

Chapter 1

Physics Motivation

In this chapter, we give an overview of the physics motivation for the SuperKEKB asymmetric B factory. The overview covers the e^+e^- environment, achievements at Belle, and the range of physics achievable at SuperKEKB with the Belle II experiment. The SuperKEKB physics program is diverse, and the range of physics topics that can be studied is very broad. This chapter provides justifications for the design integrated luminosity, and plans for running at different centre-of-mass energies.

1.1 Overview

The SuperKEKB facility designed to collide electrons and positrons at centre-of-mass energies in the regions of the Υ resonances. Most of the data will be collected at the $\Upsilon(4S)$ resonance, which is just above threshold for B -meson pair production where no fragmentation particles are produced. The accelerator is designed with asymmetric beam energies to provide a boost to the centre-of-mass system and thereby allow for time-dependent charge-parity (CP) symmetry violation measurements. The boost is slightly less than that at KEKB, which is advantageous for analyses with neutrinos in the final state that require good detector hermeticity.

SuperKEKB has a design luminosity of $8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$, about 40 times larger than of KEKB. This luminosity will produce 5×10^{10} b , c and τ pairs, at a rate of about 10ab^{-1} per year (see Table 1.1).

1.1.1 The Intensity Frontier

The Standard Model (SM) is, at the current level of experimental precision and at the energies reached so far, is the best tested theory. Despite its tremendous success in

Table 1.1: Beauty, Υ , charm and τ yields. Per year integrals are at design luminosity and are for guidance only.

Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$	7.7×10^8	4.8×10^8	1.1×10^{10}
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8		1.8×10^{11}
$\Upsilon(2S)$	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}

describing the fundamental particles and their interactions, excluding gravity, it does not provide answers to many fundamental questions.

The SM does not explain why there should be only three generations of elementary fermions and why there is an observed hierarchy in the fermion masses. The masses and mixing parameters of the SM bosons and fermions are not predicted and must therefore be determined experimentally. The origin of mass of fundamental particles is explained within the SM by spontaneous electroweak symmetry breaking, resulting in a scalar particle, the Higgs boson. However, the Higgs boson does not account for neutrino masses. It is also not yet clear whether there is a only single SM Higgs boson or whether there may be a more elaborate Higgs sector with other Higgs-like particle as in supersymmetry or other NP models.

Studies of symmetries have often illuminated our understanding of nature. At the cosmological scale, there is the unresolved problem with the matter-antimatter asymmetry in the universe. While the violation of CP symmetry (CPV) is a necessary condition for the evolution of a matter-dominated universe, the observed CPV within the quark sector that originates from the complex phase of the Cabibbo-Kobayashi-Maskawa (CKM) matrix is many orders of magnitude too small to explain the dominance of matter in the universe. Hence, there must exist undiscovered sources of the CP asymmetry. Furthermore, the elements of the CKM matrix exhibit a roughly diagonal hierarchy, even though the SM does not require this. This may indicate the presence of a new mechanism, such as a flavour symmetry, that exists unbroken at a higher energy scale. Considering the open questions that in the SM remain unanswered, it is fair to conclude that the present theory is an extremely successful but phenomenological description of subatomic processes at the energy scales up to $\mathcal{O}(1 \text{ TeV})$. Many New Physics (NP) scenarios have been proposed to explain these shortcomings of the SM, in

many of them new particles and new processes arise.

Experiments in high energy physics are designed to address the above questions through searches of NP using complementary approaches. One approach is at the energy frontier with the main experiments being ATLAS and CMS at the Large Hadron Collider (LHC) at CERN. The second is the intensity frontier, exemplified by the LHCb experiment at the LHC, the BESIII experiment at the BEPCII charm factory, and the Belle II experiment at SuperKEKB.

At the energy frontier, the LHC experiments will be able to discover new particles produced in proton-proton collisions at a centre-of-mass energy of up to 14 TeV. Sensitivity to the direct production of a specific new particle depends on the cross section and on the size of the data sample. At the intensity frontier, signatures of new particles or processes can be observed through measurements of suppressed flavour physics reactions or from deviations from SM predictions. An observed discrepancy can be interpreted in terms of NP models. This is the approach of Belle II.

The sensitivity of Belle II to NP depends on the strength of the flavour violating couplings of the NP. The mass reach for new particle/process effects can be as high as $\mathcal{O}(100 \text{ TeV}/c^2)$ if the couplings are enhanced compared to the SM [1]. Sensitivity to the contribution of a new particle or process to a particular flavour physics reaction depends on the NP model and on the size of the data sample. In the past, measurements of processes quantum corrections have given access to high mass scale physics before accelerators were available to directly probe these scales.

The history of particle physics is instructive on this point. The suppression of $K_L \rightarrow \mu^+ \mu^-$ decays allowed theorists to deduce the existence of the charm quark, through the GIM mechanism, and calculate its mass from the observed rate of $K - \bar{K}$ oscillations. Later, the unexpected discovery of large $B - \bar{B}$ oscillations indicated that the top quark was heavier than the mass scale at which the direct searches were being carried out, contrary to the theoretical prejudices of the time. The unexpected observation of CPV in K meson decays fifty years ago was used to predict the existence of a third generation of quarks, and revolutionised how we think about extensions of the SM. About two orders of magnitude more data are now needed to determine whether the observed CPV effects in B meson decays are consistent with the SM.

The high-energy and intensity frontiers are associated with the complementary direct versus indirect nature of the contribution of new particles or processes to the ensemble of available measurements and the distinct predictions from NP models in these two regimes. Belle II and SuperKEKB will exploit our strengths at the intensity frontier by moving beyond a simple observation of a NP effect to its detailed characterisation through over-constraining measurements in several related flavour physics

reactions.

1.1.2 Motivations for Belle II

Further study of the quark sector, beyond the first generation B factories, is necessary to reveal NP at high mass scales that may manifest in flavour observables. For example, some rare flavour changing neutral current (FCNC) processes are sensitive to mass scales as high as 100 TeV, well beyond the reach of direct searches at the LHC. Conversely, if new particles are found at the LHC, measurements in the flavour sector may allow diagnosis of their nature. There are several important questions that can only be addressed by further study of loop processes and rare decays in flavour physics, described in turn below.

- *Are there new CP violating phases?* The answer to this question will require new measurements of time-dependent CPV in $b \rightarrow s$ decays such as $B \rightarrow \phi K^0$, $\eta' K^0$ with a data sample of order 50 ab^{-1} . If there is NP in $b \rightarrow d$ transitions, precise measurements of CKM parameters in mixing and in tree processes will be required.
- *Are there right-handed currents from NP?* In this case, the experimental approach involves measurement of time-dependent CPV in $B \rightarrow K^{*0}(\rightarrow K_S^0 \pi^0) \gamma$, or related modes.

Another interesting approach involves triple-product CPV asymmetries in $B \rightarrow VV$ decays. Data samples with luminosity of order 50 ab^{-1} are required for either approach. Right handed currents will also be probed in charged weak interactions, for example $B \rightarrow V \ell \nu$, $V = D^*, \pi$.

- *Are there quark FCNCs beyond the SM?* It is of great interest to measure $b \rightarrow s \nu \bar{\nu}$ transitions such as $B \rightarrow K^{(*)} \nu \bar{\nu}$, part of a class of decays with large missing energy. It is desirable to measure FCNCs with comparable accuracy in $b \rightarrow d$, $b \rightarrow s$ and $c \rightarrow u$ transitions.
- *Are there sources of LFV beyond the SM?* Neutrino experiments have found large mixing between the ν_μ and ν_τ , raising the question: are there flavour changing processes such as $\tau \rightarrow \mu \gamma$ visible at the 10^{-8} level? LFV in charged lepton decay is a key prediction in many neutrino mass generation mechanisms.
- *Are there new operators with quarks enhanced by NP?* Experimentally, it is crucial to measure forward-backward asymmetries as a function of the q^2 of the dilepton, $A_{\text{FB}}(q^2)$, in inclusive $b \rightarrow s \ell^+ \ell^-$ decays and in charged weak interactions. Another

example of this approach to NP is measuring the rates and asymmetries in *all* $B \rightarrow K\pi$ modes to a precision that we can determine whether or not there are enhanced electroweak penguins.

- *Does nature have multiple Higgs bosons?* Many extensions to the SM, such as two-Higgs-doublet models (2HDM), predict charged Higgs bosons in addition to a neutral SM-like Higgs. The charged Higgs will be searched for in flavour transitions to τ leptons, including $B \rightarrow \tau\nu$ and $B \rightarrow D^{(*)}\tau\nu$.
- *Does NP enhance CPV via $D^0 - \bar{D}^0$ mixing to an observable level?* The SM predicts negligible CPV in this case. Hence CPV in the D system would be a “smoking gun” for NP.

It is worth noting that not only will Belle II measure the current array of CKM observables with unprecedented precision, it will also allow measurements of a large number of new observables and new modes relevant to NP in the quark sector.

1.1.3 Advantages of SuperKEKB

There are many experimental reasons to choose SuperKEKB to address puzzles in flavour physics: they are discussed in turn.

- Running on the $\Upsilon(4S)$ resonance produces a very clean sample of $B^0\bar{B}^0$ pairs in a quantum correlated 1^{--} state. The low background environment allows for reconstruction of final states containing photons from B and π^0 , ρ^\pm , η , η' etc decays. Neutral K_L^0 mesons are also efficiently reconstructed.
- Detection of the decay products of one B allows the flavour of the other B to be tagged.
- Due to low track multiplicities and detector occupancy, the B , D and τ reconstruction efficiency is high and the trigger bias is low. This substantially reduces correction and systematic uncertainties in many types of measurements, *e.g.* Dalitz plot analyses.
- By utilising asymmetric beam energies, the Lorentz boost of the e^+e^- system can be made large enough so that B or D mesons travel an appreciable distance before decaying, allowing precision measurements of lifetimes, mixing parameters, and CPV. Note that measurement of the D lifetime provides a measurement of the mixing parameter y_{CP} , while measurement of the B lifetime (which is already well measured), can be used to determine the decay time resolution function from data.

- Since the absolute delivered luminosity is measured with Bhabha scattering, an e^+e^- experiment measures absolute branching fractions.
- Since the initial state is completely known, “missing mass” analyses can be performed to infer the existence of new particles via energy/momentum conservation rather than reconstructing their final states. By fully reconstructing a B decay in a hadronic or semileptonic final state, rare decays with neutrinos can be observed or measured with minimal model dependence. Similar approaches can be applied to charm physics.
- In addition to producing large samples of B and D decays, an e^+e^- machine produces large samples of τ leptons allowing for measurements of rare τ decays and searches for lepton flavour and lepton numbers violation τ decays in a very low background environment, often with zero expected background.

1.1.4 Belle achievements

The legacy of the B -factories laid the groundwork for many areas that will be further exploited at SuperKEKB. To illustrate the expected sensitivity of Belle II and SuperKEKB to NP phenomena, we examine some of the major achievements at the Belle experiment.

The Belle experiment accomplished its main mission, which was the verification of Kobayashi and Maskawa’s proposal that a single irreducible complex phase can explain CP violating phenomena. Belle’s (and BaBar’s) observation of large time-dependent CP asymmetries in modes such as $B \rightarrow J/\psi K_S^0$ demonstrated that the KM proposal was correct and laid the foundation for their 2008 Nobel Prize in Physics. The results provided a theoretically clean measurement of one of the angles of the unitarity triangle (UT), β . After the accumulation of the $\sim 1 \text{ ab}^{-1}$ data set, the measurements of β became precision results and important calibrations for NP. To check the consistency of the SM, Belle measured the other two angles of the UT, α and γ . The results for the sides and angles of the UT are consistent. However, NP contributions of order 10% the size of the SM amplitude, are still allowed. In parallel with the work on fixing the weak interaction parameters of the UT, Belle also completed a decade of studies and publications on rare decays and QCD.

In rare decays Belle established the existence of a number of highly suppressed processes including $b \rightarrow d\gamma$ and $b \rightarrow s\ell^+\ell^-$. In addition, as the data sample has increased, there have been a number of intriguing hints of NP in various channels, *e.g.* exclusive hadronic $b \rightarrow s$ CP violating modes, and $B \rightarrow D^{(*)}\tau\nu$, with no compelling

evidence at the current level of sensitivity. Exploration of NP will require the luminosity of SuperKEKB.

In the τ sector searches for lepton-flavour-violating (LFV) decays and CPV have reached an interesting sensitivity at Belle but so far no NP signals have been found. The foundation for Belle II explorations of the charm sector have also been established. The highlights include two classes of unexpected and unanticipated results: the discovery of $D^0 - \bar{D}^0$ mixing and the existence of a large number of new charmonium-like resonances. The latter was completely unexpected by the theoretical community and was guided by Belle data. Belle is also the world's leading two-photon facility.

KEKB's capabilities to operate in a range of centre of mass energies allowed Belle to record a number of unique large data sets at the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(5S)$ resonances. The $\Upsilon(5S)$ data were used to study some properties and decays of B_s mesons. It also led to the discovery a series of peculiar bottomonium-like resonances and to finding missing bottomonia states.

A timeline of specific Belle highlights are listed below.

- 2002: Belle observed mixing-induced time-dependent CPV ($TCPV$) in neutral B mesons and provided a measurement of $\sin 2\beta$ through analysis of $B^0 \rightarrow J/\psi K^0$ and related decays.
- 2003: Belle presented evidence of $TCPV$ in $B^0 \rightarrow \pi^+\pi^-$ decays and a measurement of the UT angle α . Now α (combining with BaBar) is also measured precisely to a level of approximately 4%.
- In the same year, Belle measured $TCPV$ in the penguin-dominated modes $B^0 \rightarrow \phi K_S^0$, $K^+K^-K_S^0$ and $\eta'K_S^0$ and observed that the parameter $\sin 2\beta$ deviated somewhat from the value measured in tree-dominated $B^0 \rightarrow J/\psi K_S^0$ decays. The discrepancy has become less significant with more data, but is still statistically limited.
- In 2003 Belle discovered a new neutral resonance named $X(3872)$, produced in B decays, exhibiting properties that were inconsistent with conventional mesons. It has been joined by discovery of a large number of other interesting new particles, including the electrically charged $Z(4430)^+$ in 2007.
- 2004: Data revealed for the first time direct CPV ($DCPV$) in B decays to $\pi^+\pi^-$ and $K^+\pi^-$.
- In the same year, Belle released the first measurement of γ , using a new method: a time-independent measurement of the Dalitz distribution in $B \rightarrow D^{(*)}K$ decays.

This approach has proven to be the most sensitive method and will be exploited by Belle II.

- 2005: The first measurements of $TCPV$ in $B^0 \rightarrow K^{*0}\gamma$ were reported. The CP asymmetry in this decay is strongly suppressed by fermion helicity conservation in the SM, but can be enhanced in some NP models.
- 2006: The purely leptonic decay $B \rightarrow \tau\nu$, was observed for the first time. The branching fraction is sensitive to the magnitude of the least well known CKM matrix element, V_{ub} and the B decay constant. In NP scenarios, it can be enhanced by the contribution of a charged Higgs boson.
- 2007: Belle and BaBar found the first evidence for the phenomenon of mixing in the system of neutral charmed mesons D^0 . The large rate can be accommodated by NP but may also be explained by difficult to calculate long-distance strong interaction effects in the SM.
- 2008: A measurement of the branching fraction and photon energy spectrum for fully inclusive $B \rightarrow X_s\gamma$ (radiative penguin diagram) decays was performed with an energy threshold of 1.7 GeV. This result is in agreement with the SM and provides strong constraints on charged Higgs bosons from NP.
- In the same year, a measurement of $DCPV$ in $B^+ \rightarrow K^+\pi^0$, proved it to be different than the same quantity in $B^0 \rightarrow K^+\pi^-$ decays, contrary to the naive expectation from the presence of electroweak penguin diagrams. In combination with other $B \rightarrow K\pi$ measurements and with the larger Belle II data set, strong interaction effects can be controlled, and therefore the validity of the SM can be tested in a model-independent way.
- 2011: Belle made first observations of bottomonium and bottomonium-like resonances, h_b and Z_b respectively. The latter is a charged bottomonium-like particle and therefore the first beauty hadron found to contain four quarks.

Belle successfully established the KM model, measuring weak interaction parameters, and observed suppressed SM processes. At the next stage in Belle II at SuperKEKB, the focus will shift to NP exploration.

1.2 NP-sensitivity at Belle II

To illustrate the unprecedented sensitivity to the presence of NP effects at the intensity frontier that the improved performance of the Belle II detector and the much larger

data set will offer, we expand on some of the previous listed measurements. The measurements presented are just few examples of the broad physics program of Belle II. Belle II is able to perform measurements in $B^{0(\pm)}$ and $B_s^{(*)}$ meson decays, charm physics, τ lepton physics, spectroscopy, and electroweak (weak mixing angle) measurements. A large number of planned measurements will over-constrain the SM as well as its extensions and will shed light on the nature of NP.

1.2.1 CKM matrix and the Unitarity Triangle

SuperKEKB can improve on all the measurements of the Unitarity Triangle (UT) angles, α , β , γ to a precision of about 1° , 0.3° and 1.5° , respectively. This is sufficient to perform a percent level determination of the apex of the UT using only angles. The determinations of β and γ will still be theoretically clean at the end of data taking. The measurement of α will be theory limited and achieving such high precision requires a suite of measurements with varying strong phases [2–4]. The measurement of γ will be done via a range of methods using $B \rightarrow D^{(*)}K^{(*)}$ decays.

At the end of the B factory era the tension between inclusive and exclusive determinations of $|V_{ub}|$ [5–7] and $|V_{cb}|$ [8–11] still remain, and are still the least well measured side length parameters. The challenge at SuperKEKB is to determine new techniques to understand this tension, based on the larger data sets at hand.

The angle γ and $|V_{ub}|$ are determined from tree-level processes and thus considered to have minimal sensitivity to contributions from NP. They provide the SM “reference” determination of the CKM UT (its apex, the values of $\bar{\rho}$ and $\bar{\eta}$). The CKM matrix element, $|V_{ub}|$ is measured from inclusive and exclusive $b \rightarrow u\ell\nu$ processes. There is an on-going effort to improve the theory predictions using both the continuum methods and lattice QCD, and a factor of a few improvement on the errors seems feasible. For example, the present theory error on $|V_{ub}|$ from exclusive $B \rightarrow \pi\ell\nu$ can be reduced from present 8.7% to 2% by 2018 [12]. The persistent inclusive-exclusive puzzle must be understood before using this precision as a test of the SM. The theoretical uncertainties in the measurement of γ from $B \rightarrow DK$ decays are even smaller. All the required hadronic matrix elements can be measured in the cascade $B \rightarrow DK$, $D \rightarrow f$ decay, if enough final states f are taken into account. The irreducible theoretical errors thus enter only at the level of one-loop electroweak corrections and are below $\mathcal{O}(10^{-6})$. The present experimental errors are $\pm 12^\circ$ in the average of the Belle [13–16] and BaBar measurements (LHCb also provides a competitive result). The tree-level determinations of $\bar{\rho}$ and $\bar{\eta}$ can then be compared with the measurements from loop-induced FCNCs, for example with the time-dependent CP asymmetry in $B \rightarrow J/\psi K_S^0$ and related modes determining the angle β .

1.2.2 CP violation

One of the main strengths of Belle II is the ability to make precision measurements of CPV , and this capability will be exploited to search for NP. The difference between B^0 and \bar{B}^0 decay rates to a common self-conjugate state is sensitive to both direct CPV (*i.e.* occurring in the B^0 and \bar{B}^0 decay amplitudes), and indirect CPV from interference between the $B \rightarrow f$ decay and $B \rightarrow \bar{B}^0 \rightarrow f$ mixing amplitudes. The indirect CPV was originally measured at Belle and BaBar for all charged final states such as $J/\psi K_0$ and $\pi^+\pi^-$; at Belle II this measurement will be extended to precision studies of more challenging final states such as $B \rightarrow K_S^0 K_S^0$, $B \rightarrow K^0 \pi^0$ and $B \rightarrow X_{s,d} \gamma$.

$b \rightarrow s\bar{s}s$ Penguin decays

An important search for NP is to compare the time-dependent CP asymmetries of penguin dominated $b \rightarrow s\bar{s}s$ processes with the tree dominated $b \rightarrow c\bar{c}s$ decays. Observables that probe this are the differences of CP asymmetries, which include $S_{J/\psi K_S^0} - S_{\phi K_S^0}$ and $S_{J/\psi K_S^0} - S_{\eta' K_S^0}$. Statistically limited studies of this class of decays were performed in Belle [17–19]. CP asymmetry measurements have small theoretical uncertainties as they involve ratios of rates, from which the leading amplitudes cancel.

The value of $\sin \beta$ as measured in $B^0 \rightarrow \phi K_S^0$ and similar $b \rightarrow s$ transitions is currently in agreement with the value measured in $B \rightarrow J/\psi K_S^0$ decays, the current world average difference being $\Delta S = \sin 2\beta_{\phi K_S^0} - \sin 2\beta_{J/\psi K_S^0} = 0.07 \pm 0.13$. While the CKM matrix elements included in the amplitudes of these decays are approximately real, the possibility of $B^0 - \bar{B}^0$ mixing before the decay introduces an additional factor $(V_{tb}^* V_{td})^2 \propto e^{-2i\beta}$. Hence, the decay time distribution of both decays is sensitive to $\sin 2\beta$, and the difference in the value measured in the two decays is expected to vanish within small corrections, $\Delta S = 0.03 \pm 0.01$. However, NP can contribute through loops to $B \rightarrow \phi K_S^0$ decays, and change the expectation for ΔS .

In $B \rightarrow K^+ K^- K_S^0$ decays, ϕK_S^0 is just one of several intermediate resonant contributions to the final state. The value of $\sin 2\beta(\phi K_S^0)$ is determined with a decay time dependent Dalitz plot analysis, where the accuracy of $K^+ K^- K_S^0$ vertex determination and particle identification are crucial for background suppression. With $\mathcal{L} = 10 \text{ ab}^{-1}$ of data, the experimental and theoretical uncertainties will be comparable.

Radiative B decays

Radiative decays were the cornerstone of NP searches in the B factory era. While the branching fraction expectation appears to be reaching the theory barrier, the study of CPV both offers a theoretically clean way of probing NP that is less sensitive to decay

dynamics. CPV in inclusive $B \rightarrow X_{s+d}\gamma$ is expected to reach 0.5% precision. Radiative decays $b \rightarrow s\gamma$ are also sensitive probes of new right-handed weak currents, absent in the SM. The helicity structure of the effective Hamiltonian that describes this loop process allows only for $b_R \rightarrow s_L\gamma_L$ and $b_L \rightarrow s_R\gamma_R$ decays, where the subscript denotes the handedness of the particle. The amplitude of the former (latter) process depends on the helicity flip and is proportional to m_b (m_s). In mesons the $b_L \rightarrow s_R\gamma_R$ transition, for example, can proceed directly or via $\bar{B}^0 \rightarrow B^0$ mixing; the interference leads to a small time dependent CP asymmetry that is proportional to m_s/m_b . In various NP models (*e.g.* left-right symmetric models) the right-handed currents are not suppressed and can lead to a sizeable CP asymmetry. A prominent example of such transitions is $B^0 \rightarrow K_S^0\pi^0\gamma$ [20]. Within the SM, the decay time dependent CP asymmetry in this decay is estimated to be $S \equiv -2(m_s/m_b)\sin 2\beta \equiv -0.04$; some SM predictions allow for a value of $|S|$ up to 0.1. On the other hand, in $L - R$ symmetric models, the asymmetry can be as large as $S \equiv 0.67\cos 2\beta \equiv 0.5$. The decay-time dependence in $B^0 \rightarrow K_S^0\pi^0\gamma$ is measured through reconstruction of the B meson decay vertex using only pions from $K_S^0 \rightarrow \pi^+\pi^-$ decay that are constrained to the e^+e^- interaction region. The Belle II vertex detector will improve the vertex position resolution and, more importantly, increase the reconstruction efficiency of K_S^0 decays with charged pion hits in the silicon detectors. With a data set corresponding to 50 ab^{-1} , the sensitivity of the measurement will reach 0.035 and thus test a range of NP predictions.

Charmless radiative decays will come to the fore in Belle II, such as $S(B \rightarrow \rho\gamma)$, which should be measurable with a precision of better than 0.1. This will be complemented by $DCPV$ studies of $b \rightarrow d$ transitions [21, 22].

Charmless B decays

Charmless 2-body B meson decays are another example of rare SM processes in which the possible contribution of NP could be observed in the future. The decays $B \rightarrow K\pi$ proceed through a tree diagram but are suppressed by the small CKM matrix element $|V_{ub}|$. Thus, the contribution of the loop penguin diagram is of similar magnitude. The interference of the two leads to a direct CP asymmetry. Neglecting additional diagrams contributing to B^+ decays only, the asymmetries $A_{CP}^{K^+\pi^0}$ in $B^\pm \rightarrow K^\pm\pi^0$ decays and $A_{CP}^{K^+\pi^-}$ in $B^0(\bar{B}^0) \rightarrow K^\pm\pi^\mp$ decays are expected to be the same. However, a precise CP measurement by Belle showed a significant difference between the two, $\Delta A = A_{CP}^{K^+\pi^0} - A_{CP}^{K^+\pi^-} = 0.164 \pm 0.035 \pm 0.013$ [23]. The difference could be due to the neglected diagrams contributing to charged B meson decays, for which the theoretical uncertainty is large, or to some unknown NP effect that violates isospin. To resolve this issue, a sum rule has been proposed demanding precision measurements of all isospin

states.

The most demanding of these measurements is the all-neutral final state $K^0\pi^0$. It requires vertex reconstruction of the charged pions from the neutral kaon decays and depends crucially on a vertex detector with a large radial acceptance. Reconstruction of the neutral pion requires very good electromagnetic calorimetry. For the final states with charged kaons and pions, an excellent separation between the two particle species must be provided by the particle identification system. The main systematic uncertainty contributions (tag side interference) in the Belle measurement of $B^0 \rightarrow K^0\pi^0$ are expected to be reduced with a larger data sample. At Belle II the uncertainty on $\mathcal{A}(K^0\pi^0)$ from time dependent analyses is expected to be reach approximately $\sim 3\%$, sufficient for NP studies.

1.2.3 Rare B decays

SuperKEKB and Belle II are very well equipped to study a broad variety of rare B decays. Excellent reconstruction of charged and neutral particles, and particle identification, with a near 100% efficient trigger allow the study of decay chains involving neutral and very weakly interacting particles. The latter can be studied using hadronic and semileptonic tagging techniques, developed for the B factories. Numerous rare B decays that were observed with low statistics at Belle and BaBar, or not at all, will become accessible at Belle II.

Leptonic decays

The highest profile example of a rare leptonic B decays is $B \rightarrow \tau\nu$, which in the SM results from a W -exchange diagram and has an expected branching fraction of $(0.74_{-0.07}^{+0.09}) \times 10^{-4}$ [24]. This mode is sensitive to models and that predict the existence of a charged Higgs. The effect of a possible charged Higgs boson on the partial leptonic decay width of B mesons is given by $\Gamma(B^+ \rightarrow \tau^+\nu) = \Gamma_{\text{SM}}(B^+ \rightarrow \tau^+\nu)[1 - (m_B^2/m_H^2) \tan^2 \beta]^2$, where $\Gamma_{\text{SM}}(B^+ \rightarrow \tau^+\nu)$ denotes the SM partial decay width, and $\tan \beta$ denotes the ratio of the vacuum expectation values of the two Higgs fields and is a free parameter of the models.

The final state contains multiple neutrinos and thus is measurable only in a e^+e^- experiment. Experimentally the leptonic branching fraction measurement consists of (partial) reconstruction of the accompanying B meson in the event, called the tagging B meson (B_{tag}). B_{tag} can be fully reconstructed in a number of hadronic decays (hadronic tagging) or partially reconstructed in semileptonic decays (semileptonic tagging), where the hadronic system (and the charged lepton) of the final state is detected while the

neutrino escapes detection. The hadronic tagging method has better purity in the B_{tag} sample, but suffers from a lower efficiency compared to semileptonic tagging. The remaining particles in the event are assigned to the signal B meson (B_{sig}); if they are consistent with a possible τ decay, the undetected part of the event consists of one or more neutrinos from (semi-)leptonic decays. The signature of such event is thus a little or no residual energy detected in the electromagnetic calorimeter, after removing the contributions from the particles used in the reconstruction of B_{tag} and the τ from $B_{\text{sig}} \rightarrow \tau\nu$. The current average branching fraction from Belle [25, 26] and BaBar [27, 28] is $(1.14 \pm 0.22) \times 10^{-4}$, slightly higher than the SM expectation. Belle II should reduce this uncertainty to around 3%. The related channel $B \rightarrow \mu\nu$ will be measured to about 6% precision, and will increase the overall sensitivity to NP in leptonic B decays.

Semileptonic decays with tau leptons

In the B factory era, semileptonic B decays were used to precisely determine the CKM parameters. It turns out that semileptonic decays with a τ lepton are also very sensitive to NP, with the added advantage over $B \rightarrow \tau\nu$ of being sensitive to the handedness of the NP current through polarisation studies. Compared to ordinary semileptonic decays $B^0 \rightarrow D^{*\pm}\ell^-\nu$ with $\ell = e$ or μ , $B \rightarrow D^{(*)}\tau\nu$ decays, occurring through a quark-level $b \rightarrow c\tau\nu$ process, are kinematically suppressed because of the large τ mass. The predicted branching fractions, based on the SM, are approximately 1.4% and 0.7% for $B \rightarrow D^*\tau\nu$ and $B \rightarrow D\tau\nu$ decays, respectively. On the other hand, the large τ lepton mass makes them sensitive to interactions with a charged Higgs. Therefore, these $B \rightarrow D^{(*)}\tau\nu$ modes can be a very effective probe to search for indirect evidence of charged Higgs or other NP hypotheses beyond the SM. Furthermore, in practice the ratio of branching fractions, $\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)/\mathcal{B}(B \rightarrow D\ell\nu)$ is measured, which minimises SM form factor and some experimental normalisation uncertainties. Thus this has the potential to be a very precise test of the SM.

An interesting anomaly in the B -factory data is the deviation from the SM of the $B \rightarrow D^{(*)}\tau\nu$ decay rates observed by both BaBar and Belle. In the BaBar analysis alone, the difference from the SM prediction in the rates was approximately 3.4σ [29]. No such deviation is seen in $B \rightarrow \tau\nu$. Although the $B \rightarrow D^{(*)}\tau\nu$ anomaly could be accommodated with a NP charged Higgs exchange, it would require non-minimal flavour structure. To settle this case the SuperKEKB dataset will be required.

Electroweak penguins

SuperKEKB will provide access to studies of electroweak penguin processes in all lepton species final states, *i.e.* charged e , μ and τ pairs, and neutral ν pairs. The latter, involving $\nu\bar{\nu}$ are theoretically very clean, and Belle II should reach the SM level in $B \rightarrow K^{(*)}\nu\bar{\nu}$; while the current constraints are an order of magnitude weaker [30]. Hadronic and semileptonic tagging will be used to isolate the non-signal B meson in the event. The signature is a single kaon candidate accompanied by momentum imbalance.

There is also a long list of interesting measurements in $b \rightarrow s\gamma$ and $b \rightarrow s\ell^+\ell^-$ in both inclusive and exclusive analysis, of rates, CP asymmetries, isospin asymmetries, angular distributions, triple product correlations, exploiting the possibility of hadronic and semileptonic tagging [31–35]. Belle II can uniquely measure inclusive processes such as $B \rightarrow X_{s+d}\ell^+\ell^-$ for which theoretical predictions have less uncertainty than those for exclusive processes, measured by Belle and BaBar [36, 37]. In exclusive analyses, Belle II will precisely measure electron final states, and search for as-yet-unseen tau final states, thereby complementing studies of muon modes at LHCb [38].

Furthermore, the branching fraction of $b \rightarrow s\gamma$ [39–41] can also be experimentally improved upon by a factor of two or more.

1.2.4 B physics at $\Upsilon(5S)$

It is expected that SuperKEKB will produce of order 5 ab^{-1} of data near the $\Upsilon(5S)$. The flavour physics program for this data set is to perform searches for NP, and precision tests of the SM under SU(3) transformation. Key NP modes are those with neutral final states or missing energy, such as $B_s \rightarrow \gamma\gamma$ [42, 43] and $B_s \rightarrow \tau\tau$. The latter will exploit hadronic tagging, as done in analogous searches at $\Upsilon(4S)$ [44]. SuperKEKB will also contribute to the general understanding of B_s decays, with inclusive and comprehensive studies of decay final states only possible at SuperKEKB [45]. Precision measurements of absolute branching fractions will have an important impact on NP reach, *e.g.* in $B_s \rightarrow \mu\mu$.

1.2.5 Charm Physics

Indirect searches for NP with charm quarks provide complementary, and analogous constraints to searches in B decays. At tree level, NP contributions can be discerned. Some highly calculable processes, *e.g.* leptonic decays of D_s mesons ($D_s \rightarrow \mu\nu$, $D_s \rightarrow \tau\nu$), can be used to determine decay constant f_{D_s} and CKM parameters $|V_{cs}|$ [46]. Studies of processes forbidden in the SM at tree level in the charm sector are promising

avenues for NP searches. Examples include $D^0 - \bar{D}^0$ mixing, or inclusive and exclusive transitions mediated by $c \rightarrow u\gamma$ [47] or $c \rightarrow ull$.

FCNC decays in the charm system, such as $D \rightarrow \mu\mu$ have received renewed interest, after the measurement of $B_s \rightarrow \mu\mu$. While heavily GIM-suppressed, long distance contributions from $D^0 \rightarrow \gamma\gamma$ [48, 49], for example, also contribute and must be constrained from experiment. Direct constraint on the decay $D^0 \rightarrow \gamma\gamma$ would limit these contributions to the dimuon mode to below 10^{-10} .

Searches for CP violation in charm decays [50, 51] and oscillations [52] is another important example involving a FCNC. Unlike B decays, where golden channels can be readily identified in time-dependent measurements, in D^0 mixing, hadronic effects are larger and therefore a more challenging to tackle in any given mode [53]. This issue can be resolved by measuring a multitude of final states, only possible with SuperKEKB. For example, to resolve A_{CP} in $D \rightarrow KK$ or $K\pi$, penguin contributions must be isolated through an isospin analysis with neutral modes. Belle II is also able to determine absolute A_{CP} for each given mode, rather than ΔA_{CP} at hadron colliders, thus providing further experimental information. SuperKEKB will be sensitive to both of the mixing parameters x_D and y_D in a number of golden CP self-conjugate decay modes, hence allowing mixing induced CP violation to be observed.

The observation of processes forbidden or extremely suppressed in the SM, provide high-impact discovery potential. Examples include lepton and baryon number violating transitions, and D decays to $\nu\bar{\nu}$ [54]. The latter are precisely calculable in the SM due to the absence of long distance contributions, and thereby provide a clean NP probe. Such challenging modes can be studied using charm tagging based on the hadronic full reconstruction technique developed at Belle.

There are also examples of where Belle II will perform important measurements in charm that impact on results from other results, *e.g.* the strong phase, ϕ , as a function of position in the Dalitz plot for $D^0 \rightarrow K_S^0\pi^+\pi^-$ decays that feed into D^0 mixing and γ measurements. In B decays, Decays such as $B \rightarrow \rho\gamma$ have yielded measurements of the CKM matrix element $|V_{td}|$, and probes of NP in short-range electroweak processes, whereas long-range contributions are suppressed. The situation is reversed in the charm sector, where radiative decays are expected to be dominated largely by non-perturbative processes by up to 3 orders of magnitude. Given the expected dominance of long-range processes, radiative charm decays, $\mathcal{B}(D^0 \rightarrow V\gamma)$, $V = K^*$, ϕ , provide an excellent laboratory in which to test QCD-based calculations that currently limit the sensitivity of searches of NP in the charm sector.

1.2.6 Tau physics

Belle II will collect vast quantities of τ lepton decays that can be used in a number of NP searches and SM precision tests. These include searches for LFV, CP violation, precision measurements of the electric dipole moment and $g - 2$ of the τ , and precision SM quantities such as $|V_{us}|$. The expected sensitivities to rare and forbidden τ decays will be unrivalled. A high luminosity τ factory at the $\Upsilon(4S)$ peak is an ideal facility for most τ physics measurements as the data analysis can exploit correlated production without collision background. Lepton flavour changing processes are highly suppressed in the SM, with very small but finite branching fractions due to the light mass of the neutrinos. However, in many scenarios of physics beyond the SM, large enhancements of charged LFV are predicted, often dependent on the size of the neutrino mixing parameters. To determine the underlying nature of any NP affecting the lepton sector we must combine results from both τ and μ decay studies with results from the neutrino sector. One must constrain all three types of possible transitions between charged lepton generations, two of which are studied in Belle II. The Belle II design integrated luminosity of 50 ab^{-1} provides a LFV sensitivity seven times better than Belle for background limited modes such as $\tau \rightarrow \mu\gamma$ and up to 50 times better for the cleanest searches such as $\tau \rightarrow eee$ to limits of 5×10^{10} .

It is also expected that Belle II will measure CP asymmetries in τ decays at a level that bounds many models of NP in a complementary way to the LFV searches. For example, CPV in $\tau \rightarrow K_S^0\pi\nu$, which is very precisely predicted in the SM, is expected to be measured with 10^{-4} precision, an order of magnitude better than Belle. In some models this is equivalent to a $\mathcal{B}(\tau \rightarrow \ell\ell\ell)$ limit of 10^{-10} [55].

1.2.7 Quarkonium(like) Spectroscopy

Over the past decade, the B -factories and hadron machines have discovered a large number of states that were not predicted by conventional meson interpretation, and are instead only described by a larger number of constituents. The actual identification of such states represents a revolution in our understanding of particle physics, and in particular our understanding of QCD in the low energy regime. The existence of a new fundamental type of state implies the existence of a number of new states. Under the assumption of the molecular model there are more than 15 new states predicted for each J^{PC} . To build a complete picture of new states requires a comprehensive overview afforded by SuperKEKB. One of the cleanest way of studying new particles is to produce them near resonance, achievable by adjusting the machine energy. The clean environment of the machine implies good detection capabilities for all neutral

and charged particles, crucial for fully evaluating charged and neutral exotic hadrons.

Charmonium(like)

In e^+e^- collisions at CM energies near $\sqrt{s} = 10.58$ GeV, there are a number of ways to produce final states that contain a $c\bar{c}$ quark pair. These include: *i*) B-meson decays, in which $b \rightarrow c\bar{c}s$ is a favoured transition; *ii*) $\gamma\gamma$ fusion, which is proportional to the square of the quark charge and, thus, favours production of $c\bar{c}$ and $u\bar{u}$ pairs over $s\bar{s}$ and $d\bar{d}$ pairs; *iii*) near-threshold s -channel $c\bar{c}$ production via initial-state radiation; and *iv*) $c\bar{c}$ associated production with J/ψ mesons in e^+e^- annihilation, which Belle found to be the dominant mechanism for J/ψ productions in e^+e^- annihilation near $\sqrt{s} = 10$ GeV. Belle exploited all four of these processes to make a series of discoveries in the spectroscopy and interactions of $c\bar{c}$ charmonium mesons.

In the last decade, the observations of the spin-singlet charmonium states $h_c(1P)$ and $\eta_c(2S)$ have completed the charmonium multiplets below the open-charm threshold. Experiments have also revealed a large number of unexpected $c\bar{c}$ mesons above the open charm threshold, known as the XYZ states. Both neutral and charged states have been found, including the $Z(4430)^0$ [56]. These states may be manifestations of either tetra-quarks, $c\bar{c}g$ hybrids, meson molecules or other exotica. Many of the XYZ states are narrow and some are manifestly exotic, indicating a gap in our understanding of the QCD spectrum.

Bottomonium (like)

Recent observations of the spin-singlet states $h_b(1P)$, $h_b(2P)$ [57], and $\eta_b(2S)$ [58] have contributed greatly to our understanding of bottomonium multiplets below the open-bottom threshold. The unexpected discovery of narrow, manifestly exotic $b\bar{b}$ mesons above the open-bottom threshold has revealed a gap in our understanding of QCD. These include the $Z_b(10610)$ and $Z_b(10650)$, where the former is only 2.6 ± 2.2 MeV above the $m_B + m_{B^*}$ mass threshold and the latter is only 2.0 ± 1.6 MeV above $2m_{B^2}$. Combined with a $J^P = 1^+$ assignment, it is suggestive of $B\bar{B}^*$ and $B^*\bar{B}^*$ S -wave molecule-like states.

Future data will probably reveal additional $b\bar{b}$ threshold states. Comparisons of these bottomonium states with the XYZ states in the charmonium system will provide additional insight. The next phase of measurement with Belle II will systematically investigate the spectroscopy of these new states in both charmonium and bottomonium.

1.2.8 Direct searches for NP

Most of the NP searches at Belle II are indirect. However there are models that predict NP particles at the MeV–GeV scale. Bottomonium decays can be very sensitive to new particles at this mass scale that may have escaped detection up to now due to small couplings with ordinary matter. This includes Weakly and non-Weakly Interacting Massive Particles that couple to the SM via new $U(1)$ gauge symmetries [59–61].

These models often predict a rich sector of hidden particles, that include dark matter candidates, dark photons (A') and dark Higgs (h') at the GeV scale. These may decay to SM photons via a process known as kinetic mixing, with coupling strength ϵ . There are two associated scenarios that Belle II can probe: searches for dark matter, and searches for new gauge bosons.

The former, low mass dark matter(χ) scenario, predicts invisible radiative decays of $\Upsilon(1S)$ mesons through kinetic mixing with the hidden sector. Such signatures can be measured in the $\Upsilon(3S) \rightarrow \pi^+\pi^-$ *invisible* decay [62]. The sensitivity of this search is limited by similarly behaved background that needs to be subtracted and by $\Upsilon(1S) \rightarrow \ell\ell$ where the leptons are undetected. In the SM, invisible $\Upsilon(1S)$ decays proceed through the $\nu\bar{\nu}$ final state with a branching fraction $\mathcal{B}(\Upsilon(1S) \rightarrow \nu\bar{\nu}) \sim (1 \times 10^{-5})$, well below the current experimental sensitivity. Calculations based on the thermal DM relic density predict a rate $\Upsilon(1S) \rightarrow \chi\chi$ larger by one or two orders of magnitude than that of $\Upsilon(1S) \rightarrow \nu\bar{\nu}$.

Dark photons can for example be searched for at Belle II in various Υ and B reactions through their coupling to lepton pairs. Dark Higgs candidates will be searched for in “Higgstrahlung” processes, $e^+e^- \rightarrow A'h, h' \rightarrow A'A'$. Belle II will have the best sensitivity in the mass range 100 MeV–2 GeV and is thus complementary to the dedicated JLAB dark photon search and other planned experiments in Europe [63].

It is anticipated that in 2017 as many as 500 million $\Upsilon(3S)$ mesons will be produced on resonance, for searches of radiative Υ transitions to DM. The data set will be an order of magnitude greater than those currently available. Ultimately Belle II may reach limits 2 orders of magnitude lower than previous direct NP searches at the B factories.

1.3 Centre-of-mass energies

There are a multitude of physics topics unique to the physics program of Belle II, with rare decays and CP asymmetries in B decays at the forefront. The program provides simultaneous studies of a wide range of areas in b -quark, c -quark, tau lepton, two-photon, quarkonium and exotic physics. The latter two topics have come to fore

in recent time, concerning puzzles in our understanding of QCD in describing 4-quark states, and the search for a dark sector and light Higgs. Open questions will be addressed with extended run periods at $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(5S)$, near the $\Upsilon(6S)$, and fine energy scans in intermediate regions. Measurements at $\Upsilon(5S)$ also offer unique insight into B_s decays. The physics runs will commence on the $\Upsilon(4S)$ to calibrate the detector. It will be the primary energy point for the duration of the experiment, as was the case for KEKB.

1.4 Summary

The physics goals of Belle II, as a next generation flavour factory, are to search for NP in the flavour sector at the precision frontier, and to further reveal the nature of QCD in describing matter. A summary of the expected sensitivities for individual observables at selected integrated luminosities is given in Tables 1.2 and 1.3.

The physics motivation for the e^+e^- SuperKEKB is independent of results from the LHC: if LHC finds NP, precision flavour input is essential to further understand those discoveries. On the other hand, if the LHC finds no evidence for NP, the high statistics b , charm and τ samples provide a unique way to probe for NP beyond the TeV scale. On the interplay between e^+e^- machines and LHCb: the two experiments are highly complementary. LHCb will have high statistics samples of both B_s and B mesons and will produce measurements that dominate the all-charged final states. However, SuperKEKB will dominate B measurements of final states with neutrinos, or multiple photons. The e^+e^- program also includes extensive precision studies of the tau and a number of other non-flavour physics topics.

Table 1.2: Expected errors on several selected flavour observables with an integrated luminosity of 5 ab^{-1} and 50 ab^{-1} of Belle II data. The current results from Belle, or from BaBar where relevant (denoted with a †) are also given. Items marked with a ‡ are estimates based on similar measurements. Errors given in % represent relative errors.

	Observables	Belle	Belle II	
		(2014)	5 ab^{-1}	50 ab^{-1}
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$ [64]	0.012	0.008
	α [°]	85 ± 4 (Belle+BaBar) [24]	2	1
	γ [°]	68 ± 14 [13]	6	1.5
Gluonic penguins	$S(B \rightarrow \phi K^0)$	$0.90_{-0.19}^{+0.09}$ [19]	0.053	0.018
	$S(B \rightarrow \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$ [65]	0.028	0.011
	$S(B \rightarrow K_S^0 K_S^0 K_S^0)$	$0.30 \pm 0.32 \pm 0.08$ [17]	0.100	0.033
	$\mathcal{A}(B \rightarrow K^0 \pi^0)$	$-0.05 \pm 0.14 \pm 0.05$ [66]	0.07	0.04
UT sides	$ V_{cb} $ incl.	$41.6 \cdot 10^{-3}(1 \pm 1.8\%)$ [8]	1.2%	
	$ V_{cb} $ excl.	$37.5 \cdot 10^{-3}(1 \pm 3.0\%_{\text{ex.}} \pm 2.7\%_{\text{th.}})$ [10]	1.8%	1.4%
	$ V_{ub} $ incl.	$4.47 \cdot 10^{-3}(1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$ [5]	3.4%	3.0%
	$ V_{ub} $ excl. (had. tag.)	$3.52 \cdot 10^{-3}(1 \pm 8.2\%)$ [7]	4.7%	2.4%
Missing E decays	$\mathcal{B}(B \rightarrow \tau \nu)$ [10^{-6}]	$96(1 \pm 27\%)$ [26]	10%	3%
	$\mathcal{B}(B \rightarrow \mu \nu)$ [10^{-6}]	< 1.7 [67]	20%	7%
	$R(B \rightarrow D \tau \nu)$	$0.440(1 \pm 16.5\%)$ [29]†	5.2%	2.5%
	$R(B \rightarrow D^* \tau \nu)$ †	$0.332(1 \pm 9.0\%)$ [29]†	2.9%	1.6%
	$\mathcal{B}(B \rightarrow K^{*+} \nu \bar{\nu})$ [10^{-6}]	< 40 [30]	< 15	30%
	$\mathcal{B}(B \rightarrow K^+ \nu \bar{\nu})$ [10^{-6}]	< 55 [30]	< 21	30%
Rad. & EW penguins	$\mathcal{B}(B \rightarrow X_s \gamma)$	$3.45 \cdot 10^{-4}(1 \pm 4.3\% \pm 11.6\%)$	7%	6%
	$A_{CP}(B \rightarrow X_{s,d} \gamma)$ [10^{-2}]	$2.2 \pm 4.0 \pm 0.8$ [68]	1	0.5
	$S(B \rightarrow K_S^0 \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$ [20]	0.11	0.035
	$S(B \rightarrow \rho \gamma)$	$-0.83 \pm 0.65 \pm 0.18$ [21]	0.23	0.07
	$C_7/C_9(B \rightarrow X_s \ell \ell)$	$\sim 20\%$ [36]	10%	5%
	$\mathcal{B}(B_s \rightarrow \gamma \gamma)$ [10^{-6}]	< 8.7 [42]	0.3	–
	$\mathcal{B}(B_s \rightarrow \tau \tau)$ [10^{-3}]	–	< 2 [44]‡	–

Table 1.3: Continued from previous page

	Observables	Belle	Belle II	
		(2014)	5 ab ⁻¹	50 ab ⁻¹
Charm Rare	$\mathcal{B}(D_s \rightarrow \mu\nu)$	$5.31 \cdot 10^{-3}(1 \pm 5.3\% \pm 3.8\%)$ [46]	2.9%	0.9%
	$\mathcal{B}(D_s \rightarrow \tau\nu)$	$5.70 \cdot 10^{-3}(1 \pm 3.7\% \pm 5.4\%)$ [46]	3.5%	3.6%
	$\mathcal{B}(D^0 \rightarrow \gamma\gamma)$ [10 ⁻⁶]	< 1.5 [49]	30%	25%
Charm <i>CP</i>	$A_{CP}(D^0 \rightarrow K^+K^-)$ [10 ⁻²]	$-0.32 \pm 0.21 \pm 0.09$ [69]	0.11	0.06
	$A_{CP}(D^0 \rightarrow \pi^0\pi^0)$ [10 ⁻²]	$-0.03 \pm 0.64 \pm 0.10$ [70]	0.29	0.09
	$A_{CP}(D^0 \rightarrow K_S^0\pi^0)$ [10 ⁻²]	$-0.21 \pm 0.16 \pm 0.09$ [70]	0.08	0.03
Charm Mixing	$x(D^0 \rightarrow K_S^0\pi^+\pi^-)$ [10 ⁻²]	$0.56 \pm 0.19 \pm_{0.13}^{0.07}$ [52]	0.14	0.11
	$y(D^0 \rightarrow K_S^0\pi^+\pi^-)$ [10 ⁻²]	$0.30 \pm 0.15 \pm_{0.08}^{0.05}$ [52]	0.08	0.05
	$ q/p (D^0 \rightarrow K_S^0\pi^+\pi^-)$	$0.90 \pm_{0.15}^{0.16} \pm_{0.06}^{0.08}$ [52]	0.10	0.07
	$\phi(D^0 \rightarrow K_S^0\pi^+\pi^-)$ [°]	$-6 \pm 11 \pm \frac{4}{5}$ [52]	6	4
Tau	$\tau \rightarrow \mu\gamma$ [10 ⁻⁹]	< 45 [71]	< 4.6	< 0.5
	$\tau \rightarrow e\gamma$ [10 ⁻⁹]	< 120 [71]	< 12	< 1.2
	$\tau \rightarrow \mu\mu\mu$ [10 ⁻⁹]	< 21.0 [72]	< 4.5	< 0.5

Bibliography

- [1] J. Charles, S. Descotes-Genon, Z. Ligeti, S. Monteil, M. Papucci, et al., *Future sensitivity to new physics in B_d , B_s and K mixings*, Phys.Rev. **D89** (2014) 033016, arXiv:1309.2293 [hep-ph].
- [2] A. Somov et al., Belle Collaboration, *Improved measurement of CP-violating parameters in $B \rightarrow \rho^+ \rho^-$ decays*, Phys.Rev. **D76** (2007) 011104, arXiv:hep-ex/0702009 [hep-ex].
- [3] A. Kusaka et al., Belle Collaboration, *Measurement of CP Asymmetry in a Time-Dependent Dalitz Analysis of $B^0 \rightarrow (\rho\pi)^0$ and a Constraint on the CKM Angle ϕ_2* , Phys.Rev.Lett. **98** (2007) 221602, arXiv:hep-ex/0701015 [hep-ex].
- [4] I. Adachi et al., Belle Collaboration, *Measurement of the CP Violation Parameters in $B^0 \rightarrow \pi^+ \pi^-$ Decays*, arXiv:1302.0551 [hep-ex].
- [5] P. Urquijo et al., Belle Collaboration, *Measurement Of $|V_{ub}|$ From Inclusive Charmless Semileptonic B Decays*, Phys.Rev.Lett. **104** (2010) 021801, arXiv:0907.0379 [hep-ex].
- [6] H. Ha et al., Belle Collaboration, *Measurement of the decay $B^0 \rightarrow \pi^- \ell^+ \nu$ and determination of $|V_{ub}|$* , Phys.Rev. **D83** (2011) 071101, arXiv:1012.0090 [hep-ex].
- [7] A. Sibidanov et al., Belle Collaboration, *Study of Exclusive $B \rightarrow X_u \ell \nu$ Decays and Extraction of $|V_{ub}|$ using Full Reconstruction Tagging at the Belle Experiment*, Phys.Rev. **D88** (2013) 032005, arXiv:1306.2781 [hep-ex].
- [8] C. Schwanda et al., Belle Collaboration, *Measurement of the Moments of the Photon Energy Spectrum in $B \rightarrow X_s \gamma$ Decays and Determination of $|V_{cb}|$ and m_b at Belle*, Phys.Rev. **D78** (2008) 032016, arXiv:0803.2158 [hep-ex].

- [9] C. Schwanda et al., Belle Collaboration, *Moments of the Hadronic Invariant Mass Spectrum in $B \rightarrow X_c \ell \nu$ Decays at Belle*, Phys.Rev. **D75** (2007) 032005, arXiv:hep-ex/0611044 [hep-ex].
- [10] W. Dungen et al., Belle Collaboration, *Measurement of the form factors of the decay $B^0 \rightarrow D^{*-} \ell^+ \nu$ and determination of the CKM matrix element $|V_{cb}|$* , Phys.Rev. **D82** (2010) 112007, arXiv:1010.5620 [hep-ex].
- [11] P. Urquijo et al., Belle Collaboration, *Moments of the electron energy spectrum and partial branching fraction of $B \rightarrow X_c e \nu$ decays at Belle*, Phys.Rev. **D75** (2007) 032001, arXiv:hep-ex/0610012 [hep-ex].
- [12] USQCD Collaboration, T. Blum et al., *Lattice QCD at the intensity frontier*, 2013. <http://www.usqcd.org/documents/13flavor.pdf>.
- [13] K. Trabelsi, Belle collaboration, *Study of direct CP in charmed B decays and measurement of the CKM angle gamma at Belle*, (2013) , arXiv:1301.2033 [hep-ex].
- [14] Y. Horii et al., Belle Collaboration, *Evidence for the Suppressed Decay $B \rightarrow DK^-$, $D \rightarrow K^+ \pi^-$* , Phys.Rev.Lett. **106** (2011) 231803, arXiv:1103.5951 [hep-ex].
- [15] A. Poluektov et al., Belle Collaboration, *Evidence for direct CP violation in the decay $B \rightarrow D^{(*)} K$, $D \rightarrow K_s \pi + \pi^-$ and measurement of the CKM phase ϕ_3* , Phys.Rev. **D81** (2010) 112002, arXiv:1003.3360 [hep-ex].
- [16] H. Aihara et al., Belle collaboration, *First Measurement of ϕ_3 with a Model-independent Dalitz Plot Analysis of $B \rightarrow DK$, $D \rightarrow K_s \pi \pi$ Decay*, Phys.Rev. **D85** (2012) 112014, arXiv:1204.6561 [hep-ex].
- [17] K.-F. Chen et al., Belle Collaboration, *Observation of time-dependent CP violation in $B^0 \rightarrow \eta' K^0$ decays and improved measurements of CP asymmetries in $B^0 \rightarrow \phi K^0$, $K_S^0 K_S^0 K_S^0$ and $B^0 \rightarrow J/\psi K^0$ decays*, Phys.Rev.Lett. **98** (2007) 031802, arXiv:hep-ex/0608039 [hep-ex].
- [18] H. Sahoo et al., Belle Collaboration, *First Observation of Radiative $B^0 \rightarrow \phi K^0 \gamma$ Decays and Measurements of Their Time-Dependent CP Violation*, Phys.Rev. **D84** (2011) 071101, arXiv:1104.5590 [hep-ex].
- [19] Y. Nakahama et al., Belle Collaboration, *Measurement of CP violating asymmetries in $B^0 \rightarrow K^+ K^- K_S^0$ decays with a time-dependent Dalitz approach*, Phys.Rev. **D82** (2010) 073011, arXiv:1007.3848 [hep-ex].

- [20] Y. Ushiroda et al., Belle Collaboration, *Time-Dependent CP Asymmetries in $B^0 \rightarrow K_S^0 \pi^0 \gamma$ transitions*, Phys.Rev. **D74** (2006) 111104, arXiv:hep-ex/0608017 [hep-ex].
- [21] N. Taniguchi et al., Belle Collaboration, *Measurement of branching fractions, isospin and CP-violating asymmetries for exclusive $b \rightarrow d\gamma$ modes*, Phys.Rev.Lett. **101** (2008) 111801, arXiv:0804.4770 [hep-ex].
- [22] P. del Amo Sanchez et al., BaBar Collaboration, *Study of $B \rightarrow X\gamma$ decays and determination of $|V_{td}/V_{ts}|$* , Phys.Rev. **D82** (2010) 051101, arXiv:1005.4087 [hep-ex].
- [23] Y.-T. Duh, T.-Y. Wu, P. Chang, G. Mohanty, Y. Unno, et al., Belle Collaboration, *Measurements of Branching Fractions and Direct CP Asymmetries for $B \rightarrow K\pi$, $B \rightarrow \pi\pi$ and $B \rightarrow KK$ Decays*, Phys.Rev. **D87** (2013) 031103, arXiv:1210.1348 [hep-ex].
- [24] J. Charles et al., CKMFitter Group, , Eur. Phys. J. C **41** (2005) 1–131, arXiv:0406184 [hep-ph].
- [25] K. Hara et al., Belle collaboration, *Evidence for $B^- \rightarrow \tau^- \bar{\nu}$ with a Semileptonic Tagging Method*, Phys.Rev. **D82** (2010) 071101, arXiv:1006.4201 [hep-ex].
- [26] I. Adachi et al., Belle Collaboration, *Measurement of $B^- \rightarrow \tau^- \bar{\nu}_\tau$ with a Hadronic Tagging Method Using the Full Data Sample of Belle*, Phys.Rev.Lett. **110** (2013) 131801, arXiv:1208.4678 [hep-ex].
- [27] J. Lees et al., BaBar Collaboration, *Evidence of $B \rightarrow \tau\nu$ decays with hadronic B tags*, Phys.Rev. **D88** (2013) 031102, arXiv:1207.0698 [hep-ex].
- [28] B. Aubert et al., BaBar Collaboration, *A Search for $B^+ \rightarrow \ell^+ \nu_\ell$ Recoiling Against $B^- \rightarrow D^0 \ell^- \bar{\nu} X$* , Phys.Rev. **D81** (2010) 051101, arXiv:0912.2453 [hep-ex].
- [29] J. Lees et al., BaBar Collaboration, *Evidence for an excess of $\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau$ decays*, Phys.Rev.Lett. **109** (2012) 101802, arXiv:1205.5442 [hep-ex].
- [30] O. Lutz et al., Belle Collaboration, *Search for $B \rightarrow h^{(*)} \nu \bar{\nu}$ with the full Belle $\Upsilon(4S)$ data sample*, Phys.Rev. **D87** (2013) 111103, arXiv:1303.3719 [hep-ex].

- [31] J. Lees et al., BaBar Collaboration, *Precision Measurement of the $B \rightarrow X_s \gamma$ Photon Energy Spectrum, Branching Fraction, and Direct CP Asymmetry $A_{CP}(B \rightarrow X_{s+d} \gamma)$* , Phys.Rev.Lett. **109** (2012) 191801, arXiv:1207.2690 [hep-ex].
- [32] S. Nishida et al., Belle Collaboration, *Measurement of the CP asymmetry in $B \rightarrow X_s \gamma$* , Phys.Rev.Lett. **93** (2004) 031803, arXiv:hep-ex/0308038 [hep-ex].
- [33] B. Aubert et al., BaBar Collaboration, *A Measurement of CP Asymmetry in $b \rightarrow s \gamma$ using a Sum of Exclusive Final States*, Phys.Rev.Lett. **101** (2008) 171804, arXiv:0805.4796 [hep-ex].
- [34] T. Hurth, E. Lunghi, and W. Porod, *Untagged $\bar{B} \rightarrow X_{(s+d)} \gamma$ CP asymmetry as a probe for new physics*, Nucl.Phys. **B704** (2005) 56–74, arXiv:hep-ph/0312260 [hep-ph].
- [35] M. Benzke, S. J. Lee, M. Neubert, and G. Paz, *Long-Distance Dominance of the CP Asymmetry in $B \rightarrow X_{s,d} + \gamma$ Decays*, Phys.Rev.Lett. **106** (2011) 141801, arXiv:1012.3167 [hep-ph].
- [36] Y. Sato et al., Belle Collaboration, *Measurement of the Lepton Forward-Backward Asymmetry in Inclusive $B \rightarrow X_s \ell^+ \ell^-$ Decays*, arXiv:1402.7134 [hep-ex].
- [37] J. Lees et al., BaBar Collaboration, *Measurement of the $B \rightarrow X_s \ell^+ \ell^-$ branching fraction from a sum of exclusive final states*, arXiv:1312.5364 [hep-ex].
- [38] R. Aaij et al., LHCb Collaboration, *Differential branching fraction and angular analysis of the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$* , JHEP **1308** (2013) 131, arXiv:1304.6325.
- [39] S. J. Lee, M. Neubert, and G. Paz, *Enhanced Non-local Power Corrections to the $\bar{B} \rightarrow X_s \gamma$ Decay Rate*, Phys.Rev. **D75** (2007) 114005, arXiv:hep-ph/0609224 [hep-ph].
- [40] M. Misiak, H. Asatrian, K. Bieri, M. Czakon, A. Czarnecki, et al., *Estimate of $B(\bar{B} \rightarrow X_{(s)} \gamma)$ at $O(\alpha(s)^2)$* , Phys.Rev.Lett. **98** (2007) 022002, arXiv:hep-ph/0609232 [hep-ph].
- [41] T. Hermann, M. Misiak, and M. Steinhauser, *$\bar{B} \rightarrow X_s \gamma$ in the Two Higgs Doublet Model up to Next-to-Next-to-Leading Order in QCD*, JHEP **1211** (2012) 036, arXiv:1208.2788 [hep-ph].

- [42] J. Wicht et al., Belle Collaboration, *Observation of $B_s^0 \rightarrow \phi\gamma$ and Search for $B_s^0 \rightarrow \gamma\gamma$ Decays at Belle*, Phys.Rev.Lett. **100** (2008) 121801, arXiv:0712.2659 [hep-ex].
- [43] A. Gemintern, S. Bar-Shalom, and G. Eilam, *$B \rightarrow X_s\gamma\gamma$ and $B_s \rightarrow \gamma\gamma$ in supersymmetry with broken R-parity*, Phys.Rev. **D70** (2004) 035008, arXiv:hep-ph/0404152 [hep-ph].
- [44] B. Aubert et al., BaBar Collaboration, *A search for the rare decay $B^0 \rightarrow \tau^+\tau^-$ at BABAR*, Phys.Rev.Lett. **96** (2006) 241802, arXiv:hep-ex/0511015 [hep-ex].
- [45] C. Oswald et al., Belle Collaboration, *Measurement of the inclusive semileptonic branching fraction $\mathcal{B}(B_s^0 \rightarrow X^-\ell^+\nu_\ell)$ at Belle*, Phys.Rev. **D87** (2013) no. 7, 072008, arXiv:1212.6400 [hep-ex].
- [46] A. Zupanc et al., Belle Collaboration, *Measurements of branching fractions of leptonic and hadronic D_s^+ meson decays and extraction of the D_s^+ meson decay constant*, arXiv:1307.6240 [hep-ex].
- [47] S. Prelovsek and D. Wyler, *$c \rightarrow u\gamma$ in the minimal supersymmetric standard model*, Phys.Lett. **B500** (2001) 304–312, arXiv:hep-ph/0012116 [hep-ph].
- [48] S. Fajfer, P. Singer, and J. Zupan, *The Rare decay $D^0 \rightarrow \gamma\gamma$* , Phys.Rev. **D64** (2001) 074008, arXiv:hep-ph/0104236 [hep-ph].
- [49] J. Lees et al., BaBar Collaboration, *Search for the Decay $D^0 \rightarrow \gamma\gamma$ and Measurement of the Branching Fraction for $D^0 \rightarrow \pi^0\pi^0$* , Phys.Rev. **D85** (2012) 091107, arXiv:1110.6480 [hep-ex].
- [50] M. Staric et al., Belle Collaboration, *Search for CP Violation in D^\pm Meson Decays to $\phi\pi^\pm$* , Phys.Rev.Lett. **108** (2012) 071801, arXiv:1110.0694 [hep-ex].
- [51] B. Ko et al., Belle Collaboration, *Search for CP Violation in the Decay $D^+ \rightarrow K_S^0 K^+$* , JHEP **1302** (2013) 098, arXiv:1212.6112 [hep-ex].
- [52] K. Abe et al., Belle Collaboration, *Measurement of $D^0 - \bar{D}^0$ Mixing Parameters in $D^0 \rightarrow K_S^0\pi^+\pi^-$ decays*, Phys.Rev.Lett. **99** (2007) 131803, arXiv:0704.1000 [hep-ex].
- [53] Y. Grossman, Y. Nir, and G. Perez, *Testing New Indirect CP Violation*, Phys.Rev.Lett. **103** (2009) 071602, arXiv:arXiv:0904.0305 [hep-ph].

- [54] G. Burdman, E. Golowich, J. L. Hewett, and S. Pakvasa, *Rare charm decays in the standard model and beyond*, Phys.Rev. **D66** (2002) 014009, arXiv:hep-ph/0112235 [hep-ph].
- [55] I. Bigi, *'Ceterum censeo Fabricam Super Saporis esse faciendam' ('Moreover I advise a Super-Flavour Factory has to be built')*, arXiv:0804.4612 [hep-ph].
- [56] R. Mizuk et al., Belle Collaboration, *Dalitz analysis of $B \rightarrow K\pi^+\psi'$ decays and the $Z(4430)^+$* , Phys.Rev. **D80** (2009) 031104, arXiv:0905.2869 [hep-ex].
- [57] I. Adachi et al., Belle Collaboration, *First observation of the P-wave spin-singlet bottomonium states $h_b(1P)$ and $h_b(2P)$* , Phys.Rev.Lett. **108** (2012) 032001, arXiv:1103.3419 [hep-ex].
- [58] R. Mizuk et al., Belle Collaboration, *Evidence for the $\eta_b(2S)$ and observation of $h_b(1P) \rightarrow \eta_b(1S)\gamma$ and $h_b(2P) \rightarrow \eta_b(1S)\gamma$* , Phys.Rev.Lett. **109** (2012) 232002, arXiv:1205.6351 [hep-ex].
- [59] M. Reece and L.-T. Wang, *Searching for the light dark gauge boson in GeV-scale experiments*, JHEP **0907** (2009) 051, arXiv:0904.1743 [hep-ph].
- [60] R. Essig, P. Schuster, and N. Toro, *Probing Dark Forces and Light Hidden Sectors at Low-Energy e^+e^- Colliders*, Phys.Rev. **D80** (2009) 015003, arXiv:0903.3941 [hep-ph].
- [61] B. Batell, M. Pospelov, and A. Ritz, *Probing a Secluded $U(1)$ at B-factories*, Phys.Rev. **D79** (2009) 115008, arXiv:0903.0363 [hep-ph].
- [62] B. Aubert et al., BaBar Collaboration, *A Search for Invisible Decays of the $\Upsilon(1S)$* , Phys.Rev.Lett. **103** (2009) 251801, arXiv:0908.2840 [hep-ex].
- [63] R. Essig, J. A. Jaros, W. Wester, P. H. Adrian, S. Andreas, et al., *Dark Sectors and New, Light, Weakly-Coupled Particles*, arXiv:1311.0029 [hep-ph].
- [64] I. Adachi et al., *Precise measurement of the CP violation parameter $\sin 2\phi_1$ in $B^0 \rightarrow (c\bar{c})K^0$ decays*, Phys.Rev.Lett. **108** (2012) 171802, arXiv:arXiv:1201.4643 [hep-ex].
- [65] L. Santelj et al., Belle Collaboration, *Measurement of time-dependent CP violation in $B^0 \rightarrow \eta'K_S^0$* , DIS 2014 Conference (2013) .

- [66] Y. Chao et al., Belle Collaboration, *Measurements of time-dependent CP violation in $B^0 \rightarrow \omega K_S^0$, $f_0(980)K_S^0$, $K_S^0\pi^0$ and $K^+K^-K_S^0$ decays*, Phys.Rev. **D76** (2007) 091103, [arXiv:hep-ex/0609006](#) [hep-ex].
- [67] N. Satoyama et al., Belle Collaboration, *A Search for the rare leptonic decays $B^+ \rightarrow \mu^+\nu$ and $B^+ \rightarrow e^+\nu$* , Phys.Lett. **B647** (2007) 67–73, [arXiv:hep-ex/0611045](#) [hep-ex].
- [68] L. Pesantez et al., Belle Collaboration, *A_{CP} in $B \rightarrow X_s\gamma$ decays*, DIS 2014 Conference (2014) .
- [69] B. R. Ko, Belle Collaboration, *CP violation and mixing in the charm sector at Belle, and current HFAG averages*, [arXiv:arXiv:1212.5320](#) [hep-ex].
- [70] N. Nisar et al., Belle Collaboration, *Search for CP violation in $D^0 \rightarrow \pi^0\pi^0$ decays*, [arXiv:1404.1266](#) [hep-ex].
- [71] K. Hayasaka et al., Belle Collaboration, *New search for $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$ decays at Belle*, Phys.Lett. **B666** (2008) 16–22, [arXiv:0705.0650](#) [hep-ex].
- [72] K. Hayasaka, K. Inami, Y. Miyazaki, K. Arinstein, V. Aulchenko, et al., *Search for Lepton Flavor Violating Tau Decays into Three Leptons with 719 Million Produced $\tau^+\tau^-$ Pairs*, Phys.Lett. **B687** (2010) 139–143, [arXiv:1001.3221](#) [hep-ex].