THE DECAYS $b \to s\gamma$, $b \to d\gamma$ AND $b \to s\ell^+\ell^-$ *

Stephen M. Playfer

School of Physics and Astronomy, University of Edinburgh
EH9 3JZ, Edinburgh, Scotland, UK

(Received February 2, 2010)

A review of experimental results on the radiative penguin decays $b \to s(d)\gamma$, and the electroweak penguin decays $b \to s\ell^+\ell^-$, emphasising the experimental techniques that have been used at the B factories by the BaBar and Belle collaborations. World averages are presented for branching fractions, rate asymmetries, and the angular distributions in $B \to K^*\ell^+\ell^-$. The sources of experimental uncertainties are compared with the theoretical uncertainties, and the sensitivity to new physics contributions beyond the Standard Model is briefly discussed.

PACS numbers: 13.20.He

1. Introduction and theory

These b decays provide important constraints on new physics contributions beyond the Standard Model. They are described by an Operator Product Expansion (OPE) with effective Wilson coefficients $C_i^{\rm eff}(\mu)$, evaluated at a scale $\mu \approx m_b$, which multiply flavour-changing operators O_i. For $b \to s\gamma$ the dominant operator is the electromagnetic pengiun O_7, but there are corrections from four quark operators O_1–O_6 and the gluonic penguin O_8. For $b \to s\ell^+\ell^-$ there are three important operators O_7, O_9 and O_{10}, where O_9 and O_{10} are the vector and axial-vector parts of electroweak couplings via a Z^0 penguin or a W box diagram.

The branching fraction for $b \to s\gamma$ has been calculated to NNLO with the result $(3.15 \pm 0.23) \times 10^{-4}$, where the main uncertainties come from non-perturbative power corrections, terms of $\mathcal{O}(\alpha_{\rm s}^3)$, and the b and c quark masses [1]. Additional information on the spectral shape and rate asymmetries can be used to constrain some of these corrections. The decay $b \to d\gamma$ is suppressed relative to $b \to s\gamma$ by $|V_{td}|/|V_{ts}|^2$, with corrections for weak annihilation, and for ratios of form factors in the case of exclusive decays.

* Presented at the FLAVIAnet Topical Workshop, "Low energy constraints on extensions of the Standard Model", Kazimierz, Poland, July 23–27, 2009.

For $b \to s\ell^+\ell^-$ there is a complicated behaviour as a function of dilepton mass-squared q^2. At low q^2 the operator O_7 dominates and there is a photon pole as $q^2 \to 0$ in $B \to K^*\ell^+\ell^-$. At high q^2 the electroweak operators dominate, and the partial branching fraction is proportional to $|C_9^{\rm eff}|^2 + |C_{10}^{\rm eff}|^2$, but there are significant uncertainties from $c\bar{c}$ contributions in this region. Most attention has been given to the region $1 < q^2 < 6\,{\rm GeV}^2/c^4$ where there is interference between the operators, and the angular distribution gives detailed information on the amplitudes. In particular the forward–backward dilepton asymmetry has a zero-crossing at $q^2 \approx 4\,{\rm GeV}^2/c^4$ which depends on the ratio of $C_7^{\rm eff}/C_9^{\rm eff}$ [2]. Deviations from the Standard Model predictions could provide evidence for right-handed couplings.

2. The inclusive decay $b \to s\gamma$

The first measurements of $b \to s\gamma$ were made by CLEO in the 1990s [3]. They measured photons with $2.0 < E_\gamma < 2.7$ GeV using 9/fb of Υ(4S) data and 4.4/fb of off-resonance data, and made an extrapolation to lower photon energies to quote a fully inclusive branching fraction $(3.21 \pm 0.43 \pm 0.27^{+0.18}_{-0.10}) \times 10^{-4}$, where the errors are statistical, systematic and model-dependent respectively.

Belle have just produced the single most accurate measurement from the B factories [4]. Using a data sample of 605/fb of Υ(4S) data, they measure a partial branching fraction $(3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$ for $1.7 < E_\gamma < 2.8\,{\rm GeV}$ in the B rest frame. Their emphasis has been on reducing the lower photon energy threshold to minimise the model dependence. The photons are required to not form a π^0 or η when combined with another low energy photon. Event shape variables or lepton tags are used to suppress continuum background, and then an off-resonance data sample of 68/fb is used for subtraction. The remaining backgrounds from other B decays increase rapidly at low E_γ. They are modelled using Monte Carlo, adjusted to match inclusive π^0 and η control samples from data. The statistical error on the measurement is largely due to the size of the off-resonance data sample. The dominant systematic errors come from other B decays, the scale of the off-resonance subtraction, and the signal efficiency. The photon energy spectrum after subtractions and corrections for efficiency and detector resolution is shown in Fig. 1.

BaBar has performed three independent analyses of $b \to s\gamma$, although none of them have yet been completed with the full 433/fb Υ(4S) data sample. The first analysis [5] is similar to the Belle analysis except that it requires the lepton tag for all events. This gives a smaller continuum subtraction, but the signal efficiency is only 2%. It does not suppress B backgrounds relative to signal, and the subtraction of other B decays is the dominant

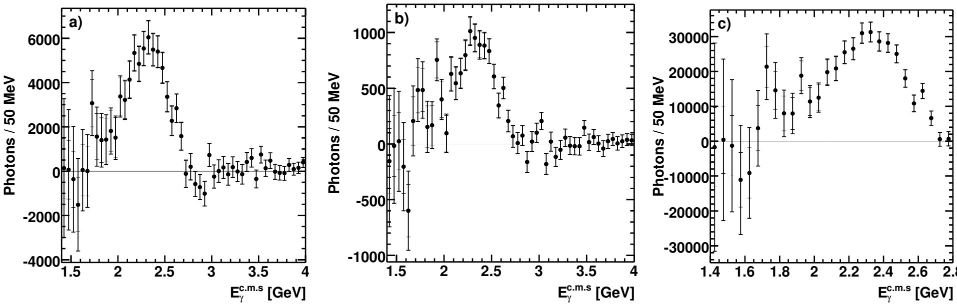

Fig. 1. Belle $b \to s\gamma$ spectrum: untagged (left), lepton-tagged (centre), combined (right). Combined plot is corrected for efficiency and resolution.

systematic error. The measured partial branching fraction using 82/fb of Y(4S) data is $(3.67 \pm 0.29 \pm 0.34 \pm 0.29) \times 10^{-4}$ for $1.9 < E_\gamma < 2.7\,\mathrm{GeV}$.

The second BaBar analysis [5] uses fully reconstructed hadronic decays of the other B in the event as tags. This removes continuum and some B backgrounds by a fit to the beam-constrained mass distribution of the tag B. The measured partial branching fraction using 210/fb of Y(4S) data is $(3.66 \pm 0.85 \pm 0.60) \times 10^{-4}$ for $1.9 < E_\gamma < 2.6\,\mathrm{GeV}$. This analysis is statistics limited at the B factories due to the 0.3% selection efficiency associated with the reconstructed B tag.

The third BaBar analysis [5] fully reconstructs a set of 38 $B \to X_s\gamma$ decays, where X_s is a hadronic system decaying to one (or three) Kaons and up to four additional pions (or etas), where only one can be a π^0 (or eta). CLEO used an early version of this approach which they called "pseudoreconstruction", but only for background suppression. The BaBar analysis explicitly measures the exclusive modes by fitting the beam-constrained B mass distribution, including corrections for the cross-feed between modes. The fit also subtracts continuum and other B backgrounds. The hadronic mass $M(X_s)$ is used to give a precise measurement of E_γ in the B rest frame, independent of the calorimeter resolution. The sum of exclusive modes can be extrapolated to an inclusive measurement using a model for the missing final states, where the X_s fragmentation is performed using JETSET, modified to match the observed distribution of the 38 reconstructed final states. The measured partial branching fraction using 82/fb of Y(4S) data is $(3.27 \pm 0.18^{+0.55+0.04}_{-0.40-0.09}) \times 10^{-4}$ for $1.9 < E_\gamma < 2.6\,\mathrm{GeV}$. This analysis has the smallest statistical error, but is already limited by the systematic error coming from the missing final states. It is hoped that this error can be improved to <10% through better understanding of the X_s fragmentation and the inclusion of more modes.

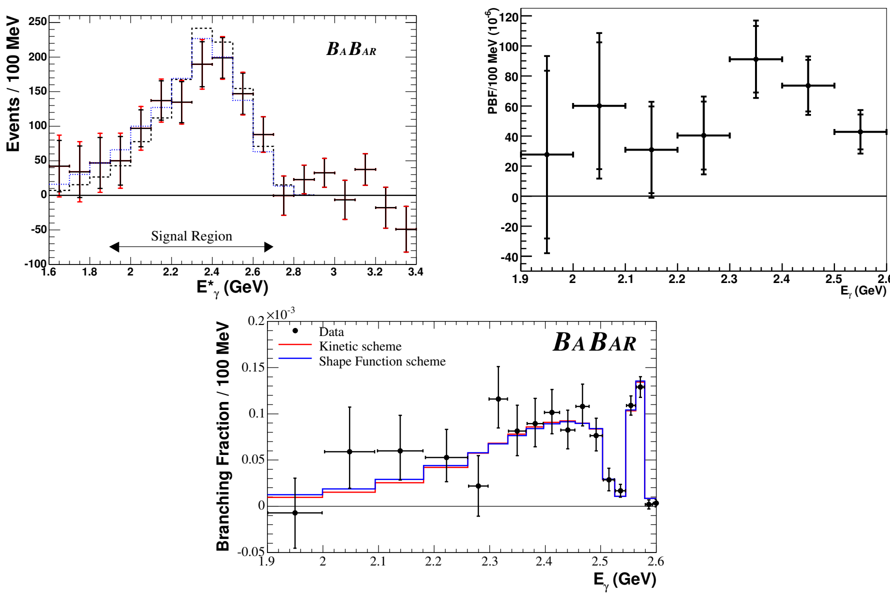

Fig. 2. BaBar $b \to s\gamma$ spectra: lepton-tagged (top-left), B-tagged (top-right), sum of exclusives (bottom). The curves are fits to kinetic and shape function models.

The shape of the photon spectrum is critical to understanding how to extrapolate to the inclusive rate from the measured partial branching fractions above a minimum photon energy threshold. The shape can be described by photon energy moments. Theoretical calculations of the spectral shape use a Heavy Quark Expansion in powers of $1/m_b$ [6]. The first moment is related to an effective b-quark mass, the second moment to a kinetic term μ_π^2, and the third moment to the Darwin term ρ_D^3. The expansion is only expected to be valid for thresholds $E_\gamma > 2.0\,\mathrm{GeV}$ and lower, and there is some debate about the level of "bias" corrections to the moments as a function of threshold. Fits to the experimental moments were made in [7]. The actual parameters vary between different schemes. In the kinetic scheme of Benson *et al.* [6] $m_b = 4.59 \pm 0.04\,\mathrm{GeV}$ and $\mu_\pi^2 = 0.40 \pm 0.04\,\mathrm{GeV}^2$. The dressed gluon exponentiation approach of Andersen, Gardi [6] uses the $\overline{\mathrm{MS}}$ mass $m_b(m_b) = 4.20 \pm 0.04\,\mathrm{GeV}$ and $\alpha_s(M_Z) = 0.118^{+0.002}_{-0.005}$. Based on the fits to data the HFAG [8] recommends a set of extrapolation factors to go from higher thresholds down to the theoretical threshold $E_\gamma > 1.6\,\mathrm{GeV}$. These are given in Table I, where we summarize the branching fraction measurements and extract world averages.

We note that the model dependence is not treated consistently in the experimental papers. They each use model parameters extracted from their data and make their own extrapolations. In principle each data sample

TABLE I

Branching fractions for $b \to s\gamma \times 10^{-4}$.

E_γ threshold	> 1.7	> 1.8	> 1.9	> 2.0
CLEO				3.06 ± 0.49
Belle	3.45 ± 0.43	3.36 ± 0.28	3.21 ± 0.19	3.02 ± 0.15
BaBar l-tag			3.67 ± 0.53	3.41 ± 0.46
BaBar B-tag			3.66 ± 0.98	3.39 ± 0.73
BaBar Σ excl.			3.27 ± 0.50	3.31 ± 0.42
World average	3.45 ± 0.43	3.36 ± 0.28	3.35 ± 0.20	3.15 ± 0.13
HFAG factor	0.985(4)	0.967(6)	0.936(12)	0.894(20)
$E_\gamma > 1.6$ GeV	3.50 ± 0.44	3.47 ± 0.29	3.58 ± 0.22	3.53 ± 0.16

should be refitted with an agreed set of world average parameters, updated to include the latest spectral shape results from Belle. Another smaller inconsistency is in the subtraction of the $b \to d\gamma$ component which is about $(4.0 \pm 1.0)\%$. This subtraction is necessary for all analyses except the BaBar sum of exclusives. There is now an experimental measurement of $b \to d\gamma$ (see below), which should be used rather than assuming the Standard Model and the CKM fit for $|V_{td}|/|V_{ts}|$.

From Table I it can be seen that the experimental error decreases rapidly as the threshold is raised, due to the reduction in the B decay background. The errors on the correction factors are smaller than this, so the most accurate value $(3.53 \pm 0.16) \times 10^{-4}$ is obtained by extrapolating from $E_\gamma > 2.0$ GeV. The consistency of the results for different thresholds confirms that there is no large uncertainty in the extrapolation factors.

3. Rate asymmetries in $b \to s\gamma$

Measuring rate asymmetries has several advantages over branching fractions. Many experimental systematic errors cancel, as do some theoretical uncertainties. In particular the branching fractions for exclusive final states are limited by knowledge of hadronic form factors, but these cancel in rate asymmetries. In the Standard Model [9], the time-integrated CP asymmetry, $A_{\rm CP}(b \to s\gamma)$ is expected to be $< 1\%$, and the combined asymmetry $A_{\rm CP}(b \to (s+d)\gamma)$ is exactly zero. The isospin asymmetry $A_{\rm I}(b \to s\gamma)$ is predicted to be $(8 \pm 3)\%$. These asymmetries have been shown to give additional constraints on New Physics, beyond those coming from the inclusive branching fraction [9].

There are new precise measurements of the exclusive decays $B \to K^*\gamma$ from BaBar using 347/fb of data [10]. They measure $A_{\rm CP}(K^*\gamma) = -0.003 \pm 0.017 \pm 0.007$ and $A_{\rm I}(K^*\gamma) = +0.066 \pm 0.021 \pm 0.022$, improving on previous measurements by a factor of two. The BaBar lepton-tagged analysis [5] constrained $A_{\rm CP}(b \to (s+d)\gamma) = -0.11 \pm 0.12$, and both BaBar and Belle have used sums of exclusive final states [11], to give a world average $A_{\rm CP}(b \to s\gamma) = -0.012 \pm 0.028$.

There has been a lot of interest in measurements of time-dependent CP asymmetries in $b \to s\gamma$. In the Standard Model the quark coupling to the photon is predominantly left-handed, with the right-handed component suppressed by $\approx m_s/m_b$. To generate a significant $A_{\rm CP}(t)$ requires interference between mixing and decay amplitudes with CP eigenstates, which can only happen if there are some right-handed quark (and left-handed antiquark) couplings. Standard Model calculations, including gluonic corrections, give a $\sin(\Delta m_d t)$ amplitude $S = 0.029 \pm 0.015$ [12].

The experimental challenge is to measure $A_{\rm CP}(t)$ in $B \to K^*\gamma$ with $K^{*0} \to K_S\pi^0$, using information from the $K_S \to \pi^+\pi^-$ decay to extrapolate back to the B decay vertex. This has been done by both BaBar and Belle [13] using their precision vertex detectors. The world average sine and cosine coefficients are $S = -0.16 \pm 0.22$ and $C = -0.04 \pm 0.14$. There have also been measurements in $K_S\rho^0\gamma$ and $\rho^0\gamma$ by Belle, and in $K_S\eta\gamma$ by BaBar, but these are very limited in statistics. All of the measurements of rate asymmetries are limited by statistical errors, and need much larger data samples to reach the theoretical predictions.

4. The radiative decay $b \to d\gamma$

The exclusive decays $B \to \rho\gamma$ have been observed by both BaBar and Belle [14], with a combined significant of $> 6\sigma$ in each experiment, and there is also evidence for $B \to \omega\gamma$ at the expected level. A difference between the two experiments is the $K \to \pi$ fake rate of 1% (BaBar) and 8% (Belle) which leads to backgrounds from $B \to K^*\gamma$. However, the dominant background is from the continuum, which is suppressed using event shape variables.

Theoretically, the ratio of the decays $B \to \rho\gamma$ and $B \to K^*\gamma$ can be related to $|V_{td}|/|V_{ts}|$ by [15]:

$$\frac{{\rm BF}(B \to \rho\gamma)}{{\rm BF}(B \to K^*\gamma)} = S_\rho \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - m_\rho^2/m_B^2}{1 - m_{K*}^2/m_B^2}\right) \zeta^2 \left[1 + \Delta R\right] , \qquad (1)$$

where $S_\rho = 1(0.5)$ for $\rho^+(\rho^0)$, ζ is a ratio of form factors, and ΔR accounts for weak annihilation and gluonic corrections. Table II summarises the experimental results and uses the theoretical predictions to obtain $|V_{td}|/|V_{ts}| = 0.21 \pm 0.03$, from the isospin averaged branching fractions. The experimental errors are mostly statistical, but they are already comparable to the theoretical uncertainties. The results from $B \to \rho\gamma$ are completely consistent with $|V_{td}|/|V_{ts}| = 0.209 \pm 0.001 \pm 0.006$ from B_d/B_s mixing [16].

TABLE II

Branching fractions for $B \to \rho(\omega)\gamma \times 10^{-6}$ and $|V_{td}|/|V_{ts}|$.

Decay	BaBar	Belle	Average	Theory	$\lvert V_{td}\rvert/\lvert V_{ts}\rvert$
$\rho^+\gamma$	1.20 ± 0.45	0.87 ± 0.30	1.03 ± 0.27	1.38 ± 0.25	0.18 ± 0.03
$\rho^0\gamma$	0.97 ± 0.22	0.78 ± 0.18	0.88 ± 0.15	0.67 ± 0.15	0.24 ± 0.03
$\omega\gamma$	0.50 ± 0.27	0.40 ± 0.22	0.45 ± 0.18	0.50 ± 0.10	0.19 ± 0.04
$\rho\gamma$	1.73 ± 0.37	1.21 ± 0.26	1.47 ± 0.23	1.36 ± 0.27	0.21 ± 0.03
$\rho(\omega)\gamma$	1.63 ± 0.33	1.14 ± 0.23	1.39 ± 0.20	1.28 ± 0.26	0.21 ± 0.03

The isospin asymmetry in $B \to \rho\gamma$ deserves some comment. In the literature there is confusion in the definition of this asymmetry between $A_{\rm I} = 2\Gamma(\rho^0)/\Gamma(\rho^+) - 1$ (Belle) and $A_{\rm I} = \Gamma(\rho^+)/2\Gamma(\rho^0) - 1$ (BaBar and most theory papers). Neither of these is consistent with the definition used for $B \to K^*\gamma$, so I will define:

$$A_{\rm I} = \frac{2\Gamma(\rho^0) - \Gamma(\rho^+)}{2\Gamma(\rho^0) + \Gamma(\rho^+)}\,. \tag{2}$$

This gives $A_{\rm I} = +0.27 \pm 0.15 \pm 0.06$ (BaBar) and $A_{\rm I} = +0.32 \pm 0.26 \pm 0.11$ (Belle). The theoretical expectation is a few %, with a strong dependence on the CKM angle γ which enters through the weak annihilation contribution. Asymmetries as large as the experimental central values are not expected within the Standard Model or extended Minimal Flavour Violation [17].

BaBar has recently made the first study of inclusive $b \to d\gamma$ [18], using a sum of 7 exclusive final states. The partial branching fraction for $M(X_d) < 1.8\,\text{GeV}$ is $(7.2 \pm 2.7 \pm 2.3) \times 10^{-6}$. As with the equivalent $b \to s\gamma$ analysis the systematic error is largely due to missing final states. This error partially cancels in the ratio:

$$\frac{\Gamma(b \to d\gamma)}{\Gamma(b \to s\gamma)} = 0.033 \pm 0.013 \pm 0.009\,. \tag{3}$$

This corresponds to $|Vtd|/|Vts| = 0.177 \pm 0.043$, and the theoretical uncertainties are expected to be smaller than in the ratio of exclusive decays.

5. The electroweak decay $b \to s\ell^+\ell^-$

The published results on inclusive $b \to s\ell^+\ell^-$ are based on data samples of only 82/fb (BaBar) and 140/fb (Belle) [19]. Both experiments use sums of exclusive final states with 1 Kaon and up to 2π (BaBar) or 4π (Belle) and either e^+e^- or $\mu^+\mu^-$. The dilepton mass range is $m(\ell\ell) > 0.2\,\text{GeV}/c^2$

to remove the photon pole in $b \to se^+e^-$, and vetos are applied to remove J/ψ and ψ' contributions. For electrons bremsstrahlung recovery of final state photons is attempted. The measured inclusive branching fractions are $(5.6 \pm 1.5 \pm 1.3) \times 10^{-6}$ (BaBar) and $(4.1 \pm 0.8 \pm 0.8) \times 10^{-6}$ (Belle), where the dominant systematic errors are associated with the model of the X_s spectrum and the missing final states. Within the limited statistics, the $m(\ell\ell)$ and $M(X_s)$ spectra are consistent with expectations. The Standard Model prediction for the inclusive branching fraction is $(4.2 \pm 0.7) \times 10^{-6}$. Even with limited statistics, the data already rule out a wrong-sign C_7^{eff} at the 3σ level [20]. At Lepton–Photon 2009, T. Iijima presented preliminary results from Belle with larger statistics, giving an inclusive rate $(3.3 \pm 0.8 \pm 0.2) \times 10^{-6}$, which more strongly rules out wrong-sign C_7^{eff}.

The exclusive decays $B \to K\ell\ell$ and $B \to K^*\ell\ell$ have been measured by BaBar, Belle and CDF [21]. The three experiments agree well on the branching fractions, with world averages $\mathcal{B}(B \to K\ell\ell) = (4.8 \pm 0.5) \times 10^{-7}$ and $\mathcal{B}(B \to K^*\ell\ell) = (10.4 \pm 1.1) \times 10^{-7}$. The di-lepton mass-squared distributions have been measured in six bins by Belle (Fig. 3), and found to be consistent with the Standard Model predictions within the form factor uncertainties [2], which are comparable to the experimental uncertainties.

Rate asymmetries have been studied by BaBar and Belle [21]. As expected in the Standard Model there is no evidence for significant CP asymmetries, $A_{\text{CP}}(B \to K\ell\ell) = -0.04 \pm 0.09$ and $A_{\text{CP}}(B \to K^*\ell\ell) = -0.06 \pm 0.09$, or for a lepton flavour asymmetry between muons and electrons (ignoring the photon pole in $K^*e^+e^-$). However, there are controversial results on the isospin asymmetries, with BaBar claiming $> 3\sigma$ evidence for large asymmetries at low q^2. Belle does not see these, but nor do they rule them out. Table III summarizes the results for A_{I}, with the world averages still being $> 3\sigma$ from zero in the low q^2 region for both $K\ell\ell$ and $K^*\ell\ell$. In the Standard Model only a small positive A_{I} is expected in $K^*\ell\ell$ near the photon pole, similar to $K^*\gamma$.

TABLE III

Isospin asymmetries A_{I}: low and high q^2 are separated by the J/ψ veto.

Mode	q^2	BaBar	Belle	Average
$K\ell^+\ell^-$	low	$-1.43^{+0.56}_{-0.85} \pm 0.05$	$-0.31 \pm 0.16 \pm 0.05$	-0.53 ± 0.18
	high	$+0.28 \pm 0.27 \pm 0.03$	$-0.11 \pm 0.19 \pm 0.05$	$+0.06 \pm 0.16$
$K^*\ell^+\ell^-$	low	$-0.56 \pm 0.16 \pm 0.03$	$-0.29 \pm 0.16 \pm 0.03$	-0.42 ± 0.11
	high	$+0.18 \pm 0.32 \pm 0.04$	$+0.03 \pm 0.14 \pm 0.05$	$+0.08 \pm 0.14$

The angular distributions in $B \to K^*\ell\ell$ have been fitted by BaBar and Belle [21] to determine the K^* longitudinal polarisation fraction $F_{\rm L}$ and the dilepton forward–backward asymmetry $A_{\rm FB}$. BaBar makes fits in two bins, $q^2 < 6.25\,{\rm GeV}^2/c^4$ and $q^2 > 10.24\,{\rm GeV}^2/c^4$, below and above the J/ψ veto region. Belle with a larger data sample makes fits in six bins (Fig. 3). The experiments are consistent with each other, and the world averages are $F_{\rm L} = 0.47 \pm 0.12$ and $A_{\rm FB} = +0.33 \pm 0.13$ in the low q^2 region, and $F_{\rm L} = 0.22 \pm 0.09$ and $A_{\rm FB} = +0.62 \pm 0.10$ in the high q^2 region. These are to be compared with Standard Model expectations of $F_{\rm L} = 0.63$ and $A_{\rm FB} = -0.03$ (low q^2), and $F_{\rm L} = 0.40$ and $A_{\rm FB} = +0.38$ (high q^2). In the low q^2 region $A_{\rm FB}$ is shifted positive in all the measured bins which is more consistent with a reversed sign $C_7^{\rm eff}$, but the discrepancy with the Standard Model is still less than 3σ. In the high q^2 region $A_{\rm FB}$ is large and positive, ruling out a significant contribution from right-handed currents. At present the experimental errors are mainly statistical and significantly larger than the theoretical uncertainties.

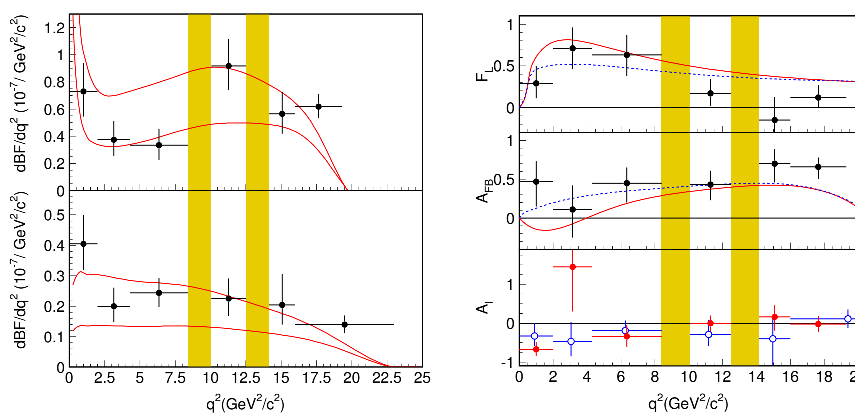

Fig. 3. Belle results for $B \to K^{(*)}\ell\ell$. Left: partial branching fractions for $K^*\ell\ell$ (top) and $K\ell\ell$ (bottom), where the curves show the range of Standard Model predictions. Right: angular fits to $K^*\ell\ell$ for $F_{\rm L}$ (top) and $A_{\rm FB}$ (middle), where the curves show predictions from the Standar Model (red full) and for reversed sign $C_7^{\rm eff}$ (blue dotted). The bottom right plot shows isospin asymmetries for $K^*\ell\ell$ (red closed) and $K\ell\ell$ (blue open).

6. Conclusion and forward look

The B factories have improved the accuracy of $b \to s\gamma$ by a factor of three, and have made the first observations of $b \to d\gamma$ and $b \to s\ell^+\ell^-$. This opens up the possibility of precision tests of flavour couplings with larger data samples. There are proposals for Super B factories at KEK and Frascati which aim at luminosities of 10^{36}cm^{-2}s^{-1}, and integrated Y(4S) samples 100× larger than BaBar and Belle. In the near future the LHCb experiment will be particularily suited to measuring the rare decays $B \to K^{*0}\mu^+\mu^-$ and $B_s \to \mu^+\mu^-$. In the case of $B \to K^{*0}\mu^+\mu^-$ the statistics should exceed BaBar and Belle after about 200/pb, and reach 10/fb after a few years. This is sufficient for a full angular analysis of $B \to K^{*0}\mu^+\mu^-$ [22], and for an observation of $B_s \to \mu^+\mu^-$ at the Standard Model level of 3.4×10^{-9}. LHCb should also be able to make rate asymmetry measurements in exclusive radiative decays such as $B_s \to \phi\gamma$ [22].

REFERENCES

[1] M. Misiak *et al., Phys. Rev. Lett.* **98**, 022002 (2007).

[2] A. Ali *et al., Phys. Rev.* **D61**, 074024 (2000); F. Krüger, J. Matias, *Phys. Rev.* **D71**, 094009 (2005); K.S.M. Lee *et al., Phys. Rev.* **D75**, 034016 (2007); C. Bobeth, G. Hiller, G. Piranishvili, *J. High Energy Phys.* **0712**, 40 (2007); W. Altmannshofer *et al.*, `arXiv:0811.1214`.

[3] M.S. Alam *et al., Phys. Rev. Lett.* **74**, 2885 (1995); S. Chen *et al., Phys. Rev. Lett.* **87**, 251807 (2001).

[4] A. Limosani *et al.*, `arXiv:0907.1384`.

[5] B. Aubert *et al., Phys. Rev. Lett.* **97**, 171803 (2006); B. Aubert *et al., Phys. Rev.* **D77**, 051003 (2008); B. Aubert *et al., Phys. Rev.* **D72**, 052004 (2005).

[6] A. Kagan, M. Neubert, *Eur. Phys. J.* **C7**, 5 (1999); D. Benson, I. Bigi, N. Uraltsev, *Nucl. Phys.* **B710**, 371 (2005); M. Neubert, *Phys. Rev.* **D72**, 074025 (2005); J. Andersen, E. Gardi, *J. High Energy Phys.* **0701**, 029 (2007).

[7] O. Büchmuller, H. Flächer, *Phys. Rev.* **D73**, 073008 (2006); C. Schwanda *et al., Phys. Rev.* **D78**, 032016 (2008).

[8] [Heavy Flavour Averaging Group] E. Barberio *et al.*, `arXiv:0808.1297`.

[9] A. Kagan, M. Neubert, *Phys. Rev.* **D58**, 094012 (1998); A. Kagan, M. Neubert, *Phys. Lett.* **B539**, 227 (2002); M.R. Ahmady, F. Mahmoudi, *Phys. Rev.* **D75**, 015007 (2007).

[10] B. Aubert *et al.*, `arXiv:0906.2177`.

[11] S. Nishida *et al., Phys. Rev. Lett.* **93**, 031803 (2004); B. Aubert *et al., Phys. Rev. Lett.* **100**, 171804 (2008).

[12] M. Matsumori, A.I. Sanda, *Phys. Rev.* **D73**, 114072 (2006); P. Ball, R. Zwicky, *Phys. Lett.* **B642**, 478 (2006).

[13] Y. Ushiroda *et al., Phys. Rev.* **D74**, 111104 (2006); B. Aubert *et al., Phys. Rev.* **D78**, 071102 (2008).

[14] B. Aubert *et al., Phys. Rev.* **D78**, 112001 (2008); N. Taniguchi *et al., Phys. Rev. Lett.* **101**, 111801 (2008).

[15] S.W. Bosch, G. Buchalla, *Nucl. Phys.* **B621**, 459 (2002); A. Ali, A.Y. Parkhomenko, `arXiv:061049`; P. Ball, G.W. Jones, R. Zwicky, *Phys. Rev.* **D75**, 054004 (2007).

[16] [Particle Data Group] C. Amsler *et al.*, *Phys. Lett.* **B667**, 1 (2008).

[17] A. Ali, E. Lunghi, *Eur. Phys. J.* **C26**, 195 (2002).

[18] B. Aubert *et al., Phys. Rev. Lett.* **102**, 161803 (2009).

[19] B. Aubert *et al., Phys. Rev. Lett.* **93**, 081802 (2004); M. Iwasaki *et al., Phys. Rev.* **D72**, 092005 (2005).

[20] A. Ali *et al., Phys. Rev.* **D66**, 034002 (2002); P. Gambino, U. Haisch, M. Misiak, *Phys. Rev. Lett.* **94**, 061803 (2005).

[21] B. Aubert *et al., Phys. Rev. Lett.* **102**, 091803 (2009); B. Aubert *et al., Phys. Rev.* **D79**, 031102 (2009); J.T. Wei *et al.*, `arXiv:0904.0770`, submitted to *Phys. Rev. Lett.*; T. Aaltonen *et al., Phys. Rev.* **D79**, 011104 (2009).

[22] U. Egede, W. Reece, CERN-LHCB-2008-041 (2009); F. Muheim, Y. Xie, R. Zwicky, *Phys. Lett.* **B664**, 174 (2008).