THE BELLE II EXPERIMENT*

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While B factories were built to check whether the Standard Model with the CKM matrix offers a correct description of CP violation, the next generation of B factories, super B factories, will look for departures from the Standard Model. For such a study, a 50 times larger data sample is needed, corresponding to an integrated luminosity of 50 ab^{-1}. To achieve the necessary increase of event rates by a factor of 40, a substantial upgrade is required both of the accelerator complex as well as of the detector. The motivation for a future super B factory at KEK and its expected physics reach will be discussed.

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1. Introduction

SuperKEKB [1] is an asymmetric electron–positron collider in Tsukuba, Japan. It consists of a 7 GeV electron storage ring and a 4 GeV positron storage ring, to achieve higher luminosity by means of increasing the beam current, focusing the beams at the interaction point and making the electromagnetic beam–beam interactions small. The target luminosity has been set to 8×10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, about 50 times higher than the KEKB's original design value. SuperKEKB has adopted a nano-beam scheme. An asymmetric beam energies provide a boost to the centre-of-mass system and thereby allow for time-dependent charge-parity (CP) symmetry violation measurements. The upgrade will be completed, and the first collision will be conducted in 2017. The highest luminosity will be achieved in 2023.

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2. Why do we need a flavor factory when we have the LHC?

The Standard Model (SM) is, at the current level of experimental precision and at the energies reached so far, 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 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.

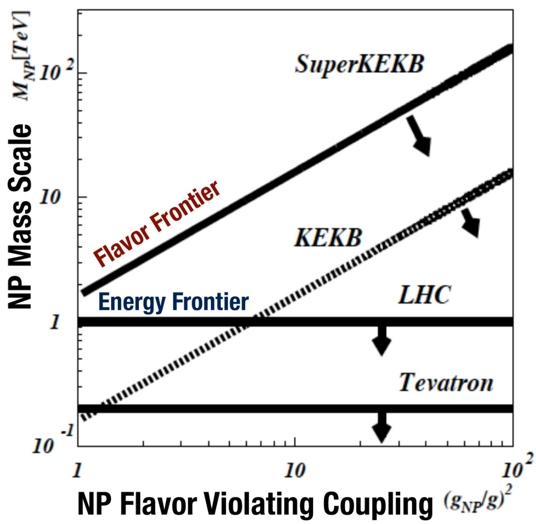

Fig. 1. Illustrative region of sensitivity to NP as a function of the flavor violating couplings (relative to the SM) in the indirect searches at KEKB and SuperKEKB, and direct searches at the LHC and Tevatron.

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 [2] and CMS [3] at the Large Hadron Collider (LHC) at CERN. The second is the intensity frontier, exemplified by the LHCb [4] experiment at the LHC, the BESIII experiment at the BEPCII charm factory, and the Belle II experiment at SuperKEKB (Fig. 1). 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 flavor 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 flavor violating couplings of the NP. The mass reach for new particle/process effects can be as high as $\mathcal{O}$ (100 TeV/c^2) if the couplings are enhanced compared to the SM [5]. 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.

3. Motivation 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 flavor observables. For example, some rare flavor 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 flavor sector may allow diagnosis of their nature. There are several important questions in flavor physics that can only be addressed by further study of loop transitions and processes with missing energy in final states, described in turn below [6].

- Are there new CP violating phases?
- Are there right-handed currents from NP?
- Are there quark FCNCs beyond the SM?
- Are there sources of LFV beyond the SM?
- Are there new operators with quarks enhanced by NP?
- Does nature have multiple Higgs bosons?
- Does NP enhance CPV via D^0–$\bar{D}^0$ mixing to an observable level?

It is worth noting that not only will Belle II measure the current array of CKM [7] observables with unprecedented precision (Fig. 2). It will also allow measurements of a large number of new observables and new modes relevant to NP in the quark sector.

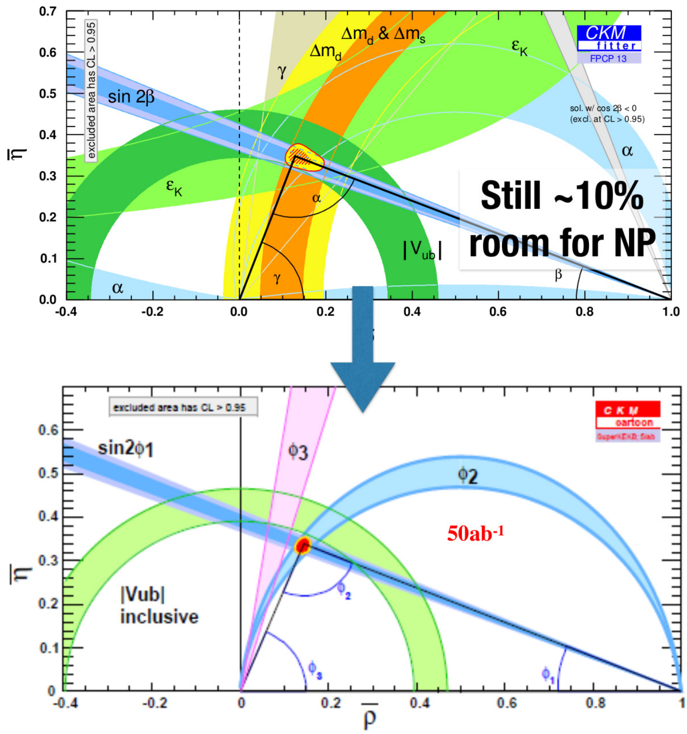

Fig. 2. Projected improvements in the CKM matrix experimental determination [8].

4. Advantages of SuperKEKB

There are many experimental reasons to choose SuperKEKB to address puzzles in flavor 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 $\pi^0, \rho^\pm, \eta, \eta'$ *etc.* decays. Neutral $K_{\rm L}^0$ mesons are also efficiently reconstructed.

— Detection of the decay products of one B allows the flavor 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 utilizing asymmetric beam energies, 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 B lifetime (which is already well measured) and can be used to determine the decay time resolution function from data.

— Since the absolute delivered luminosity is measured with the 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.
A summary of the expected sensitivities for individual missing energy decays at selected integrated luminosities is given in Table I.

— In addition to producing large sample 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 flavor and lepton numbers violation τ decays in a very low background environment, often with zero expected background.

TABLE I

Expected errors on several selected flavor observables with an integrated luminosity of 50 ab^{-1} of Belle II data.

	Observables	Belle (2014)	Belle II 50 ab^{-1}
Missing E decays	$\mathcal{B}(B \to \tau\nu)[10^{-6}]$	$96(1 \pm 27\%)$	5%
	$\mathcal{B}(B \to \mu\nu)[10^{-6}]$	< 1.7	7%
	$R(B \to D\tau\nu)$	$0.440(1 \pm 16.5\%)$	3.4%
	$R(B \to D^*\tau\nu)$	$0.332(1 \pm 9.0\%)$	2.1%
	$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})[10^{-6}]$	< 40	$< 30\%$
	$\mathcal{B}(B \to K^{+}\nu\bar{\nu})[10^{-6}]$	< 55	$< 30\%$

5. 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.

6. Summary

The physics goals of Belle II, as a next generation flavor factory, are to search for NP in the flavor sector at the precision frontier, and to further reveal the nature of QCD in describing matter. The physics motivation for the e^+e^- SuperKEKB is independent of results from the LHC: if LHC finds NP, precision flavor 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-flavor physics topics.

REFERENCES

[1] A.G. Akeroyd *et al.*, KEK Report 2009-12, `http://belle2.kek.jp/physics.html`, [`arXiv:hep-ex/0406071`].

[2] ATLAS Collaboration, *JINST* **3**, S08003 (2008).

[3] CMS Collaboration, *JINST* **3**, S08004 (2008).

[4] R. Aaij *et al.* [LHCb Collaboration], CERN-LHCC/2003-030.

[5] J. Charles *et al.*, *Phys. Rev. D* **89**, 033016 (2014) [`arXiv:1309.2293 [hep-ph]`].

[6] P. Urquijo, SuperKEKB TDR Physics Motivation (Preliminary), to be completed by B2TIP series of workshops.

[7] M. Kobayashi, T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).

[8] J. Charles *et al.*, *Phys. Rev. D* **84**, 033005 (2011) [`arXiv:1106.4041 [hep-ph]`], `http://ckmfitter.in2p3.fr/`