



Flavour physics and CP violation / Physique de la saveur et violation de CP

## *B* factories

### *Usine à meson B*

Adrian John Bevan

Queen Mary College, University of London, Mile End Road, London E1 4NS, UK

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#### ABSTRACT

The *B* factories were constructed with a very specific purpose in mind: to test the Cabibbo–Kobayashi–Maskawa description of quark mixing and CP violation in the Standard Model of particle physics. The goals of testing this part of the Standard Model were achieved, and have been surpassed beyond all expectation. As a result the *B* factories have revolutionised our understanding of many areas of the Standard Model of particle physics, and also provide a number of stringent limits on possible scenarios of physics beyond the Standard Model. In some cases these limits on new physics effects equal or surpass those achievable at the CERN based Large Hadron Collider.

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#### RÉSUMÉ

Les usines à *B* ont été construites en ayant un objectif très précis : tester la description du mélange des quarks et de la violation de la symétrie CP par la matrice de Cabibbo–Kobayashi–Maskawa. Ce but a été atteint et les résultats obtenus vont au delà des attentes. Les usines à *B* ont en effet révolutionné notre compréhension du Modèle Standard en fournissant des nombreux tests et des limites précises sur des scénarios de physique au delà du Modèle Standard. Ces limites peuvent souvent dépasser celles qui seront obtenus par le LHC.

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## 1. Introduction

The *B* factory experiments *BABAR* and Belle were designed and built to test the description of quark mixing in the Standard Model of particle physics (SM). This description provides a framework to understand how up and down-type quarks can change into each other in weak interactions. The original description of quark mixing was proposed by Cabibbo in 1963 [1] to describe the behaviour observed in leptonic hyperon decays. This simple quark mixing model worked well at the time it was proposed. However in 1964 Christenson et al. [2] made a profound discovery: matter and antimatter can behave differently. This difference is referred to as CP violation, where C is the symmetry of charge conjugation, and P is the parity operation. It was soon realised that the discovery of CP violation was related to the evolution of a matter dominated universe, but that the level of CP violation manifest in kaon decays is not enough to explain our universe. In 1973 Kobayashi and Maskawa [3] proposed extending Cabibbo's quark mixing model to three generations. By introducing two new quarks to the known set of particles, it was possible to naturally introduce a complex phase in the SM that is responsible for CP violation. The resulting ansatz is described by a  $3 \times 3$  unitary matrix called the Cabibbo–Kobayashi–Maskawa (CKM) matrix.

E-mail address: a.j.bevah@qmul.ac.uk.

**Table 1**  
Integrated luminosity ( $fb^{-1}$ ) of data recorded at different  $\sqrt{s}$  by the  $B$  factories.

$\sqrt{s}$	<i>BABAR</i>	Belle	Combined
$\Upsilon(5S)$	...	121	121
$\Upsilon(4S)$	433	711	1144
$\Upsilon(3S)$	30	3	33
$\Upsilon(2S)$	14.5	25	39.5
$\Upsilon(1S)$	...	6	6
Off-resonance	54	94	138

Given the measured level of CP violation in kaon decays, it is possible to predict the expected level of CP violation in  $B$  decays. The  $B$  factories were built to test these predictions, and the contribution to this issue by A.I. Sanda [4] reviews the motivation for the construction of the  $B$  factories and their primary measurement: The angle  $\beta = \phi_1$  of the unitarity triangle using  $B^0 \rightarrow J/\psi K_S^0$  decays. This article follows on from the motivational review to discuss the experimental journey taken by scientists working at the  $B$  factories.

## 2. Facilities and data samples

Following from the revelation that there was a potentially large CP violation effect that could be measured in  $B$  decays, there were a number of facilities proposed. Ultimately however, only two were realised: One at SLAC (now the SLAC National Laboratory) in California, and one at KEK in Japan. Both  $B$  factories are asymmetric energy  $e^+e^-$  colliders with detectors that have almost  $4\pi$  coverage at the interaction point of the collider. The SLAC experiment was comprised of the PEP-II collider [5] and the *BABAR* detector [6], and the KEK one comprised of the KEKB collider [7] and Belle experiment [8]. Both experiments were constructed and operated on similar time scales, with data taking commencing in 1999 and soon reached their respective design luminosities. After several years of operation, the SLAC and KEK  $B$  factories significantly exceeded the design luminosities, and were able to take flavour physics into a new realm of discovery. The *BABAR* experiment finished taking data in 2008 and will be followed by a next generation experiment Super*B*, to be built at the Cabibbo Laboratory in Italy, while Belle completed taking data in 2010 and is now in the process of being upgraded to Belle II [9].

These experiments have collected data at all of the  $\Upsilon$  resonances, during their lifetimes, and most of that data was accumulated while operating at a centre of mass energy  $\sqrt{s}$  corresponding to the  $\Upsilon(4S)$  resonance in order to perform the primary measurements of these experiments. In addition to this, the  $B$  factories recorded control samples of data while operating approximately 40 MeV below the  $\Upsilon(4S)$  resonance, and as in the case of Belle, a similar offset for the  $\Upsilon(5S)$  resonance. Data accumulated at the  $\Upsilon(4S)$  is referred to as on-resonance data, and that accumulated just below the  $b\bar{b}$  production is referred to as off-resonance data. Table 1 summarises the integrated luminosities accumulated by the experiments at different energies. In all, more than  $1 ab^{-1}$  was accumulated at the  $\Upsilon(4S)$  by these experiments, corresponding to more than a billion  $B$  meson pairs.

## 3. Physics results

At the time of writing this review, more than 400 papers have been published by the *BABAR* collaboration, and over 300 papers have been published by Belle. The following subsections review highlights of these results including the changes in our understanding of the phenomenon of quark mixing and CP violation in the SM, the recent discovery of mixing in charm decays, some of the new discoveries in spectroscopy, and finally direct and indirect searches for physics beyond the SM. The  $B$  factories are in the process of preparing a comprehensive review of their results. The work of this inter-experiment collaboration is expected to be finalised in 2012 [10].

### 3.1. The CKM revolution

Prior to the start of the  $B$  factories, the only direct constraints on CP violation and the CKM ansatz in the SM were from the study of neutral kaons. In addition to these direct tests, there were a number of indirect constraints that provided additional information. Together these formed the basis of measurements that could be used to predict anticipated effects in  $B$  meson decays. However, without testing the ansatz with data, it would have remained impossible to confirm or refute the applicability of the CKM mechanism as the description of CP violation in the SM. The  $B$  factory contribution to direct (indirect) tests of the CKM paradigm are described in Section 3.1.1 (3.1.2). The CKM revolution at the  $B$  factories started with the measurement of one of the angles of the unitarity triangle, and has left us with a far richer understanding of nature than anyone conceived in the early days.

#### 3.1.1. Angle measurements

The angles of the unitarity triangle have different notations for the KEK and SLAC  $B$  factories. The KEK experiment uses  $\phi_1, \phi_2$ , and  $\phi_3$ , whereas the SLAC experiment uses  $\beta, \alpha$ , and  $\gamma$ . For brevity the SLAC notation is used in the remainder of this article. As noted by Sanda, in order to measure a time-dependent CP asymmetry in  $B\bar{B}$  decays, one has to use

**Table 2**

Measurements of  $S = \sin(2\beta)$  made by the  $B$  factories. The first uncertainty is statistical, and the second is systematic. Note that for some measurements there are only statistical uncertainties quoted, and only a total statistical and systematic uncertainty is quoted for the combined results.

Decay mode	<i>BABAR</i>	<i>Belle</i>	Combined
$J/\psi K_S^0$	$0.657 \pm 0.036 \pm 0.012$	$0.643 \pm 0.038$	–
$J/\psi K_L^0$	$0.694 \pm 0.061 \pm 0.031$	$0.641 \pm 0.057$	–
$J/\psi K^0 (K_S^0 \text{ and } K_L^0)$	$0.666 \pm 0.031 \pm 0.013$	$0.642 \pm 0.031 \pm 0.017$	$0.655 \pm 0.024$
$\eta' K^0$	$0.57 \pm 0.08 \pm 0.02$	$0.64 \pm 0.10 \pm 0.04$	$0.59 \pm 0.07$
$\psi(2S) K_S^0$	$0.897 \pm 0.100 \pm 0.036$	$0.718 \pm 0.090 \pm 0.031$	$0.798 \pm 0.071$

information from both  $B$  mesons produced in an  $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$  event. Events of interest are those where one  $B$  decays into an interesting final state that is used to extract information about CP asymmetries (the  $B_{\text{rec}}$ ), and the other  $B$  meson is reconstructed in a final state that determines (tags) the flavour of the  $b$  quark in it (the  $B_{\text{tag}}$ ). In general, the decay-rate distribution  $f_+(f_-)$  of a  $B$  meson decaying into a CP eigenstate, for  $B_{\text{tag}} = B^0(\bar{B}^0)$ , as a function of the proper time difference  $\Delta t$  between the decaying  $B$  mesons is

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \left[ 1 \mp \Delta\omega \pm (1 - 2\omega)(-\eta_f S \sin(\Delta m_d \Delta t) \mp C \cos(\Delta m_d \Delta t)) \right] \otimes R[\Delta t, \sigma(\Delta t)] \quad (1)$$

where the CP eigenvalue of the final state  $f$  is  $\eta_f$ ,  $\tau = 1.525 \pm 0.009$  ps is the mean  $B^0$  lifetime, and  $\Delta m_d = 0.507 \pm 0.005$  ps $^{-1}$  is the  $B^0\bar{B}^0$  mixing frequency [11]. The parameter  $\omega$  is the probability of incorrectly assigning the flavour of the  $B_{\text{tag}}$ , and  $\Delta\omega$  is the difference in  $\omega$  for  $B^0$  and  $\bar{B}^0$  tagged events. The physical decay rate is convoluted with the detector resolution  $R[\Delta t, \sigma(\Delta t)]$ . As the difference in total decay rates  $\Delta\Gamma$  between  $B$  and  $\bar{B}$  is expected to be small in the SM, it is assumed that  $\Delta\Gamma = 0$ . The parameters  $S$  and  $C$  are defined as

$$S = \frac{2\text{Im}\lambda}{1 + |\lambda|^2}, \quad C = \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \quad (2)$$

where  $\lambda$  is related to  $B^0\bar{B}^0$  mixing and the decay amplitudes of  $B^0$  and  $\bar{B}^0$  mesons to the final state. Depending on the final state  $S$  may be related to  $\beta$  in the case of a  $b \rightarrow c$  or  $b \rightarrow d$  transition, or  $\alpha$  for a  $b \rightarrow u$  transition. The angle  $\gamma$  can be measured using charged  $B$  decays involving a  $b \rightarrow u$  transition. The value of  $C$  depends on strong phase differences, and for  $B^0 \rightarrow J/\psi K^0$  one expects  $C$  to be zero.

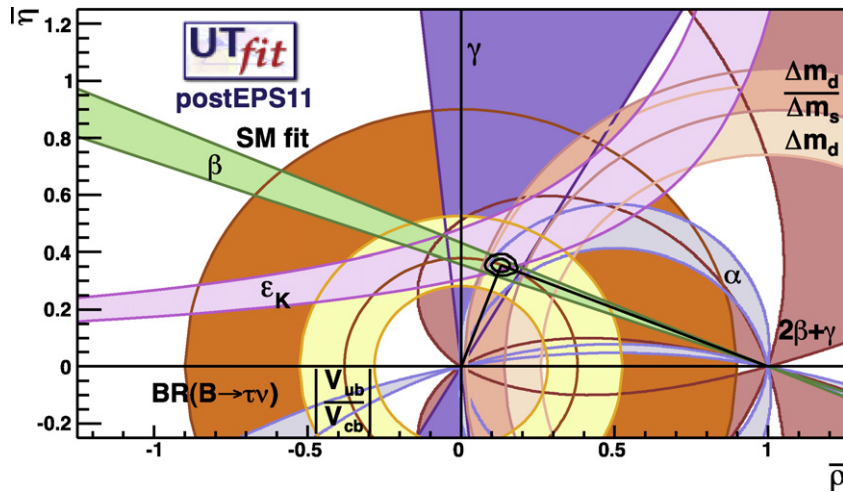
The discovery of CP violation in  $B$  meson decays in 2001 was made almost simultaneously by the  $B$  factories, with *BABAR* announcing their result less than two weeks before *Belle*. The measurement establishing CP violation in these decays was a non-zero result for  $\beta$  in  $B^0 \rightarrow J/\psi K^0$  decays [12,13]. This result was in agreement with expectations, and is the first of many. Table 2 summarises the most precise measurements of  $S = \sin 2\beta/\sqrt{1 - C^2}$  that have been made by the  $B$  factories [14–18]. These measurements surpass all of the initial expectations of the  $B$  factories, and have resulted in a precision test of the SM. The decays involving a harmonium,  $c\bar{c} = J/\psi$  or  $\Psi(2S)$ , and a neutral kaon are theoretically clean. The  $B \rightarrow \eta' K^0$  channel has a small theoretical uncertainty associated with the translation from  $S$  and  $C$  to  $\sin 2\beta$ . All of these measurements are consistent with one another, although the precision of that test has only been made at the 10% level. The angle  $\beta$  is approximately  $22^\circ$  and has been measured with a precision better than  $1^\circ$ . The fact that  $\beta \neq 0$  is an example of matter and antimatter behaving differently. In contrast to the unexpected 1964 results, the effect discovered here is large.

Just as the expectations for measuring  $\sin 2\beta$  at the  $B$  factories were surpassed, the precision with which the  $B$  factories have determined the other angles has surpassed original expectations. The most precise measurement of the angle  $\alpha$  was assumed to be via  $B$  decays into a  $\pi^+\pi^-$  final state, however theoretical uncertainties introduced through higher order loop (penguin) diagrams, complicate the extraction of this angle. In order to control the theoretical uncertainties, one has to also measure the  $\pi^\pm\pi^0$  and  $\pi^0\pi^0$  final states. We now know that this process requires substantially more data than available at the  $B$  factories in order to make a precise measurement of  $\alpha$ . Other final states have been explored in the quest to measure  $\alpha$ , including  $\rho\rho$ ,  $\rho\pi$ , and  $a_1\pi$ . For  $B \rightarrow \pi^+\pi^-$  and  $\rho^+\rho^-$  decays,  $S$  and  $C$  are related to an effective parameter via  $\sin 2\alpha_{\text{eff}} = S/\sqrt{1 - C^2}$ . The parameters  $\alpha$  and  $\alpha_{\text{eff}}$  are related to each other via  $\alpha - \alpha_{\text{eff}} = \Delta\alpha$  [19], where  $\Delta\alpha$  is a shift in the measurement resulting from loop processes. The most precise determination of  $\alpha$  comes from  $B \rightarrow \rho\rho$  decays where information from the  $\rho^+\rho^-$ ,  $\rho^\pm\rho^0$ , and  $\rho^0\rho^0$  final states is required to control theoretical uncertainties from loops [20–25]. The combined average of all measurements of this angle gives  $\alpha = (91.4 \pm 6.1)^\circ$  [26].

The measurement of  $\gamma$  is theoretically cleaner than that of  $\alpha$ , however experimentally this is a more challenging task. This angle is obtained from a study of  $B \rightarrow D^{(*)}K^{(*)}$  decays, utilising the interference between Cabibbo allowed and suppressed transitions. The results of a number of methods need to be combined together in order to obtain an estimate of this angle. On doing this one obtains  $\gamma = (74 \pm 11)^\circ$  [26].

### 3.1.2. Side measurements

Indirect measurements of the sides of the unitarity triangle predate the  $B$  factories, however with the large data samples accumulated since 1999, *BABAR* and *Belle* have been able to redefine our knowledge of these quantities. The results of these



**Fig. 1.** The direct and indirect constraints on the apex of the unitarity triangle from Ref. [26]. The apex is indicated by the elliptical contours shown in the first quadrant.

efforts culminate in an unclear picture. For both  $|V_{ub}|$  and  $|V_{cb}|$ , there is some disagreement between inclusive and exclusive determinations of these quantities. Discrepancies remain even after analysing almost all of the data available from the  $B$  factories. It won't be possible to either resolve, or unequivocally establish these discrepancies with the current generation of  $e^+e^-$  experiments.

### 3.1.3. Direct CP violation

Non-zero angles of the unitarity triangle result from interference between mixing and decay amplitudes, and these are predicted by the single phase found in the CKM matrix. Another type of CP violation can come from direct decay of the initial  $B$  into a final state. In the kaon system it took thirty five years to detect direct CP violation via the measurement of a non-zero value of  $\epsilon'/\epsilon$ . That measurement was a tour de force in rigour and detail as the magnitude of  $\epsilon'/\epsilon$  is a few  $\times 10^{-4}$ . Somewhat surprisingly for the  $B$  system, the large effects manifest in the angles were repeated in the pattern of direct CP asymmetries. Only a few years after the discovery of CP violation the  $B$  factories both discovered large direct CP violation in  $B \rightarrow K^\pm \pi^\mp$  decays. This was somewhat surprising as a priori the level of direct CP violation requires two non-zero phase differences: a difference in weak phases that change sign under CP and one in strong phases that do not change sign. Actually the asymmetry is the product of the sines these two phase differences, so in general one would have expected a small number, not something  $\sim 10\%$ . While the weak phases are predicted by CKM, the latter arise from strong interactions, and are difficult to calculate. A large number of asymmetries have been measured in the quest to uncover more signals of direct CP violation.

### 3.1.4. Global combinations

One can combine direct and indirect constraints on the unitarity triangle in a so-called 'global CKM fit'. Two groups, CKM fitter and UTfit produce updates of the global CKM fits on a regular basis. Their results are dominated by inputs from the  $B$  factories, an example of which is shown in Fig. 1, where, in general, there is agreement between all of the inputs and the result of the global CKM fit, however there is some tension introduced into the fit by some of the variables. The different constraints shown on the plot are as follows:

- $\beta$  (green): the value of the CKM angle  $\beta$  obtained from time-dependent CP asymmetry measurements of  $B^0 \rightarrow J/\psi K_S^0$ ;
- $\alpha$  (light blue): the value of the CKM angle  $\alpha$  obtained from time-dependent CP asymmetry measurements of  $B$  meson decays into  $\pi\pi$ ,  $\rho\pi$ , and  $\rho\rho$  final states. The overall precision is dominated by  $\rho\rho$  decays;
- $\gamma$  (purple): the value of the CKM angle  $\gamma$  obtained from studies of  $B$  meson decays into  $D^{(*)}K^{(*)}$  final states using the various approaches that have been proposed;
- $\sin(2\beta + \gamma)$  (dark pink): The measured combination of angles obtained from an analysis of  $B \rightarrow D^*\pi$  decays;
- $\Delta m_d$  (light peach): The mixing frequency of  $B_d^0$  and  $\bar{B}_d^0$ ;
- $\Delta m_d/\Delta m_s$  (peach): The ratio of mixing frequencies for  $B_d$  and  $B_s$  mesons;
- $|V_{ub}/V_{cb}|$  (yellow): The ratio of CKM matrix elements obtained from branching fraction measurements of  $b \rightarrow u\ell\nu$  and  $b \rightarrow c\ell\nu$  decays;
- $B \rightarrow \tau\nu$  (orange): This constraint comes from the branching fraction measurement of the rare decay  $B \rightarrow \tau\nu$ ;
- $\epsilon_K$  (lilac): This constraint corresponds to the level CP violation in kaon decays originally discovered in 1964, using the latest results from the KLOE experiment.

In particular the values of  $V_{ub}$ ,  $V_{cb}$ ,  $\sin 2\beta$ , and the rare decay  $B \rightarrow \tau \nu$  are not in good agreement with each other. The CKM ansatz has been tested at the 10% level and shown to work, these observed incompatibilities, however, raise the possibility that we may be on the verge of learning something new. Significant progress in this area will be made by next generation of experiments: LHCb, SuperB, and Belle II.

Having confirmed that the CKM ansatz is compatible with all of the measurements of the  $B$  factories and the predecessor kaon experiments, Kobayashi and Maskawa were awarded part of the Nobel Prize for physics in 2008 for their insight into nature. While this achievement, guided by the results of the  $B$  factories, has been very significant, the question remains as to how one can accommodate matter–antimatter asymmetries into the SM that would naturally allow us to explain the existence of the matter dominated universe. Indeed it should be noted that the constraints on the unitarity triangle shown in Fig. 1 are at the 10% level, so there is significant scope for physics beyond the SM to manifest effects that could deviate from the CKM ansatz.

### 3.2. Secondary revolutions

While elucidating CP violation was the dominant goal of the initial  $B$  factory revolution, there were several secondary revolutions. These encompass light meson spectroscopy and charm mixing.

#### 3.2.1. The spectroscopy revolution

Belle's discovery of the  $X(3872)$  [27] in 2003 started an industry of searches for new particles within the context of the SM. This discovery was followed in 2005 by that of  $Y(4260)$  in the study of  $J/\psi \pi \pi$  using initial state radiation (ISR) data at  $BABAR$  [28]. The  $B$  factories and other experiments have been rewriting textbooks on our knowledge of light mesons ever since. The crowning achievement was the discovery by  $BABAR$  of the ground state of the  $b\bar{b}$  system, the  $\eta_b$  [29], in 2008 after several decades of searches performed by various experiments.

During the latter years of running at  $BABAR$  and Belle, data was taken at resonances other than the  $\Upsilon(4S)$ . The harvest of results from these data samples is ongoing. These include searches for light scalar particles that could be dark matter or light Higgs particles manifest through physics beyond the SM, and other fundamental tests such as verification of Lepton universality. The Belle experiment recorded data at the  $\Upsilon(5S)$ , which gives experimenters access to a number of excited states of the  $B$  meson that can be studied in some detail.

#### 3.2.2. The charm revolution

In 2007  $BABAR$  and Belle discovered the phenomenon of mixing in the  $D^0\bar{D}^0$  system [30,31]. The current constraints on charm mixing from all available measurements is  $x = 0.65^{+0.18}_{-0.19}\%$ ,  $y = 0.72 \pm 0.12\%$  [17]. While uncertainties in the interpretation of the level of mixing are large, the existence of this phenomenon is significant. Since the discovery of mixing, it has been proposed that one may accumulate data at the  $\psi(3770)$  using an asymmetric energy collider to obtain a sample of quantum correlated  $D^0\bar{D}^0$  events to search for CP violation in analogy to the programme of measurements that formed the core of the legacy of the  $B$  factory era [32].

### 3.3. Search for physics beyond the Standard Model

Many searches for physics beyond the SM have been performed by the  $B$  factories. Two of the highlights of this work are the measurement of  $B \rightarrow \tau \nu$ , which, as mentioned above, can be used to constrain the CKM ansatz, and searches for lepton flavour violating  $\tau$  decays. The former channel,  $B \rightarrow \tau \nu$  can be used to constrain the mass of charged Higgs particles in many popular extensions of the SM. These constraints are largely independent of higher order corrections from the model, and rule out the discovery of any light charged Higgs particles. Given the luminosity profile of the LHC, it is unlikely that the LHC will enter new territory in terms of direct searches for charged Higgs particles before the end of the decade.

Limits placed on lepton flavour violating  $\tau$  decays by the  $B$  factories provide stringent upper bounds on theoretical models, and in many cases this highlights the correlation between predictions of quark mixing, charged lepton flavour violation, and neutrino mixing (for example see [33] and references therein).

The CKM revolution was led by the measurement of  $\sin 2\beta$  from tree dominated decays (Section 3.1.1), however as the  $B$  factories surpassed expectations by such a large margin there was a secondary wave of time-dependent angle measurements focusing on loop dominated process. There are many decays of a  $B$  meson into a final state via either a  $b \rightarrow s$  or a  $b \rightarrow d$  quark loop transition. The former generally occur free from contamination by tree amplitudes, whereas the latter have a combination of both contributions. New heavy particles have been postulated that could contribute to loop transitions like these. If present in loops these new particles could change the value of  $S$  measured so that it was different from  $\sin 2\beta$ . The most precise measurement of a  $b \rightarrow s$  loop transition is that of  $B \rightarrow \eta' K^0$  discussed above.

There are other  $b \rightarrow s$  transitions that are sensitive to new physics contributions, and consequently can be used to place stringent constraints on new models. In addition to the  $b \rightarrow s$  loop time-dependent measurements, there are three vertex loops such as the  $b \rightarrow s \gamma$  radiative penguin decay, and so-called flavour changing neutral currents arising from a four vertex loop, for example  $b \rightarrow s \ell^+ \ell^-$ , where  $\ell = e, \mu, \tau$ . For example, the combination of measurements of inclusive branching fractions of these inclusive processes and the CP asymmetry in  $b \rightarrow s \gamma$  can be used to constrain the magnitude of generic flavour couplings in a SUSY-CKM matrix, and in turn are related directly to the mass scale of SUSY [34,35]. Current

data allow for large new physics effects. The lack of new physics discovery so far at the LHC is suggestive of a new physics scale higher than originally implied by the hierarchy problem. This in turn is highly suggestive of a non-trivial *flavour-rich* realm of physics beyond the SM.

The measurement of the anomalous magnetic moment of the muon,  $(g - 2)/2$ , places stringent constraints on possible models of new physics, and in particular on various minimal SUSY models. Currently there is some tension between the experimental measurement and theoretical calculation of  $g - 2$ , that in itself could be an indication of physics beyond the SM. One of the inputs required in order to interpret the  $g - 2$  data is a precision measurement of the cross section for  $e^+e^- \rightarrow \pi^+\pi^-$  transitions at low energy. Using ISR data it is possible to measure the cross section of this process over a large range of energies, and in turn improve our knowledge of the anomalous muon magnetic moment [36].

#### 4. Summary

The  $B$  factories have been extremely successful in testing the SM of particle physics. The CKM mechanism has been shown to be the correct leading order description of CP violation by these experiments. Both direct and indirect tests of the predictions of this mechanism agree well, however it is not yet possible to exclude higher order corrections from physics beyond the SM manifest at the 10% level. The aim of elucidating the matter–antimatter asymmetry problem of the universe has resulted in a deeper understanding of the differences between matter and antimatter. Yet we are no closer to being able to resolve the conundrum as to why the universe came to exist in its matter dominated state. The discovery of CP violation in the decay of  $B$  mesons was one of many insights unravelled at the  $B$  factories. Other discoveries made at these experiments include the observation of a number of new meson states which have provided insights into previously unresolved puzzles. For example after many decades of searching for the ground state  $b\bar{b}$  meson, the  $\eta_b$  was found. Many of the new particles found have improved our understanding of the underlying theoretical framework, filling in a number of missing links along the way. However, there are some unresolved issues that need further investigation by experiments with more data than the  $B$  factories have. Another major discovery of these experiments was the phenomenon of neutral charm meson mixing. By discovering this effect in nature, analogous to neutral  $B$  meson mixing, one now has the opportunity to plan experiments utilising quantum correlations at the  $\psi(3770)$  in order to search for CP violation in a unique way. The inspiration for a new experimental programme to study precision CP measurements has been born from the labours of the  $B$  factories. This is an interesting prospect as CP violation characteristics of an up-type quark can be probed at a next generation of experiments. Thus far only transitions involving  $s$  and  $b$  quarks have been studied in detail, and one may uncover new clues about the matter–antimatter asymmetry problem through the study of CP violation in charm decays.

The  $B$  factories revolutionised the field of flavour physics, by quickly achieving their main goals in the study of CP violation in  $B$  meson decays. The foresight that led to the construction of these machines, enabled these experiments to surpass all of the initial expectations of physics results, and in doing so caused secondary revolutions of our knowledge of the flavour sector with charm mixing, as well as in other areas such as indirect new physics searches, and spectroscopy.

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