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Rare decays at the B factories

K. Nishimura on behalf of the Belle and BaBar Collaborations

Department of Physics and Astronomy, University of Hawai'i at Mānoa
Honolulu, Hawai'i, USA

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Summary. — Over the past ten years, the Belle and BaBar B factories have collected datasets with a combined total of over a billion $B\overline{B}$ pairs. This enormous amount of data has allowed a number of rare B meson decays to be studied in increasing detail. We review some recent results from Belle and BaBar on rare B decays, focusing on those that involve radiative, electroweak, and hadronic penguin processes.

PACS 13.20.He – Leptonic, semileptonic, and radiative decays of bottom mesons.
PACS 13.25.Hw – Hadronic decays of bottom mesons.

1. – Introduction

The two B factories, Belle at the KEKB collider at KEK, Japan, and BaBar at the PEP-II collider at SLAC, USA, have collected data sets with approximately 770 million and 470 million $B\overline{B}$ pairs, respectively. In addition to fulfilling their primary purpose, confirmation of the Kobayashi-Maskawa mechanism of CP violation [1], the large accumulated statistics and the clean experimental environments afforded by a lepton collider have allowed a number of increasingly precise studies into rare decays of the B meson. We focus in these proceedings on selected charmless B meson decays involving three types of penguin transitions: radiative penguins that probe the $b \to s\gamma$ process, the electroweak penguin processes $b \to s\ell^+\ell^-$ and $b \to s\nu\overline{\nu}$, and hadronic penguins with η or η' mesons in the final state. As all of these processes involve loop transitions, they may be influenced by amplitudes that include new particles outside of the Standard Model (SM). As such, measurements of these decays serve as searches for new physics and provide constraints on its origin. For each class of decays, we discuss both inclusive measurements and their exclusive counterparts. The inclusive studies are typically prone to higher experimental uncertainties, but can be compared with more precise theoretical expectations for their rates. The rates for the complimentary exclusive channels can usually be measured more precisely experimentally, but the corresponding theoretical predictions suffer from large hadronic uncertainties, making ratios, asymmetries, and angular observables more powerful discriminators of new physics.

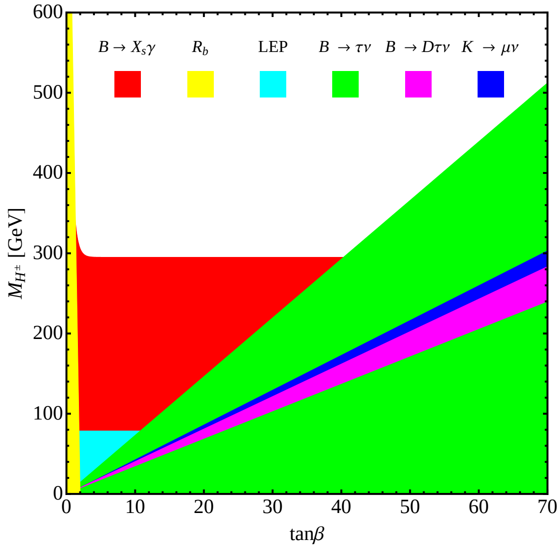

Fig. 1. – Direct and indirect bounds on $M_{H^\pm}$ in the type II two-Higgs doublet model. Plot is from ref. [10].

2. – Radiative penguins

The $b \to s\gamma$ transition provides a rich environment for both precision tests of the SM and searches for new physics. Experimental measurements of the inclusive branching fraction can be compared to precise theoretical SM predictions, while the exclusive $b \to s\gamma$ processes can serve as valuable tools to test hadronization models used by Monte Carlo generators, as well as search for anomalous asymmetries for which the SM theoretical expectations are much more constrained.

Measurements of the inclusive $B \to X_s\gamma$ process have been conducted by CLEO, BaBar, and Belle [2-6]. The most recent is a fully inclusive analysis by Belle [7] in which only the high energy photon is reconstructed and the signal is obtained by subtracting the photon spectrum of scaled off-resonance data ($68\,\text{fb}^{-1}$) from that of the on-resonance data ($605\,\text{fb}^{-1}$). The spectra from analysis streams with and without a lepton tag from the other B in the event are combined to improve the overall sensitivity. After the statistical correlations between the two streams are properly accounted for, the final branching fraction is measured over the photon energy range from 1.7 to 2.8 GeV as $\mathcal{B}(B \to X_s\gamma) = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$. This analysis has the lowest photon energy thresholds of all $b \to s\gamma$ analyses performed to date. Since the latest theoretical predictions are valid for $E_\gamma > 1.6\,\text{GeV}$, this reduction in the lower energy threshold helps to minimize theoretical uncertainties in extrapolating to the appropriate energy range. The result is consistent both with previous measurements and SM expectations [8, 9]. This measurement places very strong constraints on some new physics models. For example, in the type II two-Higgs doublet model, the measured $B \to X_s\gamma$ branching fraction imposes a limit on the charged Higgs mass of $M_{H^\pm} > 295\,\text{GeV}/c^2$ at the 95% confidence level [10]. It is especially notable that unlike many other decay modes, this limit is independent of $\tan\beta$, as demonstrated in fig. 1.

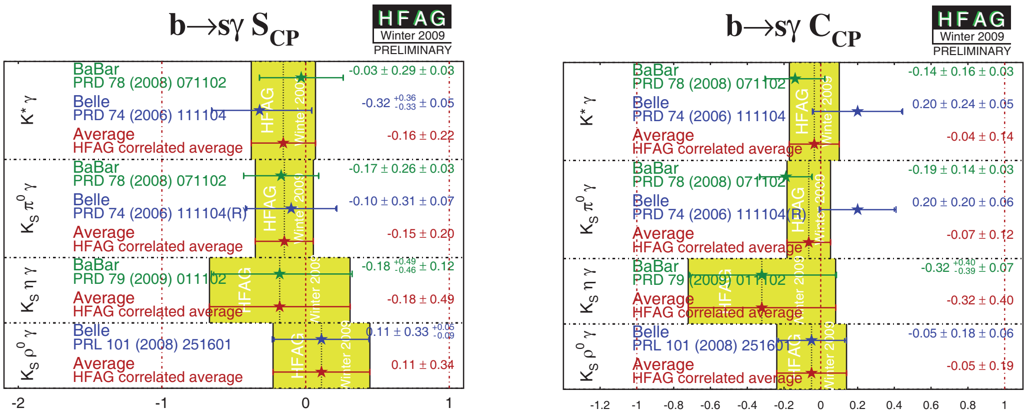

Fig. 2. – Measured time-dependent CP violating parameters S (left) and C (right) for exclusive $b \to s\gamma$ decays. Plot is from ref. [13].

In the exclusive $b \to s\gamma$ channels, the BaBar Collaboration has produced the most precise branching fraction measurement to date for $B \to K^*\gamma$ using a data sample of 383×10^6 $B\overline{B}$ pairs [11], improving upon its previous branching fraction measurement as well as those of CLEO and Belle. The measured branching fractions are $\mathcal{B}(B^0 \to K^{*0}\gamma) = (4.47 \pm 0.10 \pm 0.16) \times 10^{-5}$ and $\mathcal{B}(B^+ \to K^{*+}\gamma) = (4.22 \pm 0.14 \pm 0.16) \times 10^{-5}$. These and previous measurements are already in agreement with, and more precise than, theoretical estimates of the SM expectation. Predictions for the isospin asymmetry, Δ_{0-}, and the direct CP asymmetry, $\mathcal{A}$, are considerably more precise, and are between 2–10% for Δ_{0-} and approximately 1% for $\mathcal{A}$. BaBar has measured these parameters and finds $\Delta_{0-} = 0.066 \pm 0.021 \pm 0.022$ and $\mathcal{A} = -0.003 \pm 0.017 \pm 0.007$, both consistent with theoretical expectations.

In the SM, the $b \to s\gamma$ process produces a photon with polarizations strongly correlated with the b flavor, *i.e.* b decays produce primarily right-handed photons, and $\overline{b}$ decays produce primarily left-handed photons, with the alternate production mechanisms suppressed by a factor of m_s/m_b. In some new physics models, such as the left-right symmetric model, right-handed currents enhance the rate of these suppressed transitions, leading to the potential for mixing-induced CP violation in $b \to s\gamma$ processes, which is otherwise negligible for $b \to s\gamma$ modes in the SM.

A number of searches for such right-handed currents have been conducted. CP violating parameters for these modes are summarized in fig. 2. One of the most recent is a BaBar measurement of CP violating asymmetries in $B \to K\eta\gamma$ using 465×10^6 $B\overline{B}$ pairs [12]. The CP asymmetries of this and all other modes measured to date are consistent with zero. It is obvious from fig. 2 that significantly improved statistics will be required to find any possible CP violation in these modes.

Other exclusive $b \to s\gamma$ decays are being studied that could ultimately be used for new searches for right-handed currents. Belle has found first evidence for the decay $B^+ \to K^+\eta'\gamma$ with a branching fraction of $\mathcal{B}(B^+ \to K^+\eta'\gamma) = (3.6 \pm 1.2 \pm 0.4) \times 10^{-6}$ [14]. However, the analysis was only able to place an upper limit on the neutral mode, with branching fraction $\mathcal{B}(B^+ \to K^0_S\eta'\gamma) \leq 6.4 \times 10^{-6}$ at the 90% confidence level. This analysis uses 657×10^6 $B\overline{B}$ pairs. As this is approximately 85% of the full Belle data sample, no study of time-dependent CP violation parameters is likely to be possible,

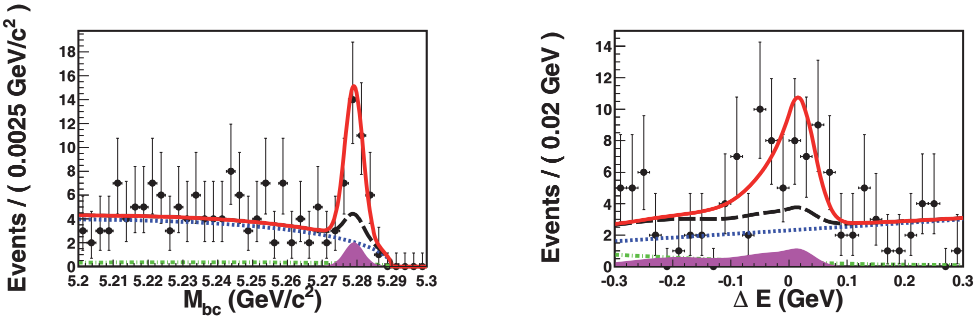

Fig. 3. – (Colour on-line) Fit projections for the Belle $B^0 \to \phi K^0_S \gamma$ analysis. (Left) The beam constrained mass, $M_{\rm bc}$, and (right) the energy difference, ΔE. In both plots, points with errors are data and the curves correspond to the total fit function (solid red), the total background function (long-dashed black), the continuum background (dotted blue), the generic $b \to c$ backgrounds (dash-dotted green), and non-resonant and other charmless backgrounds (filled magenta).

even with the entirety of Belle data. The mode $B \to \phi K \gamma$ is also being studied by Belle with 772×10^6 $B\overline{B}$ pairs. Belle has reported first observation of $B^0 \to \phi K^0_S \gamma$ with 5.4σ significance, with branching fraction $\mathcal{B}(B^0 \to \phi K^0_S \gamma) = (2.66 \pm 0.60 \pm 0.32) \times 10^{-6}$ [15]. The fitted projections for the neutral mode are shown in fig. 3. This analysis has enough events to allow for a time-dependent CP study, and this result is expected soon.

3. – Electroweak penguins

Like $b \to s\gamma$, the electroweak penguin processes $b \to s\ell^+\ell^-$ and $b \to s\nu\overline{\nu}$ can be used to probe for contributions from new physics. Predictions for the branching fraction of the exclusive channels $B \to K^{(*)}\ell^+\ell^-$ suffer from large hadronic uncertainties, making it difficult to compare them precisely with the recent data from Belle and BaBar [16,17], though they are consistent within the experimental and theoretical errors. Predictions for the lepton flavor ratio, $R_{K^{(*)}}$ are better constrained, and no deviation from the SM is seen.

Other tests of the SM can be performed using the angular observables: the forward-backward asymmetry, $A_{\rm FB}$, and longitudinal polarization fraction, F_L of the K^* mode. Results from Belle [16] and BaBar [18] can be found in fig. 4. Of particular interest are the results for $A_{\rm FB}$ and F_L, where both the Belle and BaBar data hint at a deviation from the SM, such as a model in which the Wilson coefficient C_7 is of opposite sign to the usual SM convention, though this deviation is subject to large experimental errors.

The isospin asymmetry, A_I, has also been a topic of interest, as a measurement by BaBar [19] indicated a deviation from the null value (and SM expectation) at a level of 3.9σ for the combination of the K^* and K modes. However, the recent Belle data shows no significant asymmetry. These results are also shown in fig. 4.

To gain further insight, one can examine the branching fraction of the inclusive mode $B \to X_s\ell^+\ell^-$, as this decay rate is enhanced if C_7 is of opposite sign [20]. A recent Belle measurement of this decay using the technique of a sum-of-exclusive modes shows no obvious enhancement [21]. Rather, the measured branching fraction in the range $q^2 > (0.2\,{\rm GeV}/c)^2$ is $\mathcal{B}(B \to X_s\ell^+\ell^-) = (3.33 \pm 0.80^{+0.19}_{-0.24}) \times 10^{-6}$, which is consistent within uncertainties with the SM prediction of $\mathcal{B}_{\rm SM}(B \to X_s\ell^+\ell^-) = (4.2 \pm 0.7) \times 10^{-6}$.

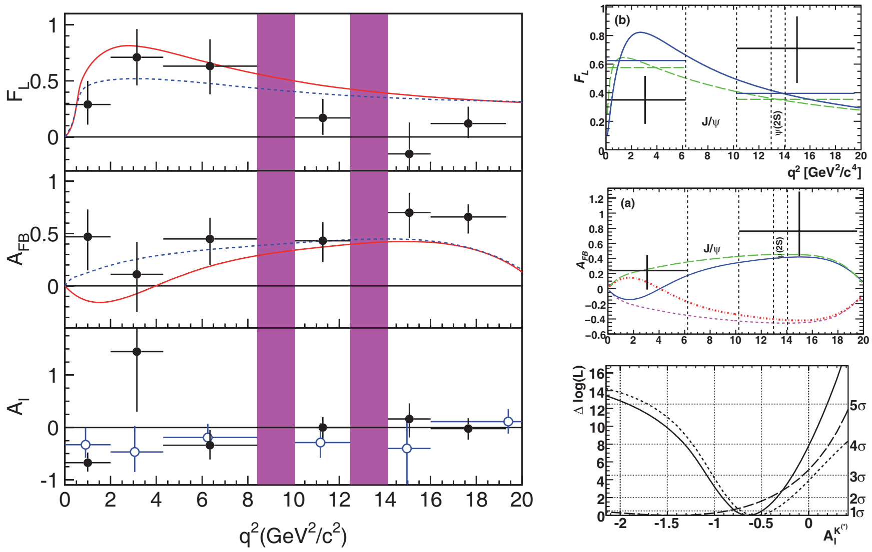

Fig. 4. – Distributions of F_L, $A_{\rm FB}$, and A_I for Belle (left) and BaBar (right). For the Belle result, the open (filled) points with errors correspond to $B \to K^{(*)}\ell^+\ell^-$. The solid curves correspond to the SM expectation, and the dotted lines represent the expectation when $C_7 = -C_7$. The solid bands are veto regions for the J/ψ and $\psi(2S)$. For the BaBar data, the points with errors in F_L and $A_{\rm FB}$ are the data for $B \to K^*\ell^+\ell^-$, and the curves correspond to the expectations with the SM (solid), $C_7 = -C_7$ (long dashed), $C_9C_{10} = -C_9C_{10}$ (short dashed), and both $C_7 = -C_7$ and $C_9C_{10} = -C_9C_{10}$ (dash-dotted). In the BaBar A_I plot, the likelihood profiles correspond to $B \to K^*\ell^+\ell^-$ (dashed), $B \to K\ell^+\ell^-$ (long dashed), and the two modes combined (solid).

The decay $B \to K\nu\overline{\nu}$ is theoretically similar to $b \to s\ell^+\ell^-$, providing another rare electroweak penguin to test against SM predictions. Previous measurements have been able to set only an upper limit on this process, with Belle setting the lowest limits of $\mathcal{B}(B^+ \to K^+\nu\overline{\nu}) < 1.4 \times 10^{-5}$ and $\mathcal{B}(B^0 \to K^0\nu\overline{\nu}) < 16 \times 10^{-5}$ [22]. BaBar has recently improved [23] on both of these limits with a multivariate analysis using bagged decision trees [24]. They find, using a data sample of $459 \times 10^6 B\overline{B}$ events, improved upper limits of $\mathcal{B}(B^+ \to K^+\nu\overline{\nu}) < 1.3 \times 10^{-5}$ and $\mathcal{B}(B^0 \to K^0\nu\overline{\nu}) < 5.6 \times 10^{-5}$. Unfortunately, these limits remain significantly above the SM expectation of $\mathcal{B}(B \to K\nu\overline{\nu}) = (3.8^{+1.2}_{-0.6}) \times 10^{-6}$.

4. – Hadronic penguins

B decays to modes with the η and η' have long been a subject of significant activity. These modes are characterized by interference patterns in their dominant amplitudes, and have a history of unexpectedly large decay rates.

BaBar has recently reported first observation of $B^+ \to \eta'\rho^+$ and $B^{(0,+)} \to \eta' K_2^*(1430)^{(0,+)}$, as well as evidence for $B^{(0,+)} \to \eta' K^{*(0,+)}$. The fitted distributions for this analysis can be seen in fig. 5. The analysis includes branching fractions and CP asymmetries, and uses the full BaBar data sample of $467 \times 10^6 B\overline{B}$ pairs [25]. No significant CP asymmetry is observed in any mode. However, the branching fractions for $B \to \eta' K_2^*(1430)$ show an unexpected enhancement over the $B \to \eta' K^*$ modes. Further, results from the $B^+ \to \eta'\rho^+$ channel seem to be more consistent with SM predictions us-

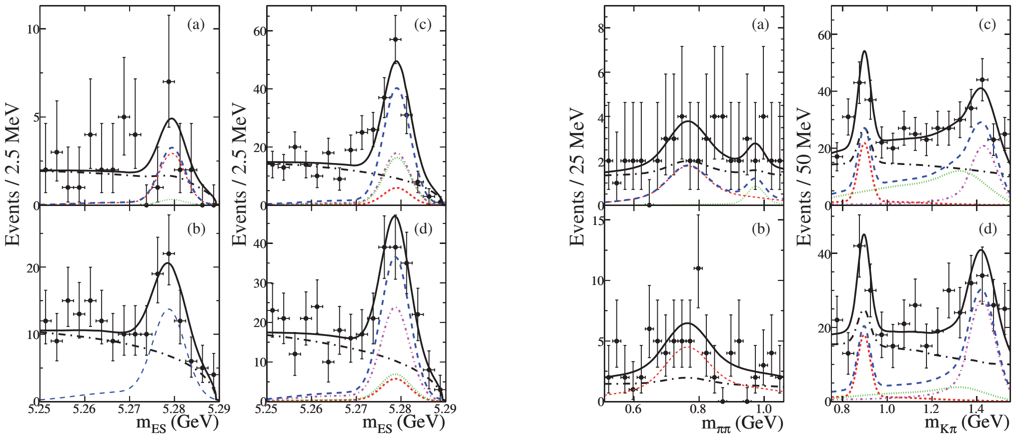

Fig. 5. – (Colour on-line) (Left) BaBar's projections of B candidate energy substituted mass, m_{ES} for (a) $\eta'\rho^0/\eta' f_0$, (b) $\eta'\rho^+$, (c) $\eta' K^{*0}$, and (d) $\eta' K^{*+}$. The solid curve is the fit function, black long-dash-dotted curve is the total background, and the blue dashed curve is the total signal contribution. For (a), the red dashed curve is the ρ^0 component and the green dotted curve is the f_0 component. In (c) and (d) the red dashed curve is $K^*(892)$ component, the green dotted is the $(K\pi)^*_0$ component, and the magenta dot-dashed is the $K^*_2(1430)$ component. (Right) The corresponding projections of $m_{\pi\pi}$ in (a) and (b), and $m_{K\pi}$ in (c) and (d). The letter and color codes are the same as for the m_{ES} distributions.

ing perturbative QCD and QCD factorization compared to those made with soft collinear effective theory (SCET), a result which may help to guide future theoretical work in these areas.

In the inclusive sector, Belle recently reported first observation of the inclusive process $B \to X_s\eta$, using a sum-of-exclusive modes method over $657 \times 10^6 B\overline{B}$ pairs [26]. The X_s mass spectrum, seen in fig. 6 contains known contributions, such as those from $B \to K\eta$ and $B \to K^*\eta$. In the higher mass regions, fit projections of which are shown in fig. 6, there are signals around the $K^*_{(0,2)}(1430)$ region, which was previously observed as an exclusive mode by BaBar [27] and for which no theoretical expectation has yet been calculated, as well as significant signal in the region $M_{X_S} > 1.8\,\mathrm{GeV}/c^2$, which was previously unobserved, and for which no predictions are currently available.

The result for the entire measured mass spectrum, $M_{X_s} < 2.6\,\mathrm{GeV}/c^2$, is $\mathcal{B}(B \to X_s\eta) = (25.5 \pm 2.7\ (\mathrm{stat.}) \pm 1.6\ (\mathrm{syst.})^{+3.8}_{-14.1}\ (\mathrm{model})) \times 10^{-5}$, where the large model errors are primarily due to uncertainties in the PYTHIA fragmentation models used to generate Monte Carlo for the signal extraction studies.

It has been suggested that the large rate measured in the complementary mode, $B \to X_s\eta'$, was due to enhancements from the QCD anomaly coupling of the singlet component of the η to two gluons. Naively, this suggests that the rate for the η process should be suppressed by a factor of $\tan^2\theta \sim 0.1$, where θ is the $\eta - \eta'$ mixing angle. The current world average for the η' branching fraction is $\mathcal{B}(B \to X_s\eta') = (42.0 \pm 9.0)10^{-5}$ [28], only a factor of ~ 2 larger than the η mode, thus implying that the QCD anomaly coupling is unlikely to explain the $B \to X_s\eta'$ decay. Rather, recent theoretical treatments using SCET indicate that non-perturbative charming penguins may play a significant role in these decays [29]. This measurement may help to guide future theoretical work by constraining the level of these non-perturbative contributions.

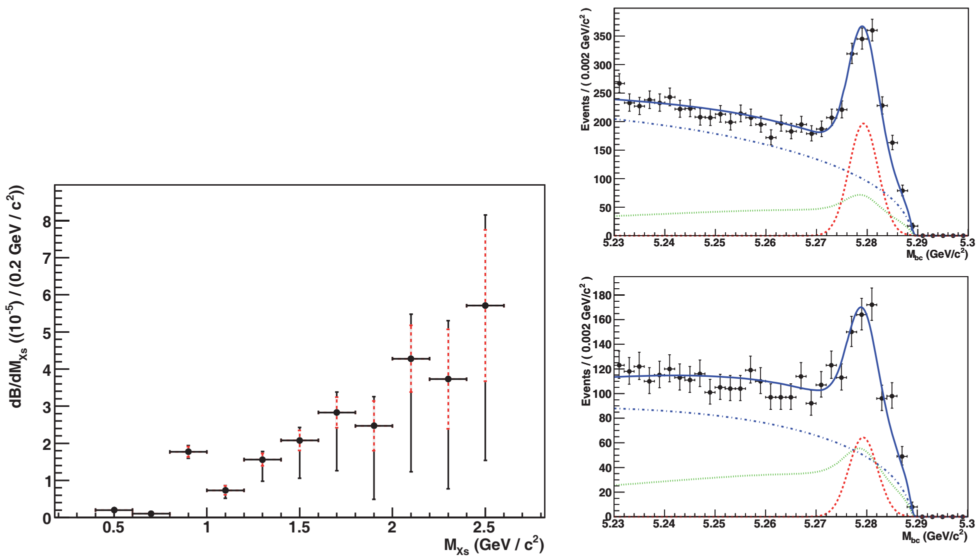

Fig. 6. – (Colour on-line) (Left) Belle's measured differential branching fraction, $\mathrm{d}\mathcal{B}/\mathrm{d}M_{X_s}$, for $B \to X_s\eta$. The error bars are statistical only (dashed red), and the quadratic sum of statistical, systematic, and modeling errors (solid black). (Upper right) Fit to M_{bc} for the X_s mass range above the $K^*(892)$, $1.0\,\mathrm{GeV}/c^2 < M_{X_s} < 2.6\,\mathrm{GeV}/c^2$. (Lower right) Fit to M_{bc} for the X_s mass range above all known kaonic resonances, $1.8\,\mathrm{GeV}/c^2 < M_{X_s} < 2.6\,\mathrm{GeV}/c^2$. The points with errors are data, the curves represent the total fit function (solid blue), the signal component (dashed red), generic $b \to c$ backgrounds (dotted green), and combinatorial background (dash-dotted blue).

5. – Conclusions

Significant progress has been made at Belle and BaBar in the experimental study of many rare B decay channels, only some of which have been discussed here. Though impressive precision has been attained in both theory and experiment for the inclusive $b \to s\gamma$ rate, no deviations from the SM predictions have yet been found. Likewise time-dependent searches for right-handed currents in exclusive $b \to s\gamma$ processes are ongoing, but remain statistically limited. Some hints of new physics may be evident in the electroweak decay $B \to K^*\ell^+\ell^-$, but seem to contradict the results in the inclusive channel. In the hadronic decays involving η and η', a number of new signals have been detected for which no predictions exist.

The B factories are completing data-taking, with BaBar already finished as of 2008 and Belle concluding later this year. We look forward to new and updated analyses of rare B decays utilizing the full data samples of these experiments. However, a common theme of many analyses we have discussed is the large statistical uncertainty. Thus, many analyses require statistical improvements beyond those available from the existing data sets, suggesting a promising future for the planned enhanced luminosity B factories [30, 31].

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