Rare B decays and new physics studies

Owen Long
University of California at Riverside, Riverside CA 92521, USA

I present a review of using rare B decays to search for physics beyond the Standard Model. B decays that proceed either through annihilation or loop topologies at leading order in the Standard Model provide unique probes in the search for new physics. The latest experimental results from the B factories (Babar and Belle) and the Tevatron experiments (CDF and D0) on rare decays and their impact on various scenarios for new physics will be presented.

1. Introduction

In the past decade, we have seen enormous progress in understanding flavor physics and CP violation. After turning on in 1999, the new asymmetric-energy B factories, PEP-II [1] and KEKB [2], quickly achieved luminosities that exceeded their design targets and the expectations of many. This allowed the corresponding experiments, Babar [3] and Belle [4], to quickly provide the first precision test of the CKM [5] mechanism for CP violation. The measurements of the proper-time-dependent CP asymmetry in charmonium-K^0 decays of neutral B mesons ($\sin 2\beta$)[6] are in very good agreement with the CKM prediction of $\sin 2\beta$ from independent constraints.

It is convenient, both for visualization and quantitative analysis, to interpret experimental results within the CKM framework as constraints on the geometry of the so-called "Unitarity Triangle" [7], which is from the first and third columns of the CKM quark mixing matrix V_{ij}

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0. \quad (1)$$

If one renormalizes the triangle by rescaling the sides by $1/V_{cb}^* V_{cd}$ and adopts the Wolfenstein phase convention [8], experimental results are interpreted as constraints on the apex of the triangle $(\bar{\rho}, \bar{\eta})$. Two independent groups (CKMfitter[9] and UTfit[10]) provide the results of this analysis. Figure 1 shows the constraints on the apex of the Unitarity Triangle as of the FPCP'06 conference. One can see that in addition to the precise determination of β, mentioned above, the B factory data strongly constrains the left side of the triangle, which is proportional to $|V_{ub}|$[11]. The B factory experiments have also measured the other two angles of triangle (α[6] and γ[11]). Finally, the Tevatron experiments, CDF and D0, have recently measured Δm_s[12], the frequency of B_s oscillations, which allows the right side of the triangle to be constrained, when combined with Δm_d and some input from lattice QCD calculations[13].

It's clear from Figure 1 that the CKM model (and thus the Standard Model) gives a remarkably consistent description of all experimental results. It's natural to ask whether there is still room for discovering

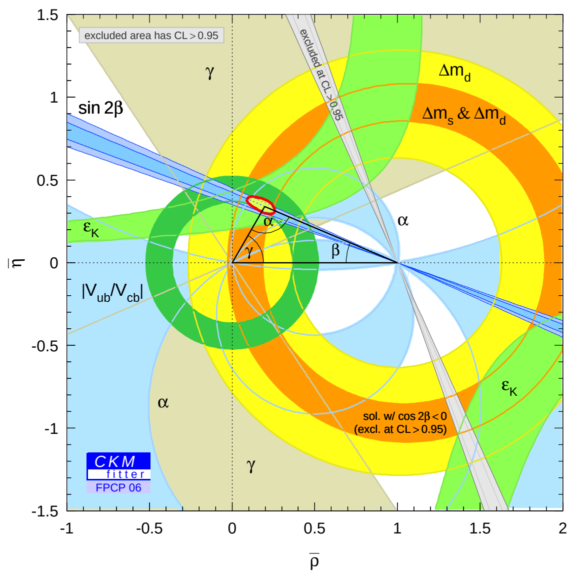

Figure 1: Constraints on the Unitarity Triangle as of the FPCP 2006 conference. Figure courtesy of the CKMfitter group[9].

physics beyond the Standard Model (or New Physics) in B decays, after seeing such consistency. The answer is yes. The most precise constraints in Figure 1 come from either tree-level B decays or from B mixing. From Figure 1, one can reasonably conclude that there is little room for substantial New Physics corrections to tree-dominated processes [14]. However, New Physics may significantly alter the observables (branching fractions, asymmetries, ...) for rare B decays without disturbing the beautiful consistency shown in Figure 1.

Rare B decays are a unique and valuable tool in the search for New Physics. Decays that are allowed at the tree level have relatively large amplitudes. If amplitudes from New Physics are small, as we expect, hadronic uncertainties will prevent us from recognizing the presence of New Physics in many cases. On the other hand, decays that proceed through annihilation or loop topologies at leading order are highly suppressed, thus considerably reducing the impact of hadronic uncertainties in the search for New Physics. Loop topologies, such as penguin decays, are particularly attractive. Virtual new particles (e.g. supersymmetric particles) with masses on the order of 100's of GeV may contribute loop contributions to these decays potentially altering the decay rate, CP asymmetry, and other observable quantities.

It is important to have Standard Model predictions for rare decay observables with theoretical uncertainties that are under control and as low as possible. An excellent way to do this is to have uncertainties cancel in a ratio, such as a CP asymmetry. Time-dependent CP asymmetries in penguin-dominated decays, such as ϕK^0 and $\eta' K^0$ are a prime example that I will discuss. Another way is to avoid hadrons in the final state. I will review the latest results on B decays to $\mu\mu$, $\tau\nu$, $s\gamma$, $d\gamma$, and $s\ell\ell$ final states. Finally, one can use both techniques. For example, the CP asymmetry in $b \to s\gamma$ or the forward-backward asymmetry in $B \to K^*\ell\ell$.

The list of topics above is certainly not a complete inventory of the avenues being pursued. I chose to focus on them because they are areas where recent progress has been made and/or because they are channels with relatively small theoretical uncertainties. Before continuing, I would like to point out that there have been very good recent reviews on many of the topics that I will cover, such as reference [15], that the reader may be interested in for more details or a different point of view.

2. CP asymmetries in $b \to s$ penguin decays

Time-dependent CP asymmetries in $b \to s$ penguin decays provide an excellent way to search for new physics [16]. As I will describe below, most hadronic uncertainties cancel in the Standard Model calculation of the expected asymmetry, so there are precise predictions to compare our measurements with. Contributions from non-Standard-Mode particles may give large (order 1) corrections to the CP asymmetries. A large deviation from the Standard Model expectation would be an unambiguous sign of New Physics.

The Standard Model interpretation of a time-dependent CP asymmetry is theoretically clean *if* one decay amplitude dominates (or, more technically, if all dominant decay amplitude contributions share the same CP-violating phase). The most familiar example of this is $B^0 \to J/\psi K^0_S$. The leading decay amplitude is a color-suppressed tree diagram. The largest amplitude with a different weak phase comes from a $b \to s$ penguin diagram with an intermediate u quark, which is suppressed with respect to the dominant amplitude by a relative CKM factor of about 0.02, loop vs tree suppression, and by the need to create a $c\bar{c}$ pair. Thus, the Standard Model predicts that the amplitude of the time-dependent CP asymmetry for the $J/\psi K^0_S$ final state is $\sin 2\beta$ with an uncertainty of less than 1% [17].

The time-dependent CP asymmetry for decays that proceed through a penguin $b \to s$ transition is also expected to be close to $\sin 2\beta$. However, the corrections from suppressed $b \to u$ amplitudes are in general larger. For $b \to s\bar{s}s$ transitions, such as $B^0 \to \phi K^0$ or $B^0 \to K^0_S K^0_S K^0_S$, the only $b \to u$ amplitude comes from the $b \to s$ penguin diagram with an intermediate u quark. Here, both the leading and CKM suppressed contributions are both penguins, differing only by the intermediate quarks in the loop. For decays such as $B^0 \to \eta' K^0$, a color-suppressed $b \to u$ tree diagram may also contribute, since the η' has both $u\bar{u}$ and $s\bar{s}$ content. In this situation, the dominant amplitudes are loop suppressed, so the $b \to u$ tree contribution is more of a concern. The key theoretical task is to determine or place an upper bound on the relative size of the $b \to u$ amplitudes, which involves calculating or constraining the ratio of hadronic matrix elements.

There has been a tremendous amount of theoretical work on estimating the Standard Model uncertainty on the CP asymmetry in $b \to s$ penguin decays [18]. Theoretical estimates are given in terms of the maximum deviation from $\sin 2\beta$ of the measured $\sin \Delta m \Delta t$ coefficient S_f of the CP asymmetry for final state f, or $\Delta S_f = S_f - \sin 2\beta$. Conservative model-independent estimates of $|\Delta S_f|$ are on the same order or larger than the current experimental errors. Model dependent calculations estimate ΔS_f, including its sign, and have uncertainties at the level of 1 to 2 %.

The most interesting channels, both experimentally and theoretically, are ϕK_0 and $\eta' K_0$. The ϕK_0 mode is a pure $b \to s\bar{s}s$ transition with a clean experimental signature. The $\eta' K_0$ mode is not a pure $b \to s\bar{s}s$ transition but model estimates predict a very small ΔS_f [19]. The $\eta' K_0$ mode also has an unusually large branching fraction so the statistical errors on the S_f measurements are best for this decay. As with the theoretical uncertainties, many experimental systematic uncertainties cancel in the CP asymmetry. Systematic uncertainties on the S_f measurements are 3 to 5 times smaller than the statistical errors. Both the Babar and Belle experiments reconstruct the K^0_S and the more challenging K^0_L final states in order to maximize their signal statistics.

Figure 2 summarizes the S_f measurements for many $b \to s$ penguin decay modes, as compiled by the Heavy Flavor Averaging Group (HFAG)[20]. None of the channels show a significant discrepancy with the Standard Model expectation of $-\eta_f\, S_f = S_{b\to c\bar{c}s} \approx \sin 2\beta$, where η_f is the CP eigenvalue of the final state f. The measurements tend to be below $\sin 2\beta$ (i.e. $\Delta S_f < 0$) which is interesting because model predictions give small *positive* values of ΔS_f [19]. There is still room for discovery, since the measurements are and will be

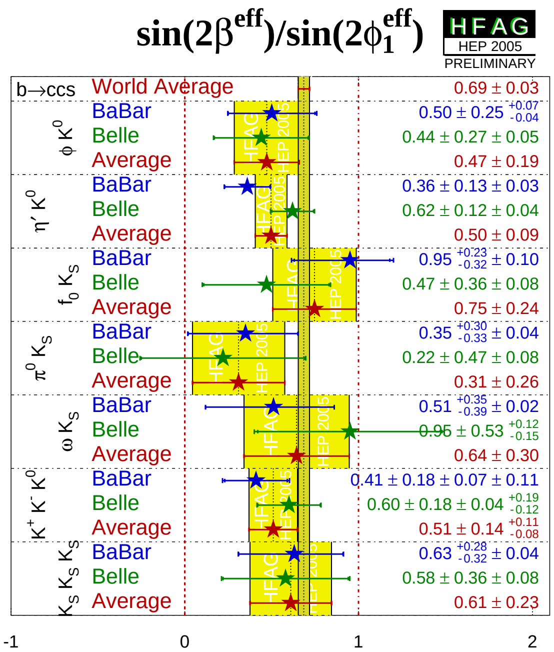

Figure 2: Measurements of S_f for several $b \to s$ penguin decays. The Standard Model predicts $-\eta_f\, S_f = S_{b\to c\bar{c}s} = \sin 2\beta$ if $b \to u$ amplitude contributions are neglected. Figure courtesy of the Heavy Flavor Averaging Group (HFAG)[20].

statistics limited for the foreseeable future, though a super B factory [21] may be required to achieve the sensitivity necessary for a discovery.

3. Leptonic B decays

B decays to purely leptonic final states are theoretically advantageous, since the hadronic uncertainties mainly come from a single parameter, the B_i meson decay constant f_i. The B decay constant can be computed using lattice QCD [13] or measured from a leptonic B decay branching fraction, as we will see. New physics can greatly enhance leptonic B decay rates in some scenarios, so searching for them is a good way to search for New Physics.

3.1. The search for $B_s \to \mu^+\mu^-$

The decay $B_s \to \mu^+\mu^-$ is highly suppressed in the Standard Model, since it can only proceed through a box diagram or a Z penguin. The current SM prediction is $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.4 \pm 0.5) \times 10^{-9}$ [22]. In some new physics scenarios, the branching fraction can be enhanced by by a high power of $\tan\beta$ (e.g. $\mathcal{B} \propto \tan^6\beta$ in supersymmetry or $\mathcal{B} \propto \tan^4\beta$ in 2 Higgs doublet models), where $\tan\beta$ is the ratio of the Higgs vacuum expectation values. For large $\tan\beta$, the branching fraction could be enhanced by two orders of magnitude, which is currently within reach of the CDF and D0 experiments.

The Tevatron has a 4-order-of-magnitude advantage over the B factories (Babar and Belle) in the $b\bar{b}$ production cross section. It also produces all types of b-quark hadrons, while $B_s\overline{B_s}$ is above threshold for the $\Upsilon(4S)$ resonance, where most of the B factory data have been collected. The main disadvantage of the Tevatron is that the $b\bar{b}$ cross section is only $\approx 1/1000$ of the total inelastic $p\bar{p}$ cross section, so for most B decays, QCD background is a major obstacle. Fortunately, both CDF and D0 can easily trigger on muons.

The CDF experiment has recently updated their search for $B_s \to \mu^+\mu^-$ with 780 pb^{-1} of Run II data [24]. They use a likelihood ratio that combines three discriminating variables to reject combinatoric background for events with a di-muon invariant mass close to the B_s. The variables are the reconstructed decay length, the consistency between the the vector that points from the primary vertex to the di-muon vertex and the di-muon momentum vector, and the degree to which the muons are isolated in the event. After requiring the likelihood ratio to be greater than 0.99, the expected background is 1.3 events. They observed one event in the signal box, consistent with the background estimate, and set an upper limit of $\mathcal{B}(B_s \to \mu^+\mu^-) < 1.0 \times 10^{-7}$ at 95% confidence level. This is only a factor of 30 above the Standard Model prediction. The D0 collaboration last updated their $B_s \to \mu^+\mu^-$ search using 300 pb^{-1} of Run II data [23].

It has been noted that $\mathcal{B}(B_s \to \mu^+\mu^-)$ has connections to cosmology and dark matter. For example, reference [25] has pointed out that the $B_s \to \mu^+\mu^-$ branching fraction is strongly correlated with the neutralino-proton scattering cross section for large $\tan\beta$. The lack of an observation of this mode at the Tevatron disfavors a large $\tan\beta$ and implies that the neutralino-proton cross section is well below the sensitivity of direct detection experiments, such as CDMS II.

3.2. Evidence for $B^+ \to \tau^+\nu$

The leptonic decay $B^+ \to \tau^+\nu$ is the least helicity suppressed, as can be seen by the relation below for the branching fraction:

$$\mathcal{B}(B^+ \to \tau^+\nu) = \frac{G_F^2\, m_B\, m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right) f_B^2\, |V_{ub}|^2\, \tau_B. \quad (2)$$

The Standard Model prediction for the branching fraction is $(1.50 \pm 0.40) \times 10^{-4}$ [26], where the uncertainty is dominated by the calculation of f_B from lattice QCD ($\approx 10\%$)[27] and $|V_{ub}|$ from semileptonic B decays ($\approx 7.5\%$)[20]. This is now within reach of the current B factories. Measuring this branching fraction is the most straightforward way to experimentally test the lattice calculation of the B decay constant f_B. Large enhancements of the branching fraction are possible in some New Physics models, such as the two-Higgs-doublet model described in reference [28] with large $\tan\beta$. The Belle experiment has recently reported evidence [26] for $B^+ \to \tau^+\nu$. I will describe their analysis in the remainder of this subsection.

This decay is very challenging due to the presence of at least two neutrinos in the final state. In B decays with only one neutrino, the neutrino can be reconstructed from the missing momentum of the event, assuming the neutrino is massless. With two or more neutrinos, the missing invariant mass is, in general, non-zero, so the kinematics can't be inferred from the missing momentum alone. The technique that has been used by both the Belle and Babar experiments has been to fully reconstruct the other B (or the "tag" B) in the event and then search for the $B^+ \to \tau^+\nu$ decay in the recoil. The tag B reconstruction efficiency is around 0.14%.

Fully reconstructing the tag B serves two purposes. First, it determines the *a priori* unknown direction of the signal B momentum vector. Secondly, and more importantly, it allows a full reconstruction of the event (minus the neutrinos). The signal τ decay is reconstructed with an efficiency of 33% in 5 decay modes that correspond to 81% of all τ decays: $e^-\bar{\nu}_e\nu_\tau$, $\mu^-\bar{\nu}_\mu\nu_\tau$, $\pi^-\nu_\tau$, $\pi^-\pi^0\nu_\tau$, and $\pi^-\pi^+\pi^-\nu_\tau$. Since all of the observable decay products (everything but the neutrinos) have been accounted for in the reconstruction of the tag B and the τ, there should be no additional tracks in the event and the unaccounted-for calorimeter energy should be close to zero.

The main discriminating variable in the Belle analysis, after all selection criteria are applied, is the remaining (extra) energy in the electromagnetic calorimeter E_{ECL}, which should be consistent with zero for signal events. The number of expected background events in a defined signal region near zero is 32.8 ± 4.6. A total of 54 events were observed in the signal region indicating the presence of a signal. An unbinned likelihood fit of the E_{ECL} spectrum gave a fitted signal yield of $21.2^{+6.7}_{-5.7}$ events for a significance of 4.2 σ, including systematic uncertainties. This corresponds to a $B^+ \to \tau^+\nu$ branching fraction [1] of $(1.06\ ^{+0.34}_{-0.28}\ ^{+0.18}_{-0.16}) \times 10^{-4}$, which is consistent with the Standard Model expectation of about 1.5×10^{-4}.

[1] An error was found in the analysis documented in [26]. This was reported at the ICHEP'06 conference in Moscow. The corrected branching fraction is $(1.79\ ^{+0.56}_{-0.49}\ ^{+0.39}_{-0.46}) \times 10^{-4}$ with a signal significance of 3.5 σ, including systematic errors. As of the writing of the report, reference [26] has not been updated to correct the reported error.

The fact that an excess over the Standard Model prediction was not observed rules out a region of charged Higgs mass vs $\tan\beta$ in the model described in [28]. In the future, improved measurements of $\mathcal{B}(B^+ \to \tau^+\nu)$ will provide a valuable experimental benchmark for the lattice QCD prediction of f_B.

4. Search for New Physics in $b \to s\,\gamma$ and $b \to s\,\ell^+\ell^-$

The phenomenology of $b \to s\,\gamma$ and $b \to s\,\ell^+\ell^-$ decays is closely linked. Standard Model calculations for these rare decays are performed using an effective Hamiltonian that is written in terms of several short-distance operators [29]. Wilson coefficients quantify the relative strength of the different short-distance contributions. Standard Model predictions for observable quantities, such as differential decay rates, can be written in terms of effective Wilson coefficients, which include higher-order corrections. The process $b \to s\,\gamma$ is dominated by the photon penguin operator, with Wilson coefficient C_7, while $b \to s\,\ell^+\ell^-$ also has contributions from semileptonic vector and axial-vector operators with Wilson coefficients C_9 and C_{10} respectively.

Experimentally, we wish to measure C_7, C_9, and C_{10}. New Physics may alter the magnitude and/or sign of the effective Wilson coefficients. If a deviation from the Standard Model is observed, it can be used to distinguish between different models for New Physics, since the New Physics predictions for the deviations are not universal [30].

4.1. Status of $b \to s\,\gamma$

Gino Isidori recently called $b \to s\,\gamma$ "The most effective NP killer" [31]. There are two complimentary experimental approaches. In the semi-inclusive $B \to X_s\,\gamma$ approach, several X_s states are explicitly reconstructed (e.g. $K\pi$, $K\pi\pi$, $KKK\pi$, etc...). The total $B \to X_s\,\gamma$ rate is then computed by estimating the contribution from the missing X_s states. The uncertainty in estimating the contribution from missing states is significant. On the other hand, only the photon is explicitly reconstructed in the fully inclusive approach. The huge background from continuum events ($e^+e^- \to q\bar{q}$ with $q = u, d, s$, or c) is suppressed by requiring the presence of a high-momentum lepton from the semileptonic decay of the other B in the event. The remaining continuum background is then subtracted using e^+e^- data taken just below the $\Upsilon(4S)$ resonance. The two methods have similar precision.

The current HFAG world average [20] for $E_\gamma >$ 1.6 GeV is

$$\mathcal{B}(b \to s\,\gamma)_{\rm expt.} = \left(355 \pm 24\ ^{+9}_{-10} \pm 3\right) \times 10^{-6}, \quad (3)$$

where the uncertainties, from left to right, are from experimental statistical and systematic sources, the E_γ shape function, and the subtraction of $b \to d\,\gamma$. The next-to-leading-order theoretical prediction of the same quantity [32] is

$$\mathcal{B}(b \to s\,\gamma)_{\rm theory} = (357 \pm 30) \times 10^{-6}. \qquad (4)$$

The remarkable agreement effectively fixes $|C_7|$ to the Standard Model value. However, the inclusive $b \to s\gamma$ rate is not sensitive to the *sign* of C_7.

New physics can hide within $b \to s\,\gamma$ without affecting the overall rate significantly. The CP asymmetry

$$A_{CP}(b \to s\,\gamma) = \frac{\Gamma(b \to s\,\gamma) - \Gamma(b \to s\,\gamma)}{\Gamma(b \to s\,\gamma) + \Gamma(b \to s\,\gamma)} \qquad (5)$$

is extremely small within the Standard Model [33] and is predicted to be $(0.42^{+0.17}_{-0.12})\%$. A large A_{CP} would be a smoking gun for New Physics and would tell us something about the nature of the New Physics. In some scenarios, such as minimal flavor violation [34], A_{CP} remains below 2%, while others allow A_{CP} to be of order 10%. The HFAG average [20] experimental value is

$$A_{CP}(b \to s\,\gamma)_{\rm expt.} = (0.4 \pm 3.6)\,\%, \qquad (6)$$

which is consistent with the Standard Model prediction. The statistical errors on the B factory measurements [35][36] are about 5% while the systematic errors are 2.6% and 1.5% respectively. These measurements are based on 80 fb^{-1} and 140 fb^{-1} of on-resonance data, so the precision of the world average will continue to improve.

4.2. Observation of $b \to d\,\gamma$

The amplitude for the process $b \to d\,\gamma$ is suppressed by a factor of $|V_{td}/V_{ts}| \approx 0.2$ with respect to $b \to s\,\gamma$. Smaller amplitudes, in general, have higher sensitivity to New Physics contributions. The branching fraction is suppressed by a factor of ≈ 0.04 making this channel extremely challenging. If the $b \to d\,\gamma$ rate is measured, it can be combined with the $b \to s\,\gamma$ rate to constrain $|V_{td}/V_{ts}|$, which is essentially the right side of the Unitarity Triangle, since many of the hadronic uncertainties cancel in the ratio of exclusive modes.

Belle has recently observed the $b \to d\gamma$ process for the first time [37], by exclusively reconstructing $B \to \rho\gamma$ and $B \to \omega\gamma$. They combined their exclusive measurements using the following isospin relation

$$\begin{aligned}\Gamma(B \to (\rho,\omega)\gamma) &\equiv \Gamma(B^- \to \rho^-\,\gamma)\\ &= 2 \times \Gamma(\overline{B^0} \to \rho^0\,\gamma)\\ &= 2 \times \Gamma(B \to \omega\,\gamma)\end{aligned}$$

and found $\mathcal{B}(B \to (\rho,\omega)\gamma) = \left(1.32\,^{+0.34}_{-0.31}\,^{+0.10}_{-0.09}\right) \times 10^{-6}$. which is consistent with the Standard Model expectation. [2]

4.3. Recent progress in $b \to d\,\ell^+\ell^-$

The process $b \to d\,\ell^+\ell^-$ has contributions from the 3 short-distance operators that correspond to the Wilson coefficients C_7, C_9, and C_{10}. The relative strength of the contributions depends on q^2, which is the square of the di-lepton invariant mass. Differential measurements as a function of q^2 measure the amount of $A - V$ interference, thus constraining the Wilson coefficients.

Some New Physics models wiggle out of the stringent constraint on $|C_7|$ from $b \to s\,\gamma$ by simply changing the *sign* of C_7. In $b \to d\,\ell^+\ell^-$, changing the sign of C_7 would enhance the overall $b \to d\,\ell^+\ell^-$ rate, particularly in the low-q^2 range, essentially by changing destructive interference into constructive interference [38].

The inclusive $b \to d\,\ell^+\ell^-$ rate has been measured in bins of q^2 by both Babar and Belle. They use the sum of many exclusive modes composed of one K_S or $K^\pm$ plus zero or more pions. The rate from K_L modes is estimated from the measured K_S rates. The regions of q^2 near the charmonium resonances are excluded from the measurement and provide a very useful control sample. The sum of exclusive modes is extrapolated to find the fully inclusive rate.

Figure 3 shows a comparison of the Belle [39] and Babar [40] measurements with theoretical predictions [41] for the Standard Model sign of C_7 and the opposite (or wrong) sign of C_7. The data clearly favor the Standard Model sign of C_7.

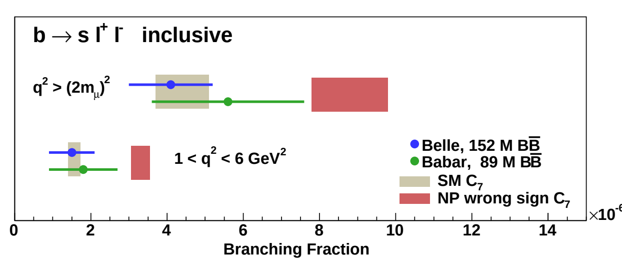

Figure 3: Comparison of the Belle [39] and Babar [40] decay rates with theoretical predictions [41] for the Standard Model sign of C_7 and the opposite (or wrong) sign of C_7. The data clearly favor the Standard Model sign of C_7.

A very interesting observable in $B \to K^*\ell^+\ell^-$ decays is the forward-backward asymmetry of the di-

[2] The Babar experiment reported a confirmation of the Belle $b \to d\,\gamma$ observation at the ICHEP'06 conference.

	$\int A_{FB}(K^*\ell\ell)$	$\int A_{FB}(K\ell\ell)$
Belle [43]	$0.50 \pm 0.15 \pm 0.02$ (3.4σ)	$0.10 \pm 0.14 \pm 0.01$
Babar [42]	> 0.55 @ 95% C. L.	$0.15^{+0.21}_{-0.23} \pm 0.08$

Table I Di-lepton forward-backward asymmetries integrated over q^2 ($\int A_{FB}$) for $B \to K^{(*)}\ell\ell$. A positive net asymmetry is expected for $K^*\ell\ell$ in the Standard Model, while no asymmetry is expected for $K\ell\ell$.

lepton system, which is defined as

$$A_{FB}(q^2) = \frac{\Gamma(q^2, \cos\theta_{B\ell^-} > 0) - \Gamma(q^2, \cos\theta_{B\ell^-} < 0)}{\Gamma(q^2, \cos\theta_{B\ell^-} > 0) + \Gamma(q^2, \cos\theta_{B\ell^-} < 0)}, \tag{7}$$

where $\cos\theta_{B\ell^-}$ is the angle between the negatively (positively) charged lepton direction and the B ($\overline{B}$) flight direction in the di-lepton center-of-mass frame. Features of the $A_{FB}(q^2)$ curve can test both the signs and magnitudes of C_9 and C_{10} [29].

In the Standard Model, $A_{FB}(q^2)$ is predicted to be zero at $q^2 = 0$, dip negative, cross zero at about $q^2 = 0.2\, m_b^2$, and rise monotonically to about 0.5 at $q^2 = 1$. New Physics can drastically change the shape of the $A_{FB}(q^2)$ curve. For example, sign of $A_{FB}(q^2)$ can be flipped, the zero-crossing point may be shifted, or $A_{FB}(q^2)$ may not even cross zero [29].

Both Babar and Belle have established signals in the $K^*\ell^+\ell^-$ channels, though the statistics are low: about signal 50 events for Babar [42] and 100 for Belle [43]. Backgrounds are also non-negligible. The background fraction in the signal region is roughly 50%. This is not enough for a precision scan of A_{FB} vs q^2, but the experiments have shown that interesting conclusions can already be made from the currently analyzed data.

Both experiments favor a positive integrated asymmetry, as expected in the Standard Model. The results are given in Table I for both $K^*\ell\ell$ and for $K\ell\ell$ where no asymmetry is expected. The Belle analysis measured A_{FB} in five bins of q^2 and then fit for the leading relative terms A_9/A_7 and A_{10}/A_7 of the effective Wilson coefficients. The fit is very consistent with the Standard Model prediction and is able to exclude a wrong-sign A_9A_{10} combination at 98.2% confidence level.

The ultimate reach of the B factories will still probably leave these measurements limited by statistical uncertainties. LHCb will pick up where the current B factories will leave off and hopefully realize the full discovery potential of the $K^*\ell\ell$ system.

5. Summary and conclusions

Studies of very rare B decays are an excellent way to search for New Physics and to constrain New Physics model parameters. Loop-mediated B decays probe New Physics at high mass scales. The B factories and the Tevatron experiments have made impressive progress which has been matched by our theoretical colleagues. As of today, there have been no serious challenges to the Standard Model from rare B decays.

The B factories plan to accumulate two to three times more data. This will leave many of the clean probes of New Physics that I discussed limited by sample statistics, not systematic errors. The LHC experiments will continue with some but not all of these studies. Many believe that a super B factory [21], an ultra-high luminosity (10^{36} cm^{2}s^{-1}) e^+e^- machine at the $\Upsilon(4S)$,would be highly desirable, in fact essential, for exploring the flavor sector of any New Physics discovered at the LHC.

Acknowledgments

The author would like to thank Joao de Mello and the rest of the organizers for hosting a very pleasant conference.

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