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Nuclear and Particle Physics Proceedings 263–264 (2015) 15–23

www.elsevier.com/locate/nppp

Physics prospects at the Belle II experiment

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Abstract

A review of the flavour physics program for the Belle II experiment is presented, including projections for precision on key observables. The Belle II experiment is located at the second generation asymmetric e^+e^- collider SuperKEKB. It will be used to search for new phenomena at the flavour frontier.

Keywords: *Flavour, B-physics, Charm-physics, electron-positron collider, CKM.*

1. Introduction

The physics goals of Belle II, as a next generation flavour factory, are to search for new physics (NP) in the flavour sector at the precision frontier, and to further reveal the nature of QCD in describing matter. The SuperKEKB facility is 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 that of KEKB. This luminosity will produce a total of 5×10^{10} b, c and τ pairs over a period of 8 years. The first data taking run for physics analyses is anticipated to begin in 2017.

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 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 origin of mass of fundamental particles is explained within the SM by spontaneous electroweak symmetry breaking, resulting in 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. 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 suc-

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http://dx.doi.org/10.1016/j.nuclphysbps.2015.04.004

cessful but phenomenological description of subatomic processes at the energy scales up to $\mathcal{O}(1\ \mathrm{TeV})$. Many New Physics (NP) scenarios have been proposed to explain these shortcoming of the SM, where 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. At the energy frontier, the LHC experiments are 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 $\mathcal{O}(100\ \mathrm{TeV}/c^2)$ if the couplings are enhanced compared to the SM [1]. 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. 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. Flavour physics questions to be addressed by Belle II

Further study of the quark sector, is necessary to reveal NP at high mass scales beyond the direct reach of the LHC that may manifest in flavour observables. There are several important questions that can only be addressed by further studies of flavour physics, described in turn below.

- *Are there new CP violating phases?* Answers will require new measurements of time-dependent CPV in $b \to s$ decays such as $B \to \phi K^0$, $\eta' K^0$. If there is NP in $b \to d$ transitions, precise measurements of CKM parameters in mixing and in tree processes will be required.

- *Are there right-handed currents from NP?* Approaches include measurements of time-dependent CPV in $B \to K^{*0}(\to K_S^0\pi^0)\gamma$, triple-product CPV asymmetries in $B \to VV$ decays, and semileptonic decays $B \to V\ell\nu$, $V = D^*$, ρ.

- *Are there quark FCNCs beyond the SM?* It is of great interest to measure $b \to s\nu\bar{\nu}$ transitions such as $B \to K^{(*)}\nu\bar{\nu}$, part of a class of decays with large missing energy. It is also important to improve FCNCs measurements of $b \to d$, $b \to s$ and $c \to u$ 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 $\tau \to \mu\gamma$ visible at the 10^{-8} level? LFV in charged lepton decay is also a key prediction in many neutrino mass generation mechanisms.

- *Are there new operators with quarks enhanced by NP?* It is crucial to measure forward-backward asymmetries as a function of the q^2 of the dilepton, $A_{\mathrm{FB}}(q^2)$, in inclusive $b \to s\ell^+\ell^-$ decays and in charged weak interactions. Another example is measuring the rates and asymmetries in *all* $B \to K\pi$ 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, 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 $B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$.

- *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 is a sign of 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.

1.2. Advantages of SuperKEKB and Belle II

There are many experimental reasons to choose SuperKEKB and Belle II to address these puzzles in flavour physics.

- 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 decays of π^0, $\rho^\pm$, η, η' etc.. 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 reduces correction and systematic uncertainties in many types of measurements, *e.g.* Dalitz plot analyses.
- With asymmetric beam energies the Lorentz boost of the e^+e^- system is large enough so that B or D mesons travel an appreciable distance before decaying, allowing precision measurements of lifetimes, mixing parameters, and CPV.
- Since the absolute delivered luminosity is measured with Bhabha scattering, an e^+e^- experiment measures absolute branching fractions.
- Since the initial state is 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 or D decay in a hadronic or semileptonic final state, rare decays with neutrinos can be observed or measured with minimal model dependence.
- 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 number violation τ decays in a very low background environment.

The legacy of the B-factories laid the groundwork for many areas that will be further exploited at SuperKEKB. Their results provided a theoretically clean measurement the unitarity triangle (UT) angle β. After the accumulation of $\sim$1 ab^{-1} of data, it proved to be a precise calibration 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 to fixing the weak interaction parameters of the UT, Belle also completed a decade of studies and publications on rare decays and QCD. Belle II builds on this experience, shifting focus to NP exploration beyond the SM.

2. NP-sensitivity at Belle II

Belle II will have unprecedented sensitivity to the presence of NP effects. Belle II is able to perform measurements in $B^{0(\pm)}$ and $B_s^{(*)}$ meson decays, charm physics, τ lepton physics, spectroscopy, and electroweak 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.

2.1. CKM matrix metrology

Belle II 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, 3, 4]. The measurement of γ will be done via a range of methods using $B \to D^{(*)}K^{(*)}$ decays. At the end of the B factory era the tension between inclusive and exclusive determinations of $|V_{ub}|$ [5, 6, 7] and $|V_{cb}|$ [8, 9, 10, 11] still remain. The challenge at Belle II is to determine new techniques to understand this tension, with the larger data sets.

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 $b \to u\ell\nu$ 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 $B \to \pi\ell\nu$ 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 $B \to DK$ decays are even smaller. All the required hadronic matrix elements can be measured in the cascade $B \to DK$, $D \to f$ 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 $O(10^{-6})$. The present experimental errors are ±12° in the average of the Belle [13, 14, 15, 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 $B \to J/\psi K_S^0$ and related modes determining β.

2.2. *CP violation*

One of the main strengths of Belle II is the ability to make precision measurements of CPV, to 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 $B \to f$ decay and $B \to \bar{B}^0 \to f$ mixing amplitudes. An important search for NP is to compare the time-dependent CP asymmetries of penguin dominated $b \to s\bar{s}s$ processes with the tree dominated $b \to c\bar{c}s$ decays. Observables that probe this are the differences of CP asymmetries, which include $S_{J/\psi K^0_S} - S_{\phi K^0_S}$ and $S_{J/\psi K^0_S} - S_{\eta' K^0_S}$. Statistically limited studies of this class of decays were performed in Belle [17, 18, 19]. CP asymmetry measurements can in principle have small theoretical uncertainties as they involve ratios of rates, from which the leading amplitudes cancel. The value of $\sin 2\beta$ as measured in $B^0 \to \phi K^0_S$ and similar $b \to s$ transitions is currently in agreement with the value measured in $B \to J/\psi K^0_S$ decays, the world average being $\Delta S = \sin 2\beta_{\phi K^0_S} - \sin 2\beta_{J/\psi K^0_S} = 0.07 \pm 0.13$. While the CKM matrix elements in the amplitudes 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 $B \to \phi K^0_S$ decays, and change the expectation for ΔS.

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 offers a theoretically clean way of probing NP that is less sensitive to decay dynamics. CPV in inclusive $B \to X_{s+d}\gamma$ is expected to reach 0.5% experimental precision. Radiative decays $b \to s\gamma$ 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 $b_R \to s_L\gamma_L$ and $b_L \to s_R\gamma_R$ 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 $b_L \to s_R\gamma_R$ transition, for example, can proceed directly or via $\bar{B}^0 \to B^0$ mixing; the interference leads to a small time dependent CP asymmetry that is proportional to m_s/m_b. In various NP models the right-handed currents are not suppressed and can lead to a sizeable CP asymmetry. A prominent example of such transitions is $B^0 \to K^0_S\pi^0\gamma$ [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 $B^0 \to K^0_S\pi^0\gamma$ is measured through reconstruction of the B meson decay vertex using only pions from $K^0_S \to \pi^+\pi^-$ 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^0_S decays with charged pion hits in the silicon detectors. Charmless radiative decays will come to the fore in Belle II, such as $S(B \to \rho\gamma)$, which should be measurable with a precision of better than 0.1. This will be complemented by DCPV studies of $b \to d$ transitions [21, 22].

2.2.1. *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 $B \to K\pi$ 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 $A^{K^+\pi^0}_{CP}$ in $B^\pm \to K^\pm\pi^0$ decays and $A^{K^+\pi^-}_{CP}$ in $B^0(\bar{B}^0) \to K^\pm\pi^\mp$ decays are expected to be the same. However, a precise CP measurement by Belle showed a significant difference between the two, $\Delta A = A^{K^+\pi^0}_{CP} - A^{K^+\pi-}_{CP} = 0.164 \pm 0.035 \pm 0.013$ [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 K^0_S decays and depends crucially on a vertex detector with a large radial acceptance. Reconstruction of the π^0 requires very good EM calorimetry. For the final states with charged kaons and pions, 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 $B^0 \to K^0\pi^0$ are expected to be reduced with a larger data sample.

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.

2.3.1. Leptonic decays

The highest profile rare leptonic B decay is $B \to \tau\nu$, which in the SM results from a W-exchange diagram and has an expected branching fraction of $(0.74^{+0.09}_{-0.07}) \times 10^{-4}$ [24]. This mode is sensitive to models and that predict the existence of a charged Higgs (H^+). The effect of a H^+ on the partial leptonic decay width of B mesons is given by $\Gamma(B^+ \to \tau^+\nu) = \Gamma_{\mathrm{SM}}(B^+ \to \tau^+\nu)[1 - (m_B^2/m_H^2)\tan^2\beta]^2$, where $\tan\beta$ denotes the ratio of the vacuum expectation values of the two Higgs fields. The final state contains multiple neutrinos and is measurable only in a e^+e^- experiment. Experimentally the leptonic branching fraction measurement consists of 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 or partially reconstructed in semileptonic decays. 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 EM calorimeter, after removing the contributions from the particles used in the reconstruction of B_{tag} and the τ from $B_{\mathrm{sig}} \to \tau\nu$. 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 $B \to \mu\nu$ will be measured to about 6% precision.

2.3.2. 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 $B \to \tau\nu$ of being sensitive to the handedness of the NP current through polarisation studies. The predicted branching fractions, based on the SM, are approximately 1.4% and 0.7% for $B \to D^*\tau\nu$ and $B \to D\tau\nu$ decays, respectively. The large τ lepton mass makes them sensitive to interactions with a H^+. Therefore, these $B \to D^{(*)}\tau\nu$ modes can be a very effective probe to search for indirect evidence of charged Higgs or other NP hypotheses beyond the SM. An interesting anomaly in the B-factory data is the deviation from the SM of the $B \to D^{(*)}\tau\nu$ 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 $B \to \tau\nu$. Although the $B \to D^{(*)}\tau\nu$ 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.

2.3.3. Electroweak and radiative 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 $B \to K^{(*)}\nu\bar{\nu}$ [30]; while the current constraints are an order of magnitude weaker [31]. 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 $b \to s\gamma$ and $b \to s\ell^+\ell^-$ 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 [32, 33, 34, 35, 36]. Belle II can uniquely measure inclusive processes such as $B \to X_{s+d}\ell^+\ell^-$ for which theoretical predictions have less uncertainty than those for exclusive processes, measured by Belle and BaBar [37, 38]. 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 [39].

2.4. B_s physics at $\Upsilon(5S)$

It is expected that SuperKEKB will produce of order 5 ab^{-1} of data near the $\Upsilon(5S)$. Key NP modes are those with neutral final states or missing energy, such as $B_s \to \gamma\gamma$ [40, 41] and $B_s \to \tau\tau$. The latter will exploit hadronic tagging, as done in analogous searches at $\Upsilon(4S)$ [42]. Belle II will also contribute to the general understanding of B_s decays (*i.e.* precision tests of SU(3) transformation), with inclusive and comprehensive studies of decay final states only possible at Belle

II [43]. Precision measurements of absolute branching fractions will have an important impact on NP reach, *e.g.* in $B_s \rightarrow \mu\mu$.

2.5. Charm Physics

Indirect searches for NP with charm quarks provide complementary 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 $|V_{cs}|$ [44]. 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 $c \rightarrow u\gamma$ [45] or $c \rightarrow u\ell\ell$.

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 $D^0 \rightarrow \gamma\gamma$ [46, 47], 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 [48, 49] and oscillations [50] 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 more challenging to tackle in any given mode [51]. This issue can be resolved by measuring a multitude of final states, only possible with Belle II: 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 able to determine absolute A_{CP} for each given mode, challenging at hadron colliders, 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, *e.g.* lepton and baryon number violating transitions, and D decays to $\nu\bar{\nu}$ [52]. 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.

There are also examples of where Belle II will perform important measurements that impact other results, *e.g.* the strong phase, ϕ, as a function of position in the Dalitz plot for $D^0 \rightarrow K^0_S\pi^+\pi^-$ 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 way to test QCD-based calculations that currently limit the sensitivity of searches of NP in the charm sector.

2.6. Tau physics

Belle II will analyse τ lepton decays in a number of NP searches and SM precision tests. These include searches for LFV, CP violation, measurements of the electric dipole moment and $g-2$ of the τ, and SM quantities such as $|V_{us}|$. The expected sensitivities to rare and forbidden τ decays will be unrivalled. The facility is ideal for most τ physics measurements, as the data analysis can exploit correlated production with minimal 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 $\tau \rightarrow K^0_S\pi\nu$, which is very precisely predicted in the SM, is expected to be measured with 10^{-4} precision, an order of magnitude better than Belle.

3. Centre-of-mass energies and non-flavour topics

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, τ-lepton, two-photon, quarkonium and exotic physics. The latter two topics have come to the fore in recent times, 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.

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 QCD in the low energy regime. The existence of a new fundamental type of state implies the existence of a number of new states. To build a complete picture of new states requires a comprehensive overview afforded by SuperKEKB. One of the cleanest ways 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.

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 are 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 [53, 54]. These models often predict a rich sector of hidden particles, that include dark matter candidates, dark photons (A') and dark Higgs (h'). The dark sector may mix with the SM via a process known as kinetic mixing. 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 $\Upsilon(3S) \to \pi^+\pi^- invisible$ decay [55]. Dark photons can be searched for at Belle II in various Υ and B reactions through their coupling to lepton pairs. It is anticipated that in 2017-2018 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.

4. Summary

A summary of the expected sensitivities for various flavour observables at selected integrated luminosities is given in Table 1 The physics motivation for the e^+e^- SuperKEKB is complementary to the LHC: if LHC finds NP, precision flavour input is essential to further understand those discoveries. 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 SuperKEKB and LHCb: the two experiments are also complementary. LHCb will have high statistics samples of both B_s and B mesons and will produce measurements that dominate 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 τ-leptons and a number of other non-flavour physics topics.

P.U. is supported by an Australian Research Council Future Fellowship.

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Table 1: 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. Note that these extrapolations are frequently updated due to new input from the *B*-factories.

	Observables	Belle	Belle II	
		(2014)	5 ab^{-1}	50 ab^{-1}
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$ [56]	0.012	0.008
	α [°]	85 ± 4 (Belle+BaBar) [24]	2	1
	γ [°]	68 ± 14 [13]	6	1.5
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$ [19]	0.053	0.018
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$ [57]	0.028	0.011
	$S(B \to K_S^0 K_S^0 K_S^0)$	$0.30 \pm 0.32 \pm 0.08$ [17]	0.100	0.033
	$\mathcal{A}(B \to K^0 \pi^0)$	$-0.05 \pm 0.14 \pm 0.05$ [58]	0.07	0.04
UT sides	$\lvert V_{cb}\rvert$ incl.	$41.6 \cdot 10^{-3}(1 \pm 1.8\%)$ [8]	1.2%	
	$\lvert V_{cb}\rvert$ excl.	$37.5 \cdot 10^{-3}(1 \pm 3.0\%_{\mathrm{ex.}} \pm 2.7\%_{\mathrm{th.}})$ [10]	1.8%	1.4%
	$\lvert V_{ub}\rvert$ incl.	$4.47 \cdot 10^{-3}(1 \pm 6.0\%_{\mathrm{ex.}} \pm 2.5\%_{\mathrm{th.}})$ [5]	3.4%	3.0%
	$\lvert V_{ub}\rvert$ excl. (had. tag.)	$3.52 \cdot 10^{-3}(1 \pm 9.5\%)$ [7]	4.4%	2.3%
Missing *E* decays	$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$96(1 \pm 27\%)$ [26]	10%	5%
	$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7 [59]	20%	7%
	$R(B \to D\tau\nu)$	$0.440(1 \pm 16.5\%)$ [29]†	5.2%	3.4%
	$R(B \to D^*\tau\nu)^{\dagger}$	$0.332(1 \pm 9.0\%)$ [29]†	2.9%	2.1%
	$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})$ $[10^{-6}]$	< 40 [31]	< 15	20%
	$\mathcal{B}(B \to K^{+}\nu\bar{\nu})$ $[10^{-6}]$	< 55 [31]	< 21	30%
Rad. & EW penguins	$\mathcal{B}(B \to X_s\gamma)$	$3.45 \cdot 10^{-4}(1 \pm 4.3\% \pm 11.6\%)$	7%	6%
	$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$ [60]	1	0.5
	$S(B \to K_S^0\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$[20]	0.11	0.035
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$ [21]	0.23	0.07
	C_7/C_9 $(B \to X_s\ell\ell)$	~20% [37]	10%	5%
	$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	< 8.7 [40]	0.3	–
	$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	–	< 2 [42]‡	–
Charm Rare	$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \cdot 10^{-3}(1 \pm 5.3\% \pm 3.8\%)$ [44]	2.9%	0.9%
	$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \cdot 10^{-3}(1 \pm 3.7\% \pm 5.4\%)$ [44]	3.5%	3.6%
	$\mathcal{B}(D^0 \to \gamma\gamma)$ $[10^{-6}]$	< 1.5 [47]	30%	25%
Charm *CP*	$A_{CP}(D^0 \to K^+K^-)$ $[10^{-2}]$	$-0.32 \pm 0.21 \pm 0.09$ [61]	0.11	0.06
	$A_{CP}(D^0 \to \pi^0\pi^0)$ $[10^{-2}]$	$-0.03 \pm 0.64 \pm 0.10$ [62]	0.29	0.09
	$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	$-0.21 \pm 0.16 \pm 0.09$ [62]	0.08	0.03
Charm Mixing	$x(D^0 \to K_S^0\pi^+\pi^-)$ $[10^{-2}]$	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$ [50]	0.14	0.11
	$y(D^0 \to K_S^0\pi^+\pi^-)$ $[10^{-2}]$	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$ [50]	0.08	0.05
	$\lvert q/p\rvert(D^0 \to K_S^0\pi^+\pi^-)$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$ [50]	0.10	0.07
	$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	$-6 \pm 11 \pm {}^{4}_{5}$ [50]	6	4
Tau	$\tau \to \mu\gamma$ $[10^{-9}]$	< 45 [63]	< 14.7	< 4.7
	$\tau \to e\gamma$ $[10^{-9}]$	< 120 [63]	< 39	< 12
	$\tau \to \mu\mu\mu$ $[10^{-9}]$	< 21.0 [64]	< 3.0	< 0.3