

The Super Flavor Factory

A. J. Bevan^{a*}

^aPhysics Department, Queen Mary, University of London, E1 4NS, UK.

The main physics goals of a high luminosity e^+e^- flavor factory are discussed, including the possibilities to perform detailed studies of the CKM mechanism of quark mixing, and constrain virtual Higgs and Non-Standard Model particle contributions to the dynamics of rare $B_{u,d,s}$ decays. The large samples of D mesons and τ leptons produced at a flavor factory will result in improved sensitivities on D mixing and lepton flavor violation searches, respectively. One can also test fundamental concepts such as lepton universality to much greater precision than existing constraints and improve the precision on tests of CPT from B meson decays. Recent developments in accelerator physics have demonstrated the feasibility to build an accelerator that can achieve luminosities of $\mathcal{O}(10^{36} \text{ cm}^{-2}\text{s}^{-1})$.

1. INTRODUCTION

Recent developments in accelerator physics show that it is feasible to construct an e^+e^- collider with a luminosity of $10^{36} \text{ cm}^{-2}\text{s}^{-1}$, which is a factor of fifty increase relative to the current B -factories [1,2]. This paper discusses the physics potential of a Super Flavor Factory (SFF) associated with such a collider. The physics potential of a SFF comes from vast samples of $B_{u,d,s}$, D mesons and τ leptons that can be produced, in addition to the flexibility of operating at different center of mass energies (\sqrt{s}). One can study $\Upsilon(nS)$ decays where $n = 1, 2, 3, 4, 5$, and perform precision measurements of the ratio $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$. Detailed reports have been compiled on the potential of a SFF [3–5].

The remainder of these proceedings discuss precision tests of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [6,7], new physics constraints from loop-dominated processes, rare charmless B decays, tests of the combined symmetry of charge-conjugation, parity and time reversal (CPT), charm and τ physics opportunities and the physics potential from analysing data accumulated at the $\Upsilon(1S, 2S, 3S, 5S)$ resonances.

*This work is supported by PPARC and the DOE under contract DE-AC02-76SF00515.

2. PRECISION CKM METROLOGY

Violation of the combined symmetry of charge-conjugation and parity (CP) was first seen in the decay of neutral kaons [8]. All CP violation (CPV) in the Standard Model (SM) is the result of a single complex phase in the CKM quark-mixing matrix. It was shown some time ago that CPV is a necessary but insufficient constraint in order to generate a net baryon anti-baryon asymmetry in the universe [9]. The other requirements for this asymmetry are a non-thermal equilibrium in the expansion of the universe and baryon number violation. In the ensuing years there has been a tremendous amount of activity to elucidate the role of CPV in the SM. All measurements of CPV produced by the *BABAR* [10] and *Belle* [11] experiments are consistent with the CKM description of CPV , and insufficient to explain the matter-antimatter asymmetry of the universe.

The SM description of CPV for $B_{u,d}$ decays is manifest in the form of a triangle in a complex plane. This triangle has three non-trivial angles, α , β , and γ , and two non-trivial sides with magnitudes $|V_{us}V_{ub}^*|/|V_{cd}V_{cb}^*|$ and $|V_{td}V_{tb}^*|/|V_{cd}V_{cb}^*|$, where V_{ij} are elements of the 3×3 CKM matrix. The limiting factor in the determination of the sides of the triangle are the magnitudes of the CKM matrix elements $|V_{ub}|$ and $|V_{td}|$. The first step toward understanding any new physics

weak phase or amplitude contribution to the flavor sector is to precisely understand the SM contributions. To this end, one has to overconstrain the parameters describing the unitarity triangle before embarking on a quest to find deviations from SM behavior.

The angle β is determined from a time-dependent analysis of $b \rightarrow c\bar{c}s$ decays [12]. This determination is from tree-dominated processes that are theoretically clean and provides a baseline to compare against the results from measurements of $b \rightarrow s$ and $c\bar{c}d$ transitions. The current results from the B -factories on this parameter are Refs. [13,14]. As the precision of these measurements increase it will become increasingly important to improve our understanding of possible SM pollution [15–17]. Open charm decays such as $B^0 \rightarrow J/\psi\pi^0$ [18,19] can be used to estimate this SM pollution [17]. A SFF will be able to improve on existing measurements of this angle and provide competitive results in the LHC era.

The measurement of α is more complicated than that of β [20,21]. The parameters of the time-dependent analysis of $b \rightarrow u\bar{u}d$ transitions do not provide a clean measurement of α , but measure an effective parameter dependent on tree and loop (penguin) contributions to the overall weak phase. The most stringent method for extracting α currently comes from the study of $B \rightarrow \rho\rho$ decays [22–24]. This result has an 8-fold ambiguity, with degenerate solutions. The degeneracy can be resolved using the result of a time-dependent Dalitz-plot analysis of $B^0 \rightarrow \pi^+\pi^-\pi^0$ decays [25,26]. The precision on α measured using $B \rightarrow \pi\pi$ decays is limited by the ability to measure $B^0 \rightarrow \pi^0\pi^0$. A SFF will enable us to perform a precision measurement of this mode. There will be sufficient statistics to measure time-dependent asymmetry parameters through $\pi^0\pi^0$ decays with photon conversions, and a precision study of $B^0 \rightarrow \pi^0\pi^0$ means that an isospin analysis of $B \rightarrow \pi\pi$ decays will become an increasingly important contribution to the overall constraint on α . The constraint on α obtained at a SFF will be a combination of results from all of these channels. The hadronic environment of LHCb results in difficulties in studying channels with neutral particles in the final state and some channels re-

quired to constrain penguins in $b \rightarrow u\bar{u}d$ transitions will only be accessible to a SFF.

A precision measurement of γ will require a systematic study of the many methods proposed in the literature [27]. One of the most promising channels to extract γ is $B \rightarrow DK$, where $D^0 \rightarrow K_s^0\pi^+\pi^-$, and the structure of the $K_s^0\pi^+\pi^-$ Dalitz plot is used in the fit [28]. A SFF with 50 ab^{-1} should be able to measure γ at the level of 2° with this method [29]. The precision of the constraint on γ using the Atwood-Dunietz-Soni [30] and Gronau-London-Wyler [31] methods is expected to be dominated by Dalitz-plot model uncertainties at a SFF.

A SFF will be able to test the closure of the unitarity triangle to a few degrees with a dataset of 50 ab^{-1} . The projected sensitivities for α , β and γ are 2° , 0.2° and 2° , respectively as shown in Figure 1. This level of sensitivity is comparable to the expectations of an upgraded LHCb experiment [32]. In addition to performing the primary measurements of the unitarity triangle angles, a SFF has the ability to perform measurements that will enable better determination of the SM theoretical pollution to the angle measurements. This is a critical aspect of searching for manifestations of a NP weak phase.

3. NEW PHYSICS FROM LOOPS

The Higgs particle and supersymmetry are introduced to the SM as the standard way to elucidate the mass generation mechanism [34] and resolve the hierarchy problem [35,36]. The energy scale of the Higgs and NP contributions are widely expected to be introduced below $\sim 1\text{ TeV}$. When extending the SM to accommodate new particles at this scale, one introduces couplings in the flavor sector that will impinge on low energy measurements of flavour-changing neutral currents (FCNCs) and processes dominated by penguin amplitudes at a B -factory. Most calculations with a NP contribution to the effective Lagrangian introduce a fine-tuning problem by setting the NP flavor parameters to zero. The rest of this section highlights a few specific examples of processes that can be used to constrain the effects of NP.

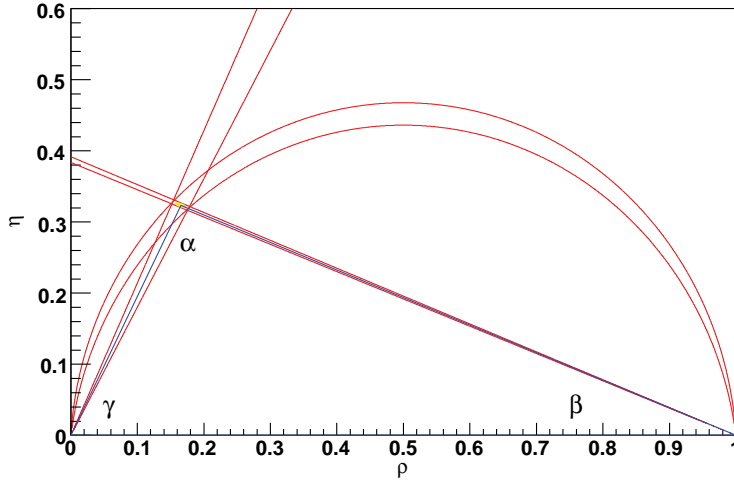


Figure 1. A prediction of the constraint on the unitarity triangle obtained at a SFF using a 50 ab^{-1} data sample. The contours represent 68.3% confidence level intervals in the $\rho - \eta$ plane (the parameters which are defined in the Wolfenstein expansion of the CKM matrix [33]).

3.1. Measurements of ΔS

The B -factories have recently observed CPV in $B \rightarrow \eta' K^0$ decays [37,38]. These $b \rightarrow s$ penguin processes are probes of NP, and have the most precisely measured time-dependent CP asymmetry parameters of all of the penguin modes. Any deviation ΔS of the measured asymmetry parameter $S_{\eta' K^0}$ from $\sin 2\beta$ is an indication of NP (for example, see Refs. [3,4]). The anticipated precision on ΔS for $\eta' K^0$ is ~ 0.015 with a data sample of 50 ab^{-1} . In addition to relying on theoretical calculations of the SM pollution to these decays [39–41], it is possible to experimentally constrain the SM pollution using $SU(3)$ symmetry [42]. This requires precision knowledge of the branching fractions of the B meson decays to the following pseudo-scalar pseudo-scalar (PP) final states $\pi^0 \pi^0, \pi^0 \eta, \pi^0 \eta', \eta \eta, \eta' \eta, \eta' \eta'$ [43,44]. As these PP channels have several neutral particles in each of their final states, they will be very difficult to study in a hadronic collider environment. The decay $B \rightarrow \phi K_S^0$ is another theoretically clean $b \rightarrow s$ penguin channel to search for

signs of NP [3–5]. The expected 50 ab^{-1} SFF precision on ΔS for $K^+ K^- K^0$, which contains the mode ϕK^0 , is ~ 0.017 .

3.2. $b \rightarrow s \gamma$

The $b \rightarrow s \gamma$ penguin decays provide one of the most sensitive constraints on possible NP (for example, see Ref. [45]). The existing experimental measurements and interpretation of results has been widely debated (for example, see Ref. [46]). Of interest are both inclusive and exclusive decays where the rate measurement is used to constrain the mass of Higgs particles (see Refs. [45,46]). However in addition to this, it is possible to measure time integrated and time dependent CP asymmetry parameters. These measurements also provide stringent constraints on NP models, and the expected precision on the charge asymmetry with 10 ab^{-1} at a SFF is $\sim 1\%$.

3.3. $b \rightarrow s ll$

The $b \rightarrow s ll$ ($l = e, \mu$) processes are the result of FCNCs. The forward-backward asymme-

try of these FCNC processes are sensitive to NP contributions. Recently the *BABAR* and Belle experiments started to study the asymmetry [47,48] and a high statistics evaluation of the forward-backward asymmetry is required to elucidate the nature of any NP contribution to these decays. The SFF will be able to study both e^+e^- and $\mu^+\mu^-$ final states. The physics reach of a SFF with these decays will be competitive with any results from an upgraded LHCb experiment. With 50ab^{-1} it is expected that the effective parameters related to the Wilson coefficients $C_{9,10}$ can be measured to 10-15% from the forward backward asymmetry in $B \rightarrow K^*l^+l^-$.

3.4. $B \rightarrow VV$ decays

The angular analysis of $B \rightarrow VV$ decays (where V is a vector meson) provides eleven observables (six amplitudes and five relative phases) that can be used to test theoretical calculations [49]. The hierarchy of A_0 , A_+ , and A_- amplitudes obtained from a helicity (or A_0 , A_{\parallel} , and A_{\perp} in the transversity basis) analysis of such decays allows one to search for possible right handed currents in any NP contribution to the total amplitude. For low statistics studies, a simplified angular analysis is performed where one measures the fraction of longitudinally polarised events defined as $f_L = |A_0|^2 / \sum |A_i|^2$, where $i = -1, 0, +1$. Current data for penguin-dominated processes ($\phi K^*(892)$ [50,51], $K^*(892)\rho$ [52,53]) that are observed to have non-trivial values of f_L can be accommodated in the SM. A SFF with a 10ab^{-1} data-set would be able to provide sub 1% measurements of A_i in ϕK^* . In addition to this, one can search for T -odd CP violating asymmetries in triple products constructed from the angular distributions [54]. It has also been suggested that non-SM effects could be manifest in a number of other observables [55]. The measured rates of electroweak penguin-dominated B decays to final states involving a ϕ meson are also probes of NP [56]. The study of $B \rightarrow AV$ decays (where A is an axial-vector meson) also provides this rich set of observables to study, however current results only yield an upper limit on $B^0 \rightarrow a_1^{\pm}\rho^{\mp}$ decays [57]. *BABAR* have recently studied the angular distribution for $B \rightarrow \phi K^*(1430)$ [50].

4. CPT

The combined symmetry CPT is conserved in locally gauge invariant quantum field theory [58–61]. It is possible to construct theories of quantum gravity where Lorentz symmetry breaks down and the quantum coherence of the $B\bar{B}$ state produced in $\Upsilon(4S)$ decays is broken (for example see [62,63]). A test of CPT is one of the fundamental tests of nature that should be performed to increasingly greater precision. Current experimental constraints on CPT in correlated $P^0\bar{P}^0$ system have been performed for neutral K and B mesons where the most stringent limit on CPT violation from B decays is discussed in Ref. [64].

5. CHARM DECAYS

Several reviews of charm physics [65] have recently highlighted the motivation to revisit studies of charm meson decays at much higher luminosities. The proceedings of the talks within this conference give an overview of the state of the art measurements in charm decays [66]. The motivation for studying charm decays at a SFF includes the continued search for D -mixing and CPV . One often neglected fact is that the multitude of precision charm measurements are instrumental to honing theoretical calculations used in the study of B meson decays. Charm physics is an integral part of the wider program pursued at a SFF.

6. STUDY OF τ LEPTONS

One of the most promising channels to experimentally constrain lepton flavor violation (LFV) in τ lepton decay is the process $\tau \rightarrow \mu\gamma$. The current experimental branching ratio limits on this process are $\mathcal{O}(10^{-7})$ [67,68] using approximately 1.5×10^9 τ pairs. An estimated 10×10^9 τ pairs will be produced each year at a SFF. The large number of recorded decays would enable one to push experimental sensitivities of LFV down to the 10^{-9} to 10^{-10} level. Such a stringent limit on LFV would impose serious constraints on many models of NP [69]. In addition to LFV, one can search for CPV in τ decay.

7. Υ DECAYS BELOW THE 4S RESONANCE

Samples of $\Upsilon(1S, 2S)$ decays can be obtained by operating a SFF at the $\Upsilon(3S)$ resonance and tagging the final state $\pi^+\pi^-\Upsilon(1S, 2S)$, or via radiative return from the $\Upsilon(4S)$ resonance.

The decays $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S, 2S)$ with $\Upsilon(1S, 2S) \rightarrow l^+l^-$ for $l = e, \mu, \tau$, have been proposed for testing lepton universality (LU) at the percent level using the existing B -factories [70]. The CLEO collaboration have recently performed such measurements for τ and μ dilepton decays of $\Upsilon(1S, 2S, 3S)$ concluding that LU holds within the $\mathcal{O}(10\%)$ precision of the measurement [71]. CLEO analysed $\mathcal{O}(1.1\text{fb}^{-1})$ of data accumulated at each of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances. The data currently show a 2.6σ deviation from the expectation of LU. Various NP scenarios exist where light CP -odd non-SM Higgs bosons could break LU [72–74]. A precision test of LU could be performed at a SFF by operating the accelerator at $\sqrt{s} = 10.355\text{ GeV}$ corresponding to the $\Upsilon(3S)$ resonance.

Most dark matter scenarios require a SM-dark matter coupling, and studies of the decays $\Upsilon(1S) \rightarrow \text{invisible}$ have been proposed in order to study such couplings [75].

8. ACCUMULATING DATA AT THE $\Upsilon(5S)$ RESONANCE

Recent work has shown that it is possible to study B_s decays produced at the $\Upsilon(5S)$ resonance with an asymmetric energy e^+e^- collider [76]. It will be possible to measure $\Delta\Gamma/\Gamma$ for the B_s system using $B_s \rightarrow D_s^{(*)}D_s^{(*)}$ decays [77], and an e^+e^- collider provides a clean environment to search for NP in the $B_s \rightarrow K^*\gamma$ and $B_s \rightarrow \phi\gamma$ loop processes [78]. One can also constrain NP parameter space through measurements of semileptonic B_s decays. The large mixing frequency of B_s mesons makes time-dependent CP asymmetry measurements challenging, and studies are underway to elucidate the prospects of such measurements with a SFF.

9. ACCELERATOR DESIGNS

The PEP-II and KEK-B asymmetric energy e^+e^- accelerators have outperformed expectations to integrate a combined luminosity of 1 ab^{-1} since the B -factory operation started in 1999. There are currently two designs being entertained for a $10^{36}\text{ cm}^{-2}\text{s}^{-1}$ collider that would integrate 50 ab^{-1} of data during their lifetimes. One is an upgraded KEK-B accelerator [1] (Super KEK-B) that benefits from ILC technological developments, and the other is the result of more recent developments in trying to harness more ILC-related technology [2] (low emittance design). Highlights of the proposed parameter sets of these machines are summarised in Table 1. The luminosity \mathcal{L} of an e^+e^- collider is proportional to $I_{e^+/e^-}\xi_{e^+/e^-,y}/\beta_y^*$ where I_{e^+/e^-} is the beam current, $\xi_{e^+/e^-,y}$ is the beam-beam parameter and β_y^* is the vertical beta-function amplitude at the interaction point. In addition to this, there is a luminosity reduction factor, the so-called hourglass effect [79], to consider when simulating the delivered \mathcal{L} from a SFF. This reduction factor is approximately 6% in the case of PEP-II. The luminosity increase of the Super KEK-B design is achieved by increasing the beam-beam term, the beam currents and reducing β_y^* . In order to reach the predicted luminosity of $0.8 \times 10^{36}\text{ cm}^{-2}\text{s}^{-1}$, the KEK-based design incorporates a number of upgrades including the use of crab cavities to rotate the colliding bunches of electrons and positrons. This technology is expected to reduce the geometric reduction factor of the luminosity. The “low emittance design” achieves its luminosity increase to $1.0 \times 10^{36}\text{ cm}^{-2}\text{s}^{-1}$ through a low emittance operation of the accelerator. While most of the studies for this design are focussed on a possible site near Frascati, this is a site-independent design. An important aspect of achieving $10^{36}\text{ cm}^{-2}\text{s}^{-1}$ is the use of so called ‘crabbed waist’ scheme [80].

There are pros and cons for both of the accelerator concepts under study, however as it is unlikely that there will be more than one SFF built in the world, the next step for a SFF is to coalesce the best of both designs to a common proposal on a timescale of the next year or two. Both de-

Table 1
Parameters of the accelerator configurations under consideration.

Parameter	Super KEK-B	low emittance
ϵ_x (nm)	9.0	0.8
ϵ_y (nm)	0.045	0.002
β_x^* (cm)	200.0	20.0
β_y^* (cm)	3.0	0.2
σ_z (mm)	3.0	7.0
I_{e^+} (A)	9.4	2.5
I_{e^-} (A)	4.1	1.4

signs are able to provide the luminosity required to achieve the physics goals outlined here. There is more potential for upgrading the low emittance design to provide higher luminosities than the initial target, however both accelerator designs still require some R&D before they can be realised.

10. SUMMARY

Both a SFF and an upgraded LHCb experiment can provide an unprecedented precision overconstraint of the CKM mechanism. While a significant fraction of the physics programs of these two experiments are overlapping, they also provide a number of complimentary constraints. The $b \rightarrow s$ penguin transitions are golden transitions to search for and constrain NP. Precision ΔS measurements of hadronic and radiative penguin modes such as $B \rightarrow \eta' K^0$, ϕK^0 and $B \rightarrow K^* \gamma$ will be able to constrain NP loop contributions to the flavor physics sector. The study of $B \rightarrow VV$ decays may shed light on models with right handed couplings, and electroweak penguin-dominated processes also probe NP in loop processes. In addition, one can search for $D^0 \bar{D}^0$ mixing, and CPV in charm decays, as well as testing CPT using B mesons. Dilepton decays of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances can be used to test LU, and models with dark matter can be tested with decays to invisible final states. Finally, the unprecedented samples of τ leptons produced at a SFF provide us with the opportunity to search for lepton-flavor-violation at sensitivities relevant to most prominent NP scenarios and also search

for CPV in the lepton sector.

It is impossible to predict *a priori* what measurements are needed to constrain NP contributions, so one has to perform as many different measurements as possible. A SFF would provide a base to perform a wide range of such measurements.

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