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Rare B decays at B factories

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The huge datasets collected at the two B factories, BaBar and Belle, have made it possible to explore the rare B decays. Recent experimental results are reviewed.

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1. Radiative and Electroweak decays

1.1 $b \to s\gamma$

To exploit the full potential of $\bar{B} \to X_s\gamma$ in constraining the parameter space of beyond the SM scenarios both the measurements and the SM calculations should be performed as accurately as possible. The most precise measurement of $\mathscr{B}(\bar{B} \to X_s\gamma)$ is the Belle inclusive result [1] with a factor 2 more data than their previous measurement. The signal is extracted by collecting all high-energy photons, vetoing those coming from π^0 and η decays to two photons. The main background contribution, coming from $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events (referred as continuum), is subtracted using the off-resonance sample (data taken 30 MeV below the $\Upsilon(4S)$ resonance). The analysis proceeds in two different streams, with a lepton tag and without, resulting in final samples that give similar sensitivity to the signal being largely statistically independent. In this measurement, the $\bar{B} \to X_s\gamma$ branching fraction was obtained with various minimum photon energy requirement, 1.7 to 2.1 GeV. Although lowering E_γ to 1.7 GeV causes larger systematic error from the background, it will encourage a deeper understanding of the theory uncertainties, especially on those related to the extrapolation. A weighted average taking into account the correlation between the two streams is shown in Fig. 1.1(left). At the 1.7 GeV threshold (97% of the $\bar{B} \to X_s\gamma$ phase space), the partial branching obtained is

$$\mathscr{B}(\bar{B} \to X_s\gamma) = (3.45 \pm 0.15(\text{stat}) \pm 0.40(\text{syst})) \times 10^{-4} \tag{1.1}$$

The dominant systematic error is coming from the size of the sample of off-resonance data used to subtract continuum. The present experimental world average, including measurements by CLEO, Belle, and BaBar, is performed by the Heavy Flavor Averaging Group [2] and reads for a photon energy cut of $E_\gamma > E_{\text{cut}}$ with $E_{\text{cut}} = 1.6$ GeV in the B-meson rest frame

$$\mathscr{B}(\bar{B} \to X_s\gamma) = (3.55 \pm 0.25 \pm 0.09) \times 10^{-4} \tag{1.2}$$

The calculation of the $\bar{B} \to X_s\gamma$ branching ratio has been completed up to Next-to-Next Leading Order (NNLO) [3] and gives for $E_{\text{cut}} = 1.6$ GeV, $\mathscr{B}(\bar{B} \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$, consistent with the experimental value. These results place tight constraints on models of new physics. For example, in the two-Higgs-doublet model II [4], the charged Higgs mass is constrained to be above 300 GeV/c^2 at the 95% confidence level (C.L.).

1.2 $b \to d\gamma$

In the SM the inclusive rate for $b \to d\gamma$ is suppressed relative to $b \to s\gamma$ by a factor $|V_{td}/V_{ts}|^2$, where $|V_{td}|$ and $|V_{ts}|$ are Cabibbo-Kobayashi-Maskawa matrix elements. Measurements of $|V_{td}/V_{ts}|$ using the exclusive modes $B \to (\rho,\omega)\gamma$ and $B \to K^*\gamma$ [5, 6] are now well-established, with theoretical uncertainties of 7% from weak annihilation and hadronic form factors [7]. Although the experimental errors are still larger than the theoretical errors, the size of the theoretical error could hardly be reduced.

A possible technique to improve the situation is the inclusive $B \to X_d\gamma$ measurement by using the "sum-of-exclusive" method. BaBar has reconstructed the $X_d\gamma$ system in seven final states [8], $\pi^+\pi^-\gamma$, $\pi^+\pi^0\gamma$, $\pi^+\pi^-\pi^+\gamma$, $\pi^+\pi^-\pi^0\gamma$, $\pi^+\pi^-\pi^+\pi^-\gamma$, $\pi^+\pi^-\pi^+\pi^0\gamma$, $\pi^+\eta\gamma$, in the mass range

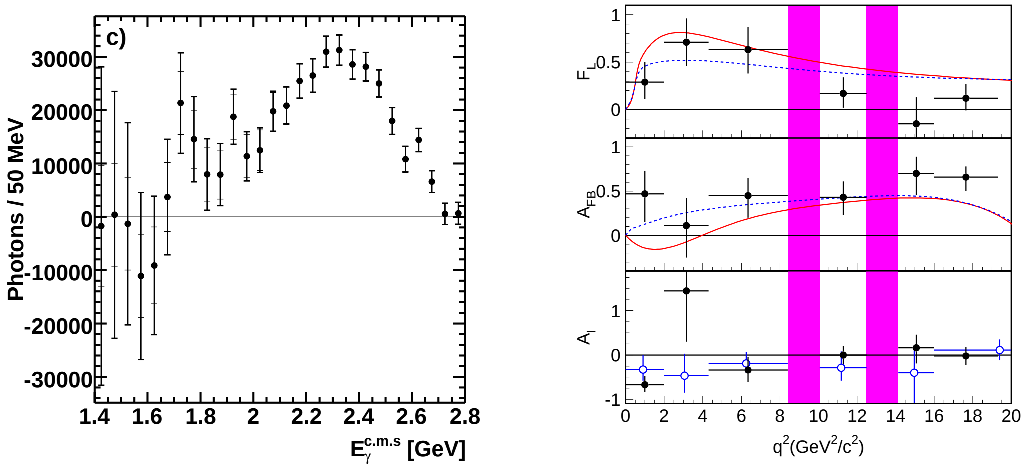

Figure 1: (left) The extracted photon energy spectrum of $B \to X_{s,d}\gamma$ by Belle after correction by the selection efficiency. (right) Longitudinal polarization fraction, forward-backward asymmetry and isospin asymmetry of $B \to K^* l^+ l^-$ by Belle. Solid lines show the SM predictions, while other curves are for non-SM extreme case (for which the sign of the Wilson coefficient C_7 is flipped).

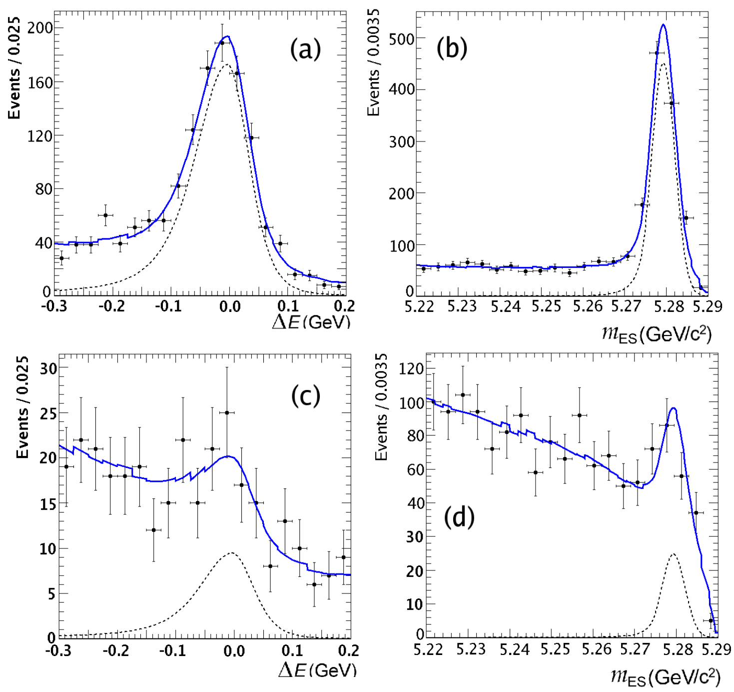

Figure 2: Projections of ΔE with $5.275 < m_{ES} < 5.286$ GeV/c^2 for (a) $B \to X_s\gamma$ and (c) $B \to X_d\gamma$, and of m_{ES} with $-0.10 < \Delta E < 0.05$ GeV for (b) $B \to X_s\gamma$ and (d) $B \to X_d\gamma$ by BaBar. Data points are compared with the sum of all the fit contributions. The dashed line shows the signal component.

$0.5 < M_{X_d} < 2.0$ GeV/c^2, which covers about 60% of the total branching fraction. In order to reduce the uncertainty due to missing modes and phase space, $X_s\gamma$ modes have also been measured in the corresponding seven final states in the same mass range, where the first π^+ is replaced with K^+. Figure 1.2 shows the fits to data for $B \to X_s\gamma$ and $B \to X_d\gamma$ in the high mass regions. This is the first significant observation of the $b \to d\gamma$ transition in the region above 1.0 GeV/c^2. The ratio of the two inclusive branching fractions has been measured to be

$$\frac{\mathscr{B}(B \to X_d\gamma)}{\mathscr{B}(B \to X_s\gamma)} = 0.040 \pm 0.009(\text{stat}) \pm 0.010(\text{syst}), \tag{1.3}$$

which is converted to $|V_{td}/V_{ts}| = 0.199 \pm 0.022(\text{stat}) \pm 0.024(\text{syst}) \pm 0.002(\text{th})$. This result is in agreement with the determination, $|V_{td}/V_{ts}| = 0.2059 \pm 0.001(\text{stat}) \pm 0.008(\text{syst})$, from the box diagrams using the ratio of B^0 and B_s^0 mixing parameters $\Delta m_d/\Delta m_s$, where Δm_d is measured at the B factories and Δm_s at Tevatron [2].

1.3 $b \to sl^+l^-$

The rare $B \to X_s l^+l^-$ decays form another class of flavour-changing neutral current (FCNC) processes, which proceed in the SM only through loop effects. The richer structure of the final state allows tests complementary to those performed in the weak radiative $B \to X_s\gamma$ decays. In addition to the total branching fraction, one can study the dilepton invariant mass, the forward-backward asymmetry, and various polarization observables.

Despite of their small branching ratios, the exclusive decay channels $B \to K^{(*)}l^+l^-$ have been measured efficiently with small background by BaBar [9] and Belle [10]. Signal yields of 247 and 162 events for $B \to Kl^+l^-$ and $B \to K^*l^+l^-$ by Belle have been subdivided into six bins of q^2 to measure the differential branching fractions and asymmetries. The most interesting observables at this stage are the fraction of longitudinal polarization F_L from the kaon angular distribution and the forward-backward asymmetry from the lepton angular distribution of the $B \to K^*l^+l^-$ decay. As shown in Fig. 1.1(right), the results have positive A_{FB} in high q^2, which set non-trivial constraints on the Wilson coefficients. Statistics is not large enough to tell if there is the zero-crossing point at low q^2, although the results favor the case with no crossing, for which the sign of the Wilson coefficient C_7 is flipped. The results are in agreement between Belle, BaBar and CDF [11].

The Belle collaboration presented an improved measurement of the branching fraction of the electroweak penguin process $B \to X_s l^+l^-$, where l^+l^- is an electron or a muon pair and X_s is an hadronic system containing an s-quark. The X_s hadronic system is reconstructed from one $K^\pm$ or K_S^0 and up to four pions, where at most one pion can be neutral. This measurement is based on a sample of $657 \times 10^6 B\overline{B}$ events. Averaging over both lepton flavors, the inclusive branching fraction is measured to be $\mathscr{B}(B \to X_s l^+l^-) = (3.33 \pm 0.8(\text{stat})^{+0.19}_{-0.24}(\text{syst})) \times 10^{-6}$ for $M_{l^+l^-} > 0.2$ GeV/c^2. The results are in good agreement with the SM prediction (Fig. 1.3) and strongly disfavor the case with flipped sign of C_7 [12].

2. Leptonic Decays $B \to l\nu$

In the SM, the purely leptonic decay $B^- \to \tau^-\overline{\nu}_\tau$ proceeds via annihilation of b and $\overline{u}$ quarks

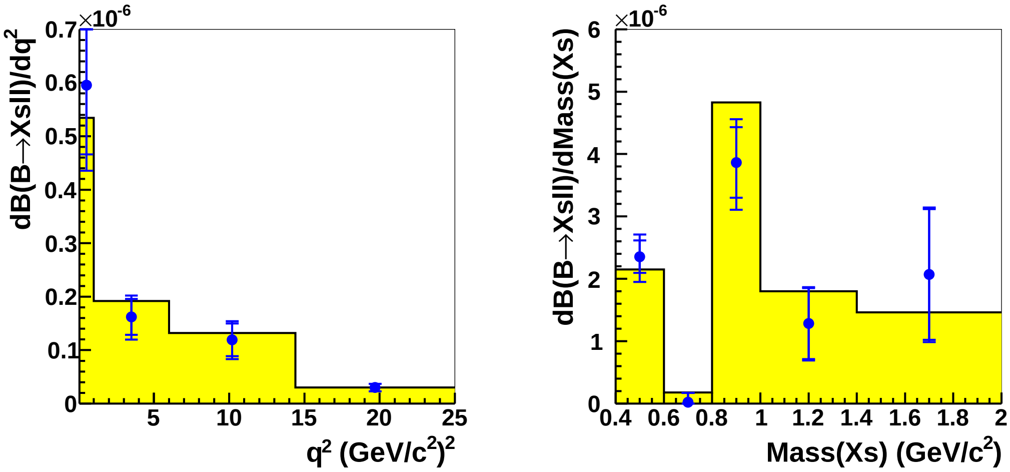

Figure 3: Spectra of X_s mass and q^2 of the dilepton system for $B \to X_s l^+ l^-$ by Belle.

to a W^- boson. The branching fraction is given by

$$\mathscr{B}(B \to l\nu) = \frac{G_F^2 m_B m_l^2}{8\pi}(1 - \frac{m_l^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B \tag{2.1}$$

where G_F is the Fermi coupling constant, m_B and m_l are the B and lepton masses, respectively, and τ_B is the B^- lifetime. In models beyond the SM there can be additional tree-level contributions such as a $H^\pm$ (s-channel) [13] or sfermions (s, t-channels) in R parity violating SUSY models [14]. The SM predictions, using recent world average values for $|V_{ub}|$, τ_B and f_B, are $\mathscr{B}(B \to e\nu) = 1.7 \times 10^{-11}$, $\mathscr{B}(B \to \mu\nu) = 7.1 \times 10^{-7}$ and $\mathscr{B}(B \to \tau\nu) = 1.2 \times 10^{-4}$. The tree-level partial width (including only $W^\pm$ and $H^\pm$ contributions) is given as follows [13]:

$$\mathscr{B}(B \to l\nu) = \frac{G_F^2 m_B m_l^2}{8\pi}(1 - \frac{m_l^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B \times r_H, \tag{2.2}$$

where r_H is independent of the lepton flavour and is given by

$$r_H = (1 - \frac{m_B^2}{m_H^2} \tan^2\beta)^2. \tag{2.3}$$

The measurement of $B \to \tau\nu$ is experimentally difficult due to the final state, and is possible only at the B factories. One of the two B mesons of the event is reconstructed ($B_{\rm tag}$), and the properties of the remaining particle(s) ($B_{\rm sig}$) are compared to those expected for signal and background. The first evidence for the decay $B \to \tau\nu$ was found by the Belle collaboration using 414 fb^{-1} of data collected at the $\Upsilon(4S)$ [15]. In this analysis, $B_{\rm tag}$ is fully reconstructed in hadronic modes, whereas in the signal side, we search for decays of $B_{\rm sig}$ into a τ and a neutrino, where the τ lepton is identified in one of the five decay modes, $\mu^-\bar{\nu}_\mu\nu_\tau$, $e^-\bar{\nu}_e\nu_\tau$, $\pi^-\nu_\tau$, $\pi^-\pi^0\nu_\tau$ and $\pi^-\pi^+\pi^-\nu_\tau$, which in total correspond to 81% of all τ decays. The most powerful variable for separating signal and background is the remaining energy in the electromagnetic calorimeter (ECL), denoted as $E_{\rm ECL}$ (or $E_{\rm extra}$), which is the sum of the energies of neutral clusters that are not associated with either

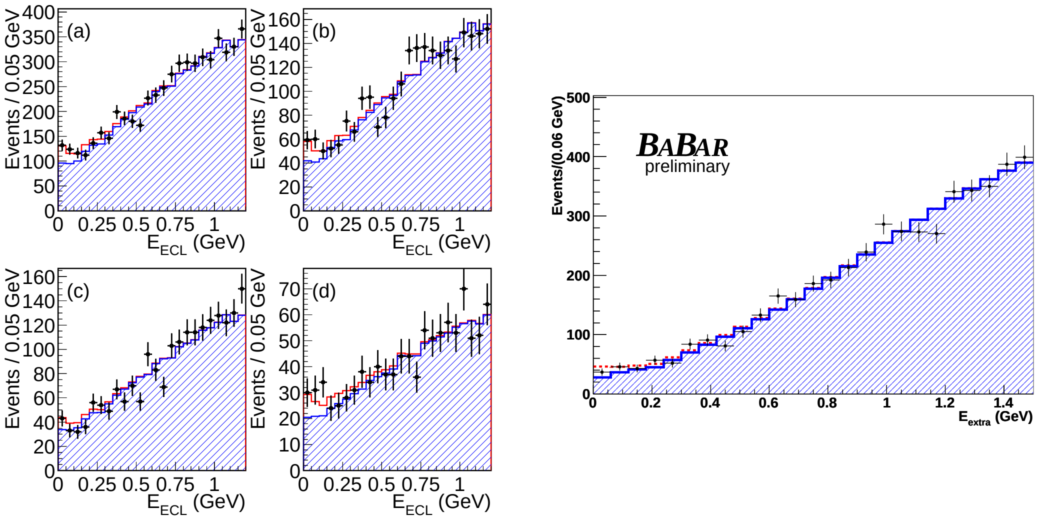

Figure 4: $E_{\rm ECL}$ distribution in the data after all selection criteria applied (except the one on $E_{\rm ECL}$) for Belle semileptonic tag (left) and BaBar hadronic tag (right). The data and background MC distribution are represented by the points and the hatched histogram.

the $B_{\rm tag}$ or the π^0 candidate from the $\tau^- \to \pi^-\pi^0\nu_\tau$ decay. $E_{\rm ECL}$ is consistent with zero for signal events. Figure 2 shows the $E_{\rm ECL}$ distribution obtained for the recent BaBar hadronic B tag [18] and the Belle semileptonic B tag results [16]. Table 1 summarizes the results obtained by the B factories, they are all in agreement and above the SM prediction.

Tag	$\mathcal{B}$ (10^{-4})	$\Sigma(\sigma)$	Reference
Hadronic	$(1.79^{+0.56+0.46}_{-0.49-0.51})$	3.5	Belle [15]
Semileptonic	$(1.54^{+0.38+0.29}_{-0.37-0.31})$	3.6	Belle [16]
Hadronic	$(1.80^{+0.57}_{-0.54} \pm 0.26)$	3.6	BaBar [17]
Semileptonic	$(1.7 \pm 0.8 \pm 0.2)$	2.3	BaBar [18]

Table 1: Summary of the branching fractions for the $B \to \tau\nu$ obtained by Belle and BaBar. Σ is the significance in standard deviations (σ).

3. $B \to D^{(*)}\tau\nu$

Measurements of semileptonic decays of B mesons to the τ lepton can also provide important constraints on the SM and its extensions. Due to the large mass of the lepton in the final state, these decays are sensitive probes of models with extended Higgs sectors [19], and provide more observables (for example, the τ polarization) sensitive to new physics than purely leptonic $B^+ \to \tau^+\nu$. The effects of new physics are expected to be larger in $B \to \overline{D}\tau^+\nu$ than in $B \to \overline{D}^*\tau^+\nu$. The predicted branching fractions for the SM are around 1.4% and 0.7% for $B^0 \to D^{*-}\tau^+\nu$ and $B^0 \to D^-\tau^+\nu$, respectively [20]. Despite of these relatively large branching fractions, multiple

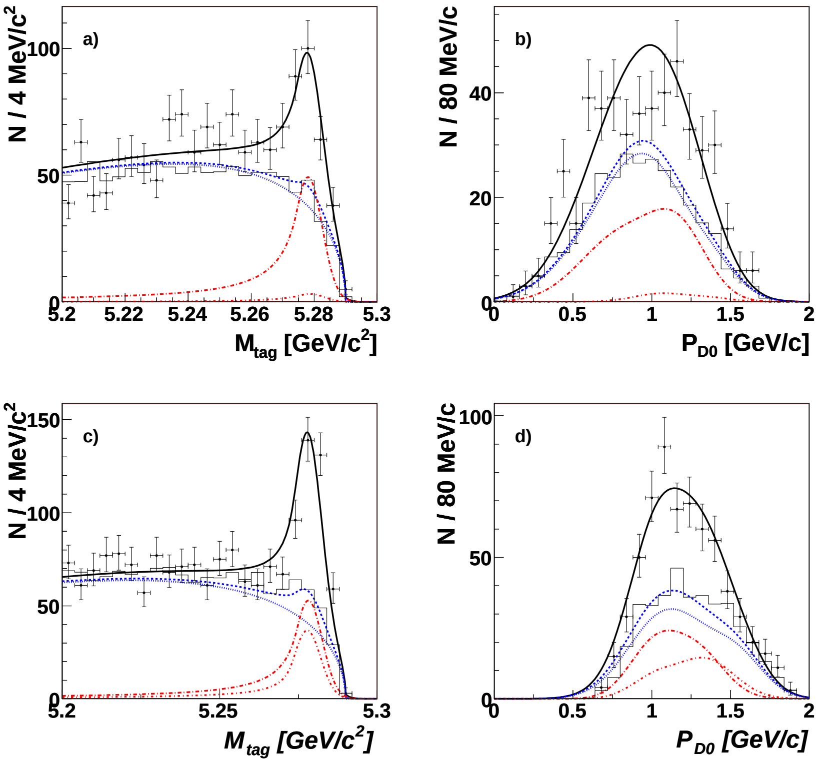

Figure 5: The fit projections to $M_{\rm tag}$ and P_{D^0} for $M_{\rm tag} > 5.26$ GeV/c^2 (a, b) for $\bar{D}^{*0}\tau^+\nu$, (c, d) for $\bar{D}^0\tau^+\nu$. The black show the result of the fits. The solid dashed curves represent the background and the dashed dotted ones show the combinatorial component. The dot-long-dashed and dot-short-dashed curves represent, respectively, the signal contributions from $\bar{D}^{*0}\tau^+\nu$ and $\bar{D}^0\tau^+\nu$. The histograms represent the MC-predicted background.

neutrinos in the final states make the search for semi-tauonic B decays very challenging. Reconstruction of the $B_{\rm tag}$, as for $B \to \tau\nu$, allows one to calculate the missing four-momentum in the $B_{\rm sig}$ which helps to separate signal events from copious backgrounds. Also the presence of a $B_{\rm tag}$ strongly suppresses the combinatorial and continuum backgrounds, but the disadvantage is the low reconstruction efficiency. To increase statistics, the $B_{\rm tag}$ can be reconstructed "inclusively" from all the remaining particles after the $B_{\rm sig}$ selection. This method was used successfully by the Belle collaboration [21] for the first observation of the $B^0 \to D^{*-}\tau^+\nu$ decay. Recently, Belle [22] applied the same procedure to measure the branching fractions of $B^+ \to \bar{D}^{*0}\tau^+\nu$ and $B^+ \to \bar{D}^0\tau^+\nu$. In a data sample of 657×10^6 $B\bar{B}$ pairs, a signal of 446^{+58}_{-56} events of the decay $B^+ \to \bar{D}^{*0}\tau^+\nu$ with a significance of 8.1 standard deviations (σ) and 146^{+42}_{-41} events of the decay $B^+ \to \bar{D}^0\tau^+\nu$ with a significance of 3.5σ are obtained from a simultaneous fit of the two modes. The latter signal provides the first evidence for this decay mode. The fit projections in $M_{\rm tag}$ and P_{D^0}, the beam-energy constrained mass and the momentum of $B_{\rm sig}$ measured in the $\Upsilon(4S)$ frame respectively, are shown in Fig. 3. The branching fractions measured are $\mathcal{B}(B \to \bar{D}^{*0}\tau^+\nu) = (2.12^{+0.28}_{-0.27}({\rm stat}) \pm 0.29({\rm syst}))\%$ and $\mathcal{B}(B \to \bar{D}^0\tau^+\nu) = (0.77 \pm 0.22({\rm stat}) \pm 0.12({\rm syst}))\%$ which are consistent within experimental uncertainties with the SM expectations [20].

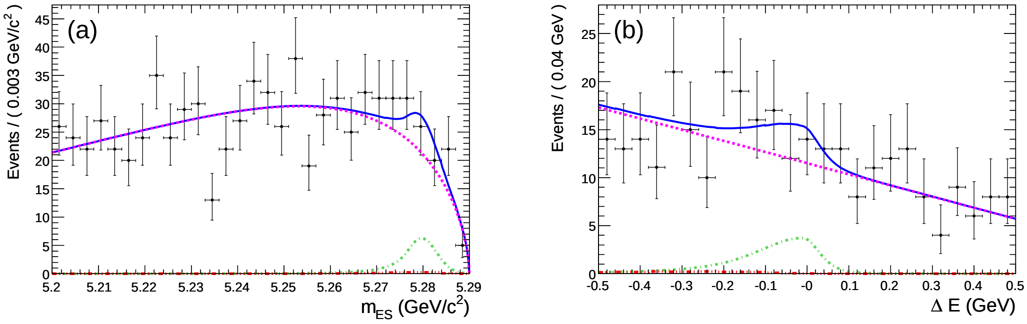

Figure 6: $m_{\rm ES}$ and ΔE projections for $B^0 \to \gamma\gamma$ by BaBar. The points represent the on-resonance data, the solid curve represents the total PDF, the dashed curve is the continuum background component, the dot-dashed curve is the signal component.

4. $B^0 \to \gamma\gamma$

In the SM, the decay $B^0 \to \gamma\gamma$ occurs through a FCNC transition involving electroweak loop diagrams. A leading order calculation for the branching fraction of $B^0 \to \gamma\gamma$ yields an estimate of $3.1^{+6.4}_{-1.6} \times 10^{-8}$ [23]. This mode is also sensitive to new physics that could lead to an enhancements of the branching fraction due to possible contributions of non-SM heavy particles occurring in the loop of the leading-order Feynman diagrams. The best previous upper limit on the branching fraction at 90% C.L. is $\mathscr{B}(B^0 \to \gamma\gamma) < 6.2 \times 10^{-7}$, obtained by Belle using a data sample of 104 fb^{-1}. A recent search for this rare decay was performed by BaBar with 426 fb^{-1} of data [24]. A signal yield 21^{+13}_{-12} is obtained (Fig. 4), with a statistical significance of 1.9σ. Based on this result, a 90% C.L. upper limit of $\mathscr{B}(B^0 \to \gamma\gamma) < 3.3 \times 10^{-7}$ is set.

5. Exotic decays

One important question regarding neutrinos is whether they are of Dirac or Majorana type. If they are Majorana-type neutrino states, such a neutrino cannot be distinguished from its own anti-particle. As a result, lepton-number-violating processes can occur where lepton number is changed by two units ($\Delta L = 2$). CLEO collaboration searched for $B^+ \to h^- l^+ l^+$ (with h= π, K, ρ and K^*) decays and placed upper limits on the corresponding branching fractions in the range $(1.0 - 8.3) \times 10^{-6}$ [25]. Using 772×10^6 $B\bar{B}$ pairs, Belle has recently performed the first search for $B^+ \to D^- l^+ l^+$ whose branching fraction could, with a heavy Majorana neutrino mass in (2-4) GeV range, be in the order of 10^{-7} or larger [26]. No events are found in the ($M_{\rm bc}$, ΔE) signal box as shown in Fig. 5. Assuming a 3-body phase space to estimate the efficiency, the following 90% C.L. upper limits on the branching fractions are set: $\mathscr{B}(B^+ \to D^- e^+ e^+) < 2.7 \times 10^{-6}$, $\mathscr{B}(B^+ \to D^- e^+ \mu^+) < 1.9 \times 10^{-6}$ and $\mathscr{B}(B^+ \to D^- \mu^+ \mu^+) < 1.1 \times 10^{-6}$.

6. Rare B_s decays at $\Upsilon(5S)$

With a large sample of data collected on the $\Upsilon(5S)$ (121 fb^{-1}), Belle can begin to search for rare

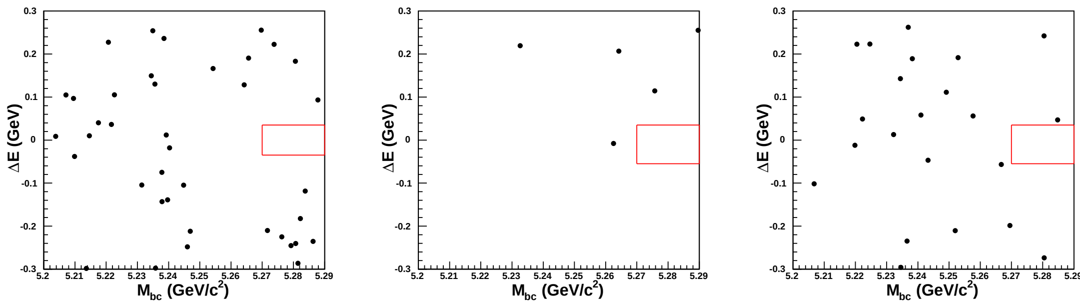

Figure 7: ΔE versus $M_{\rm bc}$ for $B^+ \to D^- e^+ e^+$ (left), $B^+ \to D^- e^+ \mu^+$ (middle) and $B^+ \to D^- \mu^+ \mu^+$ (right).

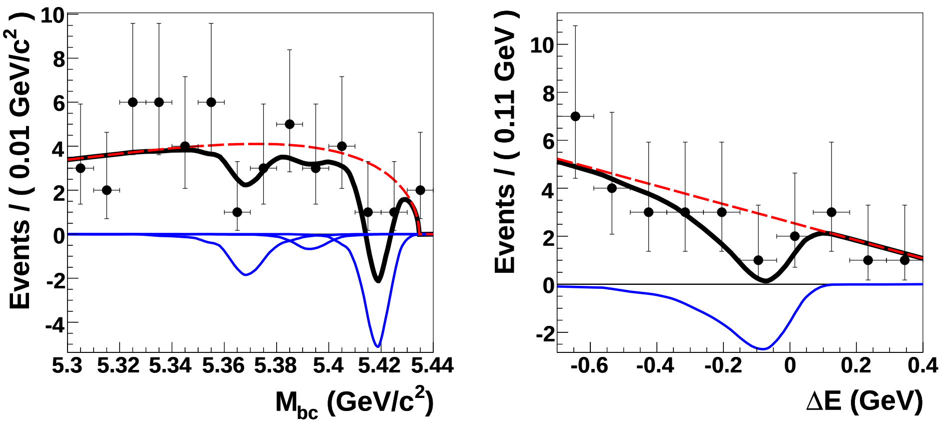

Figure 8: $M_{\rm bc}$ and ΔE projections together with fit results for the $B_s \to \gamma\gamma$ mode. The points with error bars represent the data, the thick solid curves are the fit functions, and the dashed curves show the continuum contribution. On the $M_{\rm bc}$ figure, signal from $B_s^0 \bar{B}_s^0$, $B_s^* \bar{B}_s^0$ and $B_s^* \bar{B}_s^*$ appear from left to right. On the ΔE figure, due to the requirement $M_{\rm bc} > 5.4$ GeV/c^2 only the $B_s^* \bar{B}_s^*$ contributes.

B_s decays, taking advantage of the e^+e^- environment, a low particle multiplicity and a good signal-to-background for low energy photons. Various rare loop-induced decay modes have been searched in a limited sample of 23 fb^{-1}, including $B_s \to \gamma\gamma$ (Fig. 6), $B_s \to \phi\gamma$ [27] and $B_s \to K^+K^-$ [28]. The limit $\mathscr{B}(B_s \to \gamma\gamma) < 8.7 \times 10^{-6}$, is already the most stringent in the world.

7. Conclusion

The B meson system represents an ideal framework for the study of flavor physics, the range of clean and powerful observables is very extensive. In this review we have summarized the most recent results on the rare B meson decays obtained with the large data samples of the B factories. These include $B \to X_{s,d}\gamma$, $B \to X_s l^+ l^-$, $B_{(s)} \to \gamma\gamma$ and $B \to \tau\nu$ results.

The dramatic increase in luminosity of the Super B-factories (a factor 50) will allow significant improvements in many important existing measurements, but also many channels and observables will be available for the first time.

References

[1] A. Limosani *et al.* (Belle collaboration), Phys. Rev. Lett. **103**, 241801 (2009).

[2] Heavy Flavor Averaging Group (HFAG), arXiv:1010.1589 [hep-ex].

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

[4] L.F. Abbott, P. Sikivie and M.B. Wise, Phys. Rev. D**21**, 1393 (1980).

[5] B. Aubert *et al.* (BaBar collaboration), Phys. Rev. D**78**, 112001 (2008).

[6] N. Taniguchi *et al.* (Belle collaboration), Phys. Rev. Lett. **101**, 111801 (2008).

[7] P. Ball, G. Jones and R. Zwicky, Phys. Rev. D**75**, 054004 (2007).

[8] BaBar collaboration, arXiv:1005.4087 [hep-ex].

[9] B. Aubert *et al.* (BaBar collaboration), Phys. Rev. D**79**, 031102 (2009).

[10] J.-T. Wei *et al.* (Belle collaboration), Phys. Rev. Lett. **103**, 171801 (2009).

[11] CDF Public note 10047 (2009).

[12] P. Gambino, U. Haisch, M. Misiak, Phys. Rev. Lett. **94**, 061803 (2005).

[13] W.S. Hou, Phys. Rev. D**48**, 2342 (1993).

[14] D. Guetta and E. Nardi, Phys. Rev. D**58**, 012001 (1998).

[15] K. Ikado *et al.* (Belle collaboration), Phys. Rev. Lett. **97**, 261802 (2006).

[16] K.Hara *et al.* (Belle collaboration), Phys. Rev. D**82**, 071101 (2010).

[17] B. Aubert *et al.* (BaBar collaboration), Phys. Rev. D**81**, 051101 (2010).

[18] BaBar collaboration, arXiv:1008.0104 [hep-ex].

[19] A.S. Cornell *et al.*, arXiv:0906.1652 [hep-ph] and references quoted therein.

[20] C.-H. Chen and C.-Q. Geng, JHEP 0610, 053 (2006).

[21] A. Matyja *et al.* (Belle collaboration), Phys. Rev. Lett. **99**, 191807 (2007).

[22] A. Bozek*et al.* (Belle collaboration), Phys. Rev. D**82**, 072005 (2010).

[23] S.W. Bosch and G. Buchalla, JHEP 0208:054 (2002).

[24] BaBar collaboration, arXiv:1010.2229 [hep-ex].

[25] K.W. Edwards *et al.* (CLEO collaboration), Phys. Rev. D**65**, 111102 (2002).

[26] J.-M. Zhang and G.-L. Wang, arXiv:1003.5570 [hep-ph], G.Cvetic *et al.*, Phys. Rev. D**82**, 053010 (2010).

[27] J. Wicht *et al.* (Belle collaboration), Phys. Rev. Lett. **100**, 121801 (2008).

[28] C.C.Peng *et al.* (Belle collaboration), Phys. Rev. D**82**, 072007 (2010).