# Prospects for precision measurements of the CKM triangle and rare $B$ decays at super-high-luminosity $B$ factories

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The prospects for $B$ physics at super-high-luminosity $B$ factories are discussed. With a luminosity of $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the physics opportunities for precision measurements of the CKM matrix elements and angles as well as the discovery of new physics beyond the Standard Model are very attractive. The precision of such measurements and the sensitivity for new discoveries are estimated using the existing data from the current generation of the $B$-factory experiments, Belle and Babar.

## 1. Introduction

The new experiments at $B$ factories, Belle at KEKB and Babar at PEP−II, have observed $CP$ violation in the $B$ meson system using data samples of $\sim 30\mathrm{fb}^{-1}$. This discovery is only the first of many measurements to come from $B$ factories. The $B$ factories have reached a luminosity of $4 \times 10^{33}\mathrm{cm}^{-2}s^{-1}$ in the case of PEP−II and $4.5 \times 10^{33}\mathrm{cm}^{-2}s^{-1}$ for KEKB. These machines will produce integrated luminosities of 50 to 60 $\mathrm{fb}^{-1}$ next year. The short-term upgrade plans of the $B$ factories will raise the luminosities of the machines to the level of $10^{34}\mathrm{cm}^{-2}s^{-1}$, yielding data samples of several hundred inverse femtobarns by 2006. From these large samples of $B$ meson decays, many precise and/or new measurements in the flavour physics sector of the Standard Model will emerge.

## 2. Luminosity prospects

Belle plans to accumulate a total of 100 $\mathrm{fb}^{-1}$ by the end of next year. In five years, Belle hopes to accumulate 300 $\mathrm{fb}^{-1}$, and in ten years, with upgrades to the KEKB accelerator system, 3,000 $\mathrm{fb}^{-1}$ or 3 a(tto)$\mathrm{b}^{-1}$. The following discussions are based on these luminisity assumptions.

The CDF and D0 experiments have started taking data (Run IIa) recently. They plan to accumulate 2 $\mathrm{fb}^{-1}$ in 2002–3 and 15 $\mathrm{fb}^{-1}$ in 2005–7. The ATLAS and CMS experiments will start in 2007 and take 10 $\mathrm{fb}^{-1}$/year for three years (low-luminosity run period). The LHCb and BTeV experiments will be turned on sometime after 2008, and will accumulate 2 $\mathrm{fb}^{-1}$ per year. SLAC has a very ambitious plan to upgrade (or rebuild) PEP–II to achieve $10^{36}\mathrm{cm}^{-2}s^{-1}$ luminosity.

## 3. Measurements of the CKM matrix

### 3.1. Measurements of $\sin(2\phi_1)$

1. $\sin(2\phi_1)$ with $J/\psi K_S$

Belle and Babar have made the first observations of mixing-induced CP violation in the $B$-meson system. The results are $\sin(2\phi_1) = 0.99 \pm 0.14 \pm 0.06$[1] and $0.59 \pm 0.14 \pm 0.05$[2], based on data samples of $29.1\mathrm{fb}^{-1}$ and $\sim 30\mathrm{fb}^{-1}$, respectively. Belle has used more than 1300 tagged events. The statistical errors dominate in both measurements, and a luminosity increase will help to make more precise measurements. Figure 1 shows the prospects for the precision on $\sin(2\phi_1)$ measurements as a function of time. The sensitivity of measuring $\sin(2\phi_1)$ evaluated by

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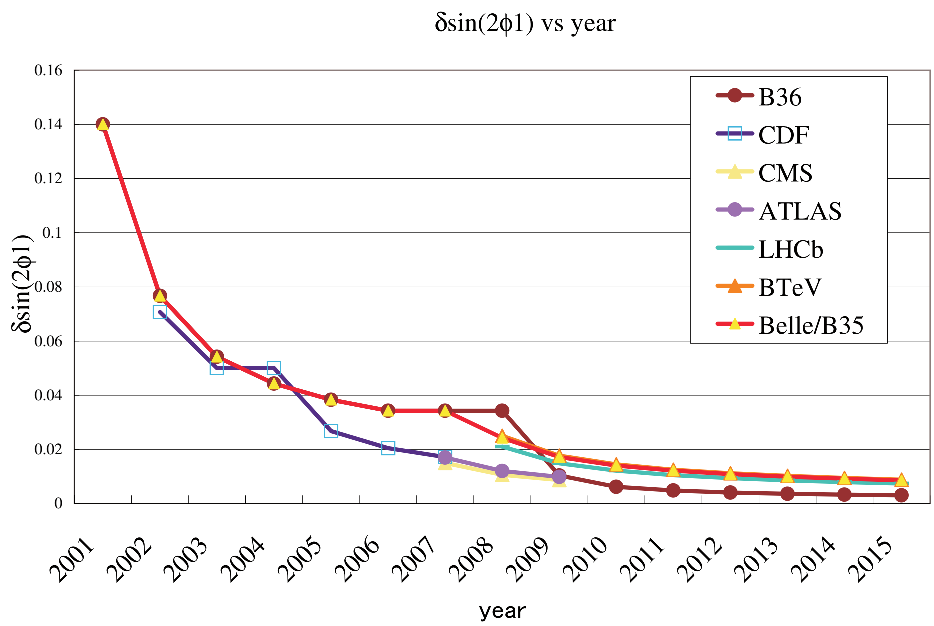


Figure 1: Sensitivity of measuring $\sin(2\phi_1)$ by B36(super PEP-II), CDF, CMS, ATLAS, LHCb, BTeV and Belle with the $10^{35}$ upgrade as a function of time (year).

competing experiments (CDF, ATLAS, CMS, LHCb, BTeV, and super Babar) are shown as well. With 300(3,000) $\mathrm{fb}^{-1}$ in 5(10) years, Belle expects to measure $\sin(2\phi_1)$ with a precision of $\delta\sin(2\phi_1) = 0.03$–$0.04(< 0.01)$. Several theoretical assumptions will break down at this precision, and thus detailed studies of the Penguin pollution etc. are necessary.

2. $\sin(2\phi_1)$ with $\phi K_S$

$B \to \phi K_S$ is another mode to measure $\sin(2\phi_1)$ via $b \to s\bar{s}s$, and may give a different result due to a difference in the contributions from New Physics. Belle has reported the branching fraction of $B^o \to \phi K_S$ to be $(0.89^{+0.34}_{-0.27} \pm 0.10) \times 10^{-5}$[3]. Belle has also measured $\mathrm{Br}(B^+ \to \phi K^+)$ to be $(1.12^{+0.22}_{-0.20} \pm 0.14) \times 10^{-5}$, based on a data sample of 21.6 $\mathrm{fb}^{-1}$. With 300(3,000) $\mathrm{fb}^{-1}$ in 5(10) years Belle will be able to measure the branching fraction of $B^o \to \phi K_S$ with a precision of less than 10(3)%. Belle will have about 600 tagged $\phi K_S, \phi \to K^+K^-, K_S \to \pi^+\pi^-$ events by 2011; the precision of the asymmetry measurement ($sin(2\phi_1)$ using $\phi K_S$) will be about 0.2. BTeV estimates that they have 240 tagged $\phi K_S$ per year with a signal-to-background ratio of 6.5. It may need a $10^{36}$ machine to make interesting measurements of $\sin(2\phi_1 + \theta_{NP})$.

### 3.2. Measurements of $\sin(2\phi_2)$

In principle, $\sin(2\phi_2)$ can be measured using the same technique as the $\sin(2\phi_1)$ measurement using the $b \to u\bar{u}(d\bar{d})d$ transition. The theoretical difficulties to extract the angle $\phi_2$ are not discussed in this paper. The Babar experiment has reported a measurement of the CP violating asymmetry, $S_{\pi^+\pi^-}$, to be $0.03^{+0.53}_{-0.56} \pm 0.11$ [4]. Babar has used $65^{+12}_{-11}$ $\pi\pi$ events in 33 million $B\bar{B}$ decays. Based on this measurement and Belle's study, we expect to measure the $\pi^+\pi^-$ asymmetry with a precision of 0.2(0.07) by 2006(2011). It is estimated that the asymmetry measurement of the neutral mode, $B \to \pi^o\pi^o$ will be 3 to 5-times less precise. CDF is now capable of triggering, and therefore measuring, the $S_{\pi^+\pi^-}$ asymmetry. The LHCb and BTeV experiments will be able to measure $\phi_2$ using $B \to \rho\pi$ decays. Their measurement precision will be $\delta\phi_2 \sim 5^\circ(\delta A_{CP} \sim 0.2)$ within a year of running at the design luminosity.

### 3.3. Measurements of $\phi_3$

#### 1. $\phi_3$ with DK

Methods to measure $\phi_3$ have been proposed by several authors. A detailed sensitivity study has been conducted by A. Soffer[7]. The author estimates, using a GEANT Monte Carlo simulation, that with a data sample of 600 fb$^{-1}$, the measurement will have a precision on $\phi_3$ of $\sigma_{\phi_3} \sim 5^\circ$–$10^\circ$, depending on the values of the phases ($\phi_3$, $\delta_B$ and $\delta_D$). However, due to eight-fold ambiguities (flip of the sign of $\phi_3$ and $\delta_B$, exchange of $\phi_3$ and $\delta_B$ and additional $\pi$ ($\phi_3 = \phi_3+\pi$, $\delta_B = \delta_B+\pi$)), the measurement may have little usefulness. The study shows that, with 6 ab$^{-1}$, ambiguities do not exist for most values of $\phi_3$ and $\delta_D$ and $\phi_3$ can be determined to a precision of 1.5–3°.

Belle has measured the asymmetry $A_1(D_{CP}K^-) = 0.04^{+0.40}_{-0.35} \pm 0.15$ based on $\sim$ 15 events into the $D_{CP\pm}K$ decay modes using a data sample of 21.3 fb$^{-1}$[5]. LHCb and BTeV can measure $\phi_3$ using $B_s \to D_sK^-$ decays. They estimate the precision to be 7–8° for one year of running.

#### 2. $\phi_3$ with $K\pi$

Belle searched for a direct CP asymmetry of $B \to K^+\pi^-$, and obtained $-0.25 < A_{CP}(K^+\pi^-)) < 0.37$ (90% confidence interval) based on $\sim 60K^\pm\pi^\mp$ events in a data sample of 10.4 fb$^{-1}$[6]. The asymmetry error ($\delta A_{CP}$) was 0.18. We therefore estimate that with 300(3,000) fb$^{-1}$ in 5(10) years Belle can measure the asymmetry with a precision of less than 0.03(0.01) using 2,000(20,000) $K^+\pi^-$ events. Ukai *et. al.* reported at this workshop, using a PQCD calculation, that there is a possibility to measure $\phi_3$ precisely using $K^+\pi^-$ and $\pi^+\pi^-$ events.

#### 3. $\phi_3$ with $D^*\pi$, $D^*\rho$ and $D^*a_0$

$\sin(2\phi_1 + \phi_3)$ can be measured using the $B \to D^*\pi$ and $D^*\rho$ decay modes. A Belle internal study shows that the measurement error, $\delta\sin(2\phi_1 + \phi_3)$, will be approximately 0.42 with a 100 fb$^{-1}$ data sample, using the partial reconstruction technique. From this study, we can expect to obtain $\sin(2\phi_1 + \phi_3)$ with a precision of 0.3(0.1) by 2006(11). Depending on the polarisation of the decay, the measurement error ($\delta A_{CP}$) from the decay $B \to D^*\rho$ is in the range of 0.3–1.0 with 30 fb$^{-1}$, and therefore 0.1–0.3(0.03–0.1) by 2006(11). $B \to D^*a_0$ may be useful to measure $\sin(2\phi_1 + \phi_3)$ as well.

By combining all of the above methods, we may be able to measure angle $\phi_3$ to a precision of 5° by 2006 and 2° by 2011.

### 3.4. Measurements of the matrix elements

Precision measurements of the sides of the triangle must be rigorously pursued. The precision of the magnitude of the CKM matrix elements depends on the experimental statistical and systematic errors as well as errors in the precision of the relevant lattice gauge theory predictions. The precision due to experimental errors is between 15 and 25% for $V_{ij}$ with the exception of the $V_{cb}$ case, which is about 2–4%. The precision will become 10–15% by 2006 and 3–5% by 2011. The precision of the theoretical quantities must improve at the same pace as that of the experimental precision.

### 3.5. Unitarity test

Whether or not the unitarity triangle is closed can be tested, for example, by summing the three angles ($\phi_1$, $\phi_2$ and $\phi_3$). The error of such a sum may be estimated from the prediction of the measurements discussed above. $\delta(\phi_1 + \phi_2 + \phi_3)$ in degree is equal to $(180/(2\pi)) \times (\delta(sin(2\phi_1))/cos(2\phi_1)) + \delta(sin(2\phi_2))/cos(2\phi_2))) + \delta\phi_3 \sim 13^\circ(< 6^\circ)$ in 2006(11).

It can also be checked using two sides and one angle of the triangle, for example, $V_{ub}$, $V_{cb}$ and $\phi_1$. The precision of these measurements will become, 10–15%, 15% and 1.5°, respectively by 2006 and 3–10%, 5% and 0.5°, respectively by 2011.

## 4. Rare decays

Flavour-changing neutral currents are forbidden in the Standard Model (SM) at the tree level, but can occur via loop or box diagrams. Additional contributions can arise from New Physics, such as charged Higgs bosons or super-symmetry particles. In this section we discuss the prospects for precision measurements of $B$ meson decays into $X_s\gamma$, $X_s\ell\ell$, and other rare decays.

### 4.1. $B \to X_s\gamma$

$B \to X_s\gamma$ has a large branching fraction. The inclusive branching fraction is predicted to be $(3.29 \pm 0.21 \pm 0.21) \times 10^{-4}$[8]. The two errors correspond to the scaling and experimental input parameter uncertainities. As we will see in the following discussion, the theory uncertainties must be reduced to $\sim$ 5% by 2011 to be compatible with the precision of the experiments.

#### 1. Inclusive $B \to X_s\gamma$

Using 9.7 million $B\bar{B}$ pairs, CLEO reported a precision measurement of the inclusive $B \to X_s\gamma$ mode: $(3.19 \pm 0.43 \pm 0.27) \times 10^{-4}$ at the 2001 Lepton Photon conference. Belle made a measurement earlier using a data sample of 10.4 fb$^{-1}$[9]. We expect the relative error on the branching fraction measurement to be $\sim$ 10% with a data sample of 30 fb$^{-1}$ using the semi exclusive reconstruction technique. Experiments at the $B$ factories take only 10% off resonance data, which may or may not limit the precision of this measurement. Assuming the measurement having a precision of 10% with a data sample of 30 fb$^{-1}$, the relative error, $\delta Br(B \to X_s\gamma)/Br(B \to X_s\gamma)$ will be 3% by 2006 and 1% by 2011. The $B$ factories are expected to measure this branching fraction better than hadron machines do.

#### 2. Exclusive $B \to K_X\gamma$

The relative error (statistical and systematic combined) on the branching fraction of $B \to K^*(892)\gamma$ will be less than 10% with a data sample of 10 fb$^{-1}$. Decays into other excited states of the K meson and $\gamma$ have larger relative errors. For example, Belle has reported a measurement of $Br(B \to K_2^*(1430)\gamma) = (1.26 \pm 0.66 \pm 0.10) \times 10^{-5}$ using a data sample of 21.3 fb$^{-1}$[10]. This branching fraction is derived from $20 \pm 10$ events. We therefore expect to obtain a precision of 5–20% on the many exclusive branching fractions, $B \to K_X\gamma$ by 2006

#### 3. $B \to X_s\gamma$ CP asymmetry

The direct CP asymmetry of $B \to X_s\gamma$ decays can be measured. Using a data sample of 30 fb$^{-1}$, the statistical error on the asymmetry ($\delta A_{CP}$) of the inclusive decays is expected to be between 0.1 and 0.2. For the exclusive decays, Babar has reported, using a data sample of 20 fb$^{-1}$, $\delta A_{CP}(B \to K^*(892)\gamma) = 0.08$. From these measurements, the precision measurements of the asymmetry of the inclusive $B \to X_s\gamma$ within 0.03–0.06 in 2006 and 0.01–0.02 in 2011 may be possible. The asymmetry of the exclusive decay, $B \to K^*(892)\gamma$ will be measured to a precision of 0.02—0.03 by 2006, using 6000 $B \to K^*(892)\gamma, K^*(892) \to K^+\pi^-$ events and 0.01 by 2011, 60,000. The indirect CP asymmetry in the $B \to K_1\gamma$ mode may be measured to a precision of 0.3 in 2006 and 0.1 in 2011.

### 4.2. $B \to X_d\gamma$

About 200 $B \to \rho\gamma$ events may be observed by 2006. However, huge backgrounds from the Cabibbo-favoured decays and continuum $q\bar{q}, q\bar{q}\gamma$ production must be overcome. It seems to be hard to measure the $B \to X_d\gamma$ branching fraction or other quantities. A detailed study must be conducted.

### 4.3. $B \to X_s\ell\ell$

The Standard Model prediction of the $B \to X_s\ell\ell$ inclusive branching fraction is $(5.7\pm1.2)\times10^{-6}$ and Br($B \to K^*(892)\ell\ell$), $(2.0 \pm 0.7) \times 10^{-6}$. Belle has observed the decays $B \to K\mu\mu$ for the first time and measured the branching fraction to be $Br(B \to K\mu\mu) = (1.0\pm0.4)\times10^{-6}$[11]. Bell has set upper limits on the inclusive branching fraction, $B \to X_s\mu\mu$ and $B \to Kee$ and other exclusive decay modes. By 2006, Belle will measure the branching fractions of these decay modes to a precision of 10–20% by observing 50–100 $K\ell\ell$ events in each decay mode and by 2011, 3–6%. Inclusive $X_s\ell\ell$ branching fractions, asymmetries, the $m_{\ell\ell}$ invariant mass spectra will be measured precisely, but a detailed estimation is necessary. LHCb(BTeV) estimates that they have 4,500(2,200) $K^*\mu\mu$ events per year with S/B of about 10. B factories should have a better signal-to-background in the low-$m_{\ell\ell}$ invariant mass region.

### 4.4. $B \to \ell\ell, \ell\nu$

The Standard Model predictions for $B \to \mu\mu$, $B \to \tau\nu$ and $B \to \mu\nu$ are $8\times10^{-11}$, 1-10$\times10^{-5}$ and 0.5–5$\times10^{-7}$, respectively. The experimental upper limits for $B \to \mu\mu$ and $B \to \mu\nu$ are $6.1 \times 10^{-7}$, and $2.1 \times 10^{-5}$, respectively. The single-event sensitivity of $B \to \mu\mu$ decay is $0.8 \times 10^{-7}$ for Belle using a data sample of 30 fb$^{-1}$. Belle has a preliminary result on the upper limit of $B \to \mu\nu$; the statistical error on the branching fraction is $2\times10^{-6}$. The $B$ factories will not be able to measure the SM $B \to \mu\mu$ branching fractions within 10 years. As for $B \to \mu\nu$, Belle may be able to observe this decay by 2011.

### 4.5. $B \to X_s\nu\nu,\ \tau\nu,\ D^*\tau\nu$

In order to observe the decays $B \to X_s\nu\nu,\ \tau\nu,\ D^*\tau\nu$, we need a fully reconstructed $B$-event sample. Assuming a full reconstruction efficiency of 0.1%, Belle will have 300,000(3 million) fully reconstructed events by 2006(2011). The single-event sensitivity could be as large as $10^{-6}$ for $B \to \tau\nu$ or $X_s\nu\nu$ by 2011. If so, and if the branching fraction is $10^{-5}$, we can measure them to a precision of 30%. However, more detailed feasibility studies are necessary, because many background events are expected to contaminate the signal.

## 5. Summary and conclusions

We have seen how the experimental precision of the $B$ meson decay properties might improve in the next five or ten years if we agressively continue to upgrade the luminosity of $B$ factories. The precision measurements of the CKM matrix elements, CP asymmetries as well as searches for rare decays provide a unique opportunity for finding and studying New Physics. Even in an LHC era, the properties and couplings of New Physics must be studied at the high-luminosity B factories. New generations of $B$ factories at a luminosity of $10^{35}$cm$^{-2}$s$^{-1}$ are the most effective way to understanding New Physics.

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