0.0 \pm 0.2 \pm 0.1$	0.0
$B^0 \to \omega\gamma$	$0.56^{+0.34+0.05}_{-0.27-0.10}$	2.3	$0.5 \pm 0.3 \pm 0.1$	1.5
$B \to (\rho/\omega)\gamma$	$1.32^{+0.34+0.10}_{-0.31-0.09}$	5.1	$0.6 \pm 0.3 \pm 0.1$	2.1
$B \to \phi\gamma$	—		< 0.85 (90% C.L.)	

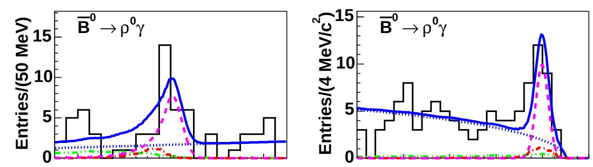

Figure 2: Projections of the fit results to M_{bc} and ΔE distributions for the Belle measurement of the decay mode $B^0 \to \rho^0\gamma$. Curves show the signal (dashed), continuum (dotted), $B \to K^*(892)\gamma$ (dot-dashed), other-B-decay background (dot-dot-dashed) components, and the total fit result (solid) [17].

The UTfit Collaboration has performed a fit to the data from the B Factories to extract $|V_{td}|/|V_{ts}|$ from the ratio $\mathcal{B}(B \to (\rho/\omega)\gamma)/\mathcal{B}(B \to K^*\gamma)$. To represent the theory uncertainties in the ratio of the QCD factorization expressions for $B \to (\rho/\omega)\gamma$ and $B \to K^*\gamma$ decays and in the ratio of the form factors, the fit assumes flat distributions [19]. The result of the fit is given in Eq. 3 and the bound on the $(\bar{\rho}, \bar{\eta})$ plane is shown in Fig. 3.

$$|V_{td}|/|V_{ts}| = 0.16 \pm 0.02\,. \qquad (3)$$

The most recent value of this ratio obtained from the Δm_s measurement by the CDF Collaboration is about two standard deviations away from this result [20]. However, it can be argued that the non-penguin contribution to the charged decay mode $B^+ \to \rho^+\gamma$ is significant. If the fit is repeated only with the neutral mode, the new result becomes $|V_{td}|/|V_{ts}| = 0.16 \pm 0.04$.

4. $b \to s\ell\ell$

4.1. Inclusive $b \to s\ell\ell$

In addition to the photon penguin diagram of $b \to s\gamma$, at the lowest-order $b \to s\ell\ell$ process has contributions from two other diagrams in the SM: a weak penguin diagram, where the Z-boson replaces the photon and a W-box diagram. Because of these contributions, OPE for $b \to s\ell\ell$ has ten operators (not counting the operators that are suppressed by increasing orders of $1/m_W$). The investigation of $b \to s\ell\ell$ can identify the sign of the Wilson coefficient C_7 of the photon penguin operator, and can provide the values for the Wilson coefficients C_9 and C_{10} of the vector and axial-vector electroweak operators.

The inclusive $b \to s\ell\ell$ rate has been measured by *BABAR* and Belle, using a sum-of-exlusive-states

[2] It should be noted that the individual fit results are in marginal agreement with the isospin relation. From Monte Carlo pseudo-experiments assuming the isospin relation, the authors of the Belle paper find that the probability to observe a deviation equal to or larger than the measurement is 4.9%.

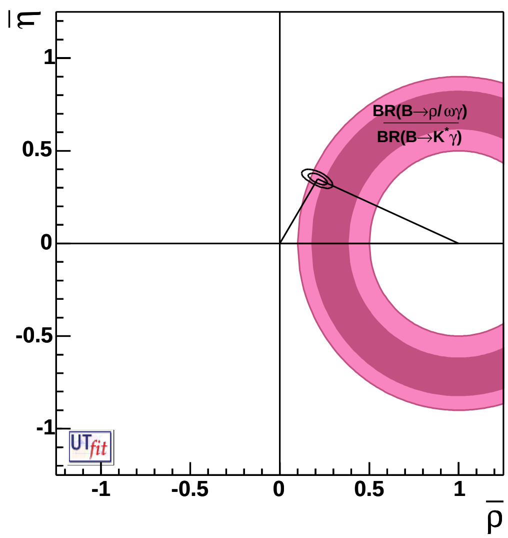

Figure 3: The bound on the $(\bar{\rho}, \bar{\eta})$ plane from the fit to the ratio $\mathcal{B}(B \to (\rho/\omega)\gamma)/\mathcal{B}(B \to K^*\gamma)$ [19].

(semi-inclusive) method. (So far, unlike $b \to s\gamma$, there has not been any fully-inclusive measurements.) The *BABAR* measurement, based on $82\,\mathrm{fb}^{-1}$ of data, reconstructs 10 hadronic final states, whereas the Belle measurement utilizes $140\,\mathrm{fb}^{-1}$ of data and reconstructs 18 hadronic final states [21]. The results of these measurements, given as a function of the dilepton mass squared q^2, have been compared with the next-to-next-to-leading-log predictions for the two choices of the sign of C_7. As listed in Table III, the sign of C_7 is quite unlikely to be different from that in the SM [22].

Table III *BABAR* and Belle measurements for the inclusive branching fraction (in units of 10^{-6}) of $B \to X_s\ell\ell$ in two ranges of the dilepton invariant mass squared. The weighted average is compared to the predictions in the SM and with reversed sign of C_7 [22].

q^2 range	$1-6\,\mathrm{GeV}^2$	$> 4m_\mu^2$
BABAR	1.8 ± 0.9	5.6 ± 2.0
Belle	1.5 ± 0.6	4.1 ± 1.1
Average	1.6 ± 0.5	4.5 ± 1.0
SM	1.6 ± 0.2	4.4 ± 0.7
$C_7 \to -C_7$	3.3 ± 0.3	8.8 ± 1.0

4.2. Exclusive $b \to s\ell\ell$

Two exclusive $b \to s\ell\ell$ decays have been studied extensively at the B Factories: $B \to K\ell\ell$ and $B \to K^*\ell\ell$, where $\ell = e, \mu$. While their branching fractions (Fig. 4) are comparable to the recently observed exclusive $b \to d\gamma$ decays,[3] they are experimentally cleaner and it is possible to measure ratios and asymmetries in the rates, which can usually be predicted more reliably than the branching fractions.

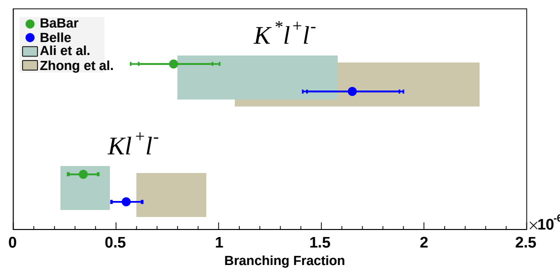

Figure 4: Comparison of Belle [24] and *BABAR* measurements [25] of the $B \to K\ell\ell$ and $B \to K^*\ell\ell$ branching fractions with two predictions from the SM, using different form factor calculations [23]. (The plot is courtesy of J. Berryhill.)

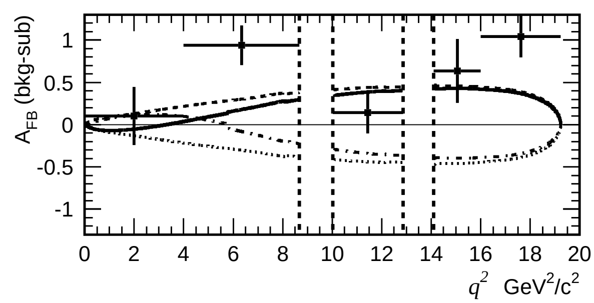

Figure 5: Forward-backward asymmetry in $B \to K^*\ell\ell$ decays as measured by the Belle Collaboration in five bins of q^2 [26]. The fit result for negative A_7 solution (solid) is shown along with some alternative choices for the signs and values of the Wilson coefficients; A_7 positive case (dashed), A_{10} positive case (dot-dashed), or both A_7 and A_{10} positive case.

Of particular interest is the forward-backward asymmetry, A_{FB}, defined for the angle of the positively charged lepton with respect to the flight direction of the B^0 or B^+ meson in the dilepton rest frame. In $B \to K^*\ell\ell$ decay, the SM predicts a distinctive pattern for this quantity as a function of q^2, but the presence of new physics can alter its sign and magnitude dramatically. A fit to A_{FB} can be used to extract the sign of C_7 and the values of C_9 and C_{10}.

Figure 5 shows the A_{FB} measurement from the Belle Collaboration, in five bins of q^2. The plot also shows the projection of the fit that has been performed

[3] Note that $B \to K\ell\ell$ is currently the lowest-branching-fraction B decay measured at better than 5σ significance.

by fixing the value of A_7 to its SM value of -0.330 and choosing A_9/A_7 and A_{10}/A_7 as fit parameters, where A_i are the leading terms in C_i. Not shown is the alternative fit in which A_7 is set to its sign-flipped value. The results of both fits, as given in Table IV, are consistent with the SM predictions. New physics scenarios with positive $A_9 A_{10}$ are excluded at 98.2% confidence.

Table IV The ratios of the Wilson coefficients obtained from the fits to the Belle A_{FB} shape in $B \to K^* \ell\ell$ decays [26]. Two independent fits have been performed, with the coefficient A_7 fixed to either its SM value (negative A_7) or fixed to its sign-flipped value. Also listed are the SM predictions for the measured ratios.

	SM value	fitted value with $A_7 = -0.33$	fitted value with $A_7 = +0.33$
A_9/A_7	-12.3	$-15.3^{+3.4}_{-4.8} \pm 1.1$	$-16.3^{+3.7}_{-5.7} \pm 1.4$
A_{10}/A_7	12.8	$10.3^{+5.2}_{-3.5} \pm 1.8$	$11.1^{+6.0}_{-3.9} \pm 2.4$

Figure 6 shows the results of the same measurement from the *BABAR* Collaboration. Similar to the Belle results, the large asymmetry observed in the high-q^2 range disfavors new physics scenarios in which the sign of the product $C_9 C_{10}$ is flipped from its SM value. For the low-q^2 range, a lower limit on the asymmetry is obtained: $A_{FB} > 0.19\%$ at 95% C.L. It should be noted that the SM prediction for this range is slightly below this lower limit [25].

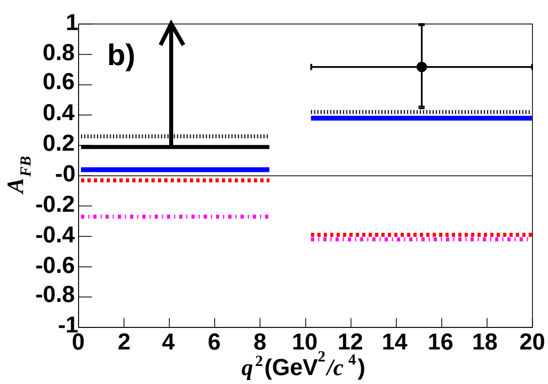

Figure 6: Forward-backward asymmetry in $B \to K^* \ell\ell$ decays as measured by the *BABAR* Collaboration in two bins of q^2 [25]. The arrow in the low-q^2 bin indicates the allowed region at 95% C.L. The SM prediction (solid) is shown, as are the predictions from C_7 sign-flipped (dotted), $C_9 C_{10}$ sign-flipped (dashed) and both C_7 and $C_9 C_{10}$ sign-flipped cases.

In addition to the A_{FB}, *BABAR* Collaboration has also measured the fraction of the longitudinal polarization, F_L, of K^*. F_L is sensitive to left-handed currents with complex phases or to right-handed currents in the photon penguin amplitude. This measurement has the potential for determining the sign of C_7 independently, however the current value is in agreement with both signs. With $1\,\mathrm{ab}^{-1}$ of data, wrong-sign C_7 could be excluded.

For $B \to K\ell\ell$, the A_{FB} prediction is zero for all q^2, both in the SM and many of its extensions. Measurements from both experiments are consistent with this prediction. In this decay, *BABAR* has also attempted to extract the fraction of (pseudo-)scalar contribution to the decay amplitude, however with the limited statistics the result is inconclusive. With more data, the developed technique will prove to be useful.

5. Conclusion

Radiative penguins have been one of the cornerstones of the search for new physics in the last decade. While the current measurements have not indicated deviations from the Standard Model, the data collected at the B Factories have significantly improved the experimental precision, putting more and more stringent constraints on the physics beyond the SM. The Wilson coefficients are now experimental observables.

The developed techniques are highly scalable. The measurements summarized in this review utilize only one-fourth to one-half of the data that is already available. Both B Factories continue running with increasing luminosities and the collected data is likely to be doubled before the end of their runs.

In addition to the direct role they play in the search for new physics, radiative penguins also provide highly-valueable auxiliary information. The heavy quark expansion parameters and the shape function derived from inclusive $b \to s\gamma$ has already been used to reduce the uncertainties in the extraction of $|V_{cb}|$ and $|V_{ub}|$. The measurement of the $b \to d\gamma$ penguin can be considered like the Δm_s of B Factories.

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