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Status and physics prospects of the SuperKEKB/Belle II project

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Summary. — Measurements at the KEKB collider and the Belle detector have provided important insights into the flavor structure of elementary particles. By upgrading to the SuperKEKB collider and the Belle II detector, we expect ~ 40 times higher luminosity with improved detections in several aspects. Measurements at the upgraded apparatus will over-constrain the parameter space of the Standard Model and its extensions and will shed light on the nature of new physics. This paper describes the status and physics prospects of the SuperKEKB/Belle II project.

PACS `12.60.-i` – Models beyond the standard model.

1. – Introduction

Measurements at the KEKB collider and the Belle detector have provided important insights into the flavor structure of elementary particles. Especially, the observation of the CP violation in the B meson system is a tremendous success in confirming the picture of quark flavor sector proposed by N. Cabibbo, M. Kobayashi, and T. Maskawa [1, 2]. Much larger data sample will be available at the upgraded experiment based on the SuperKEKB collider and the Belle II detector. In this experiment, we will quest for the physics beyond the Standard Model by searching for the deviations from the predictions of the Standard Model. Our high-precision studies will play a complementary role to the direct searches of new physics at the energy frontier. This paper describes the status and physics prospects of the SuperKEKB/Belle II project.

2. – SuperKEKB collider

The KEKB collider [3], which is an asymmetric-energy e^+e^- collider located at the High Energy Accelerator Research Organization (KEK) in Japan, will be upgraded to the SuperKEKB collider [4]. The design value of the center-of-mass energy for the SuperKEKB is on the $\Upsilon(4S)$ resonance, which is the same as the KEKB. On the other

(*) Representing the Belle II collaboration.

Table I. – *Parameters of the SuperKEKB and KEKB colliders. We show the design values for the SuperKEKB and the achieved values for the KEKB. The two values separated by a slash indicate the values for* e^+ *and* e^- *beams, respectively. The vertical beta function at IP, the beam current, and the beam-beam parameter are the crucial parameters related to the peak luminosity.*

Parameters	SuperKEKB	KEKB
Peak luminosity (10^{35} cm^{-2}s^{-1})	8.0	0.21
Vertical beta function at IP (mm)	0.27/0.30	5.9/5.9
Beam current (A)	3.6/2.6	1.64/1.19
Beam-beam parameter	0.09/0.08	0.129/0.090
Energy (GeV)	4.0/7.0	3.5/8.0

hand, the design luminosity for the SuperKEKB is 8.0×10^{35} cm^{-2}s^{-1}, which is about 40 times larger than the current world record of 2.1×10^{34} cm^{-2}s^{-1} achieved by the KEKB.

Table I shows the parameters for the SuperKEKB and the KEKB. The upgrade is based on the "nano-beam" scheme, which was first proposed for the INFN SuperB project [5]. We reduce the vertical beta function at the interaction point (IP) by a factor of about 1/20, providing a luminosity improvement by a factor of about 20. To introduce this improvement, we set the final focus magnets closer to the IP by changing the beam-crossing angle from 22 mrad to 83 mrad. The other improvement of the luminosity is available from the increase of the beam current by a factor of about 2. The design value of the beam-beam parameter, which is additional crucial parameter related to the luminosity, is at a similar level as at the KEKB.

To mitigate the emittance growth due to intra-beam scattering and the short beam lifetime due to the Touschek effect, the beam energy for the e^+ beam is changed from 3.5 GeV to 4.0 GeV. The beam energy for the e^- beam is changed from 8.0 GeV to 7.0 GeV accordingly. The effects of the reduction of the beam-energy asymmetry on the vertex measurements are found to be safely small.

Fig. 1 shows the milestone for the integrated and peak luminosities for the SuperKEKB project. After the shutdown for about four years, the commissioning will start in the second half of Japanese fiscal year 2014. The integrated luminosity will reach 50 ab^{-1} in 2020–2021, which is 50 times larger than the data size for the KEKB.

3. – Belle II detector

The Belle detector [6] will be upgraded to the Belle II detector [4]. The main concern for the Belle II detector is the higher-background environment. For evaluating the effects of the backgrounds on the detector performance, we extrapolate the results of the operations of KEKB and Belle by accounting for scaling for each component of backgrounds. The Belle II detector is designed to cope with this estimation conservatively, and has better performance than the Belle detector in some aspects.

Fig. 2 shows the dimensions of the Belle II and Belle detectors. Just outside the beam pipe, the four-layer silicon strip detector is replaced by a two-layer silicon pixel detector based on the DEPFET (DEpleted P-channel Field Effect Transistor) and a four-layer silicon strip detector. The impact parameter resolution in the beam direction is improved mainly due to the pixel detector by a factor of around two for momenta below 1 GeV. The efficiency for reconstructing K_S decays to two charged pions is improved due to the larger

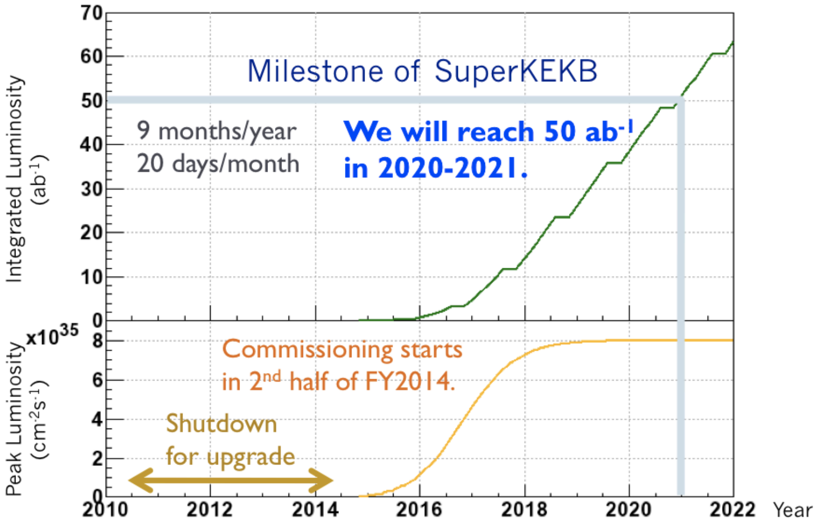

Fig. 1. – Milestone for the SupreKEKB project.

outer radius of the strip detector. The central tracking chamber has smaller drift cells, larger outer radius, and fast readout electronics, providing higher performance against the background. The particle identification system based on Cherenkov-threshold detectors is replaced by a lower-material system based on Cherenkov-imaging detectors. The probability of misidentifying a charged pion (kaon) as a charged kaon (pion) is improved from $\sim 10\%$ to $\sim 1\%$ for the kaon (pion) selection efficiency of $\sim 95\%$ at the kinematic limit of the momentum ~ 4 GeV/c. The electronics of the electromagnetic calorimeter employs a wave-form-sampling type to cope with the longer time constant ~ 1 μs of the CsI(Tl) crystals, reducing accidental overlaps by a factor of around seven. For the crystals in the endcaps, we have options for shorter time constant, e.g. pure CsI, for further upgrade. For the K_L and muon detector in the endcaps, we use scintillators instrumented with silicon photomultiplier tubes as the alternative to the resistive plate chambers to reduce the dead time. The new data acquisition system meets the requirements of a considerably higher event rates.

4. – Physics at SuperKEKB/Belle II

At the SuperKEKB collider and the Belle II detector, we have broad physics program in the fields of heavy flavor physics [7]. Our measurements will over-constrain the parameter space of the Standard Model and its extensions and will shed light on the nature of new physics by exploiting the correlations among various observables. Compared to the LHCb experiment, we have advantages in the studies of the decay modes with neutral particles in the final state. From the large number of planned measurements, several important examples on $B \to X_s\gamma$, $B \to \tau\bar{\nu}$, $B \to K\pi$, and lepton-flavor-violating τ decays are explained in the following sections.

4·1. $B \to X_s\gamma$. – The decay $B \to X_s\gamma$ occurs at one-loop order as shown in Fig. 3 (left), but still has a relatively large branching fraction of order 10^{-4} due to the top

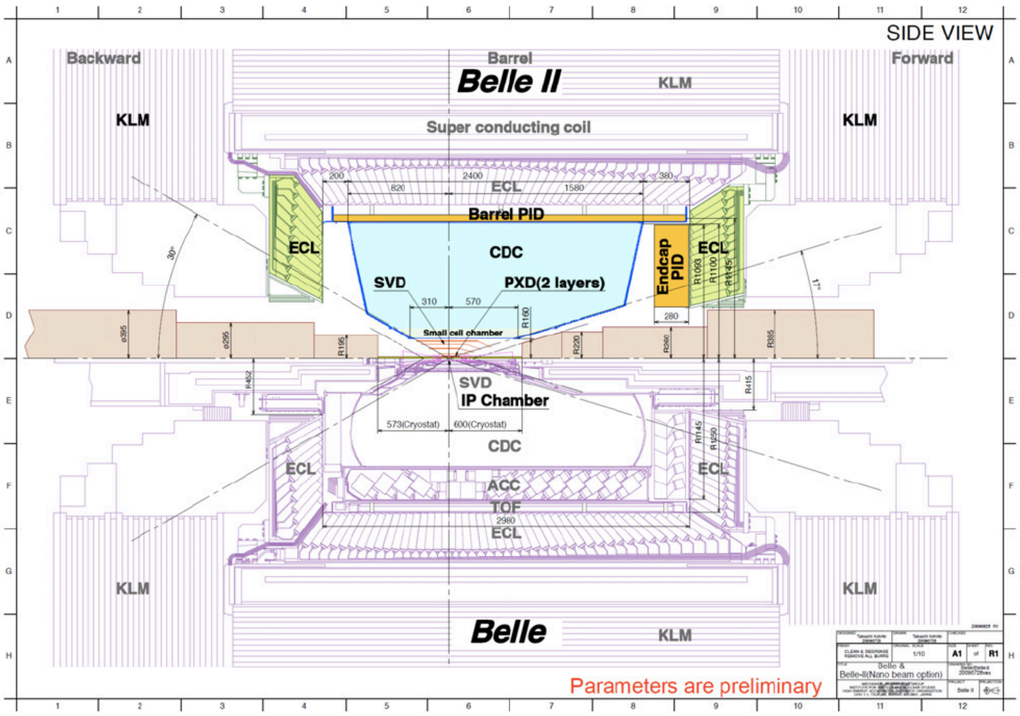

Fig. 2. – Dimensions for the Belle II (top half) and Belle (bottom half) detectors.

quark contribution. Since heavy virtual particles can be exchanged in the loop, the decay $B \to X_s\gamma$ is sensitive to new physics effects. The branching fraction, the direct CP asymmetry, and the mixing-induced CP asymmetries for the exclusive final states such as $K_S\pi^0\gamma$ could provide important information for investigating the new physics.

Various related measurements have been obtained at the Belle experiment [8, 9, 10, 11]. The measurement of the branching fraction is challenging even at the Belle II experiment, since accurate background subtraction is needed. We expect the precision of 6% at an integrated luminosity of 50 ab^{-1}, which is at the same level as the precision of the theoretical predictions. The magnitude of the direct CP-violating asymmetry predicted by the Standard Model is below 1%, while it could be above 10% in many extensions of the Standard Model [12, 13]. Expected sensitivity for the CP asymmetry at 50 ab^{-1} is 0.5% including systematic uncertainties. The magnitude of the mixing-induced CP-violating parameter, usually denoted by S, of the final state $K_S\pi^0\gamma$ is estimated to be 0.04 in the Standard Model, while it could be as high as 0.5 in left-right symmetric models [14]. As shown in Fig. 3 (right), expected sensitivity at 50 ab^{-1} is 0.03.

4˙2. $B \to \tau\bar{\nu}$. – Many models beyond the Standard Model include more than one Higgs doublet. In the so-called type II of two Higgs doublet models, one doublet yields masses of u-type quarks and the other doublet yields masses of d-type quarks. In these models, the decay rate of $B \to \tau\bar{\nu}$ is affected by the charged Higgs contribution as shown in Fig. 4 (left). The branching fraction could be modified from the value of the Standard

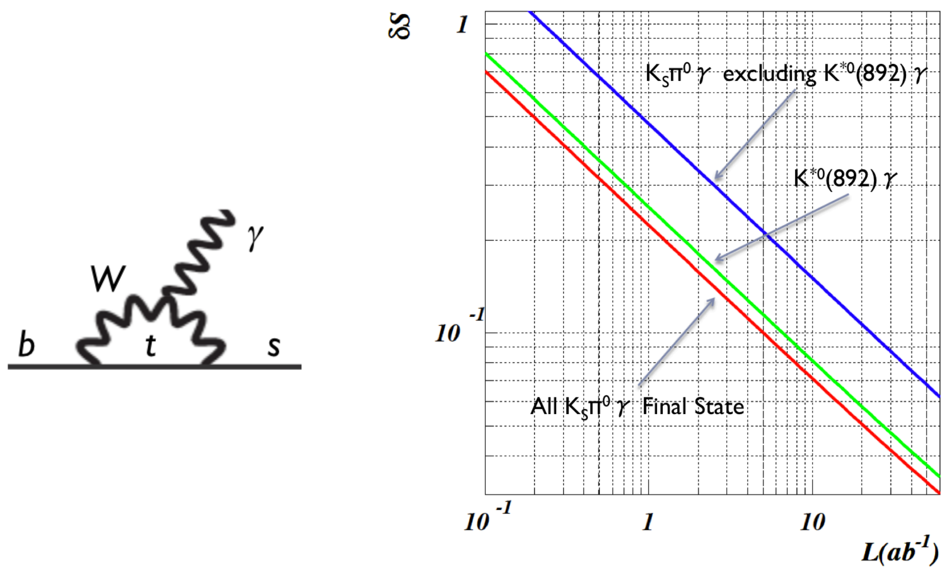

Fig. 3. – Feynman diagram for the process $b \to s\gamma$ (left). Expected precision for the mixing-induced asymmetries for $B \to K^{*0}(892)\gamma$ (green), other $K_S\pi^0\gamma$ (blue), and all $K_S\pi^0\gamma$ final state (red) as a function of integrated luminosity.

Model by a factor $(1 - m_B^2 \tan^2 \beta / m_H^2)^2$, where m_B and m_H are the masses of charged B meson and charged Higgs boson, respectively, and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets [15].

The first evidence for the decay $B \to \tau\bar{\nu}$ has been obtained by the Belle experiment by using the residual energy detected in the electromagnetic calorimeter after removing the accompanying B meson and charged decay products of the tau lepton [16]. The accompanying B meson is reconstructed in hadronic modes. The Belle has also obtained the evidence by a reconstruction of the accompanying B meson in semileptonic modes [17]. The world average of the branching fraction is obtained to be $(1.64 \pm 0.34) \times 10^{-4}$ [18], while the global fit assuming the Standard Model without including direct measurements shows $(0.763^{+0.114}_{-0.061}) \times 10^{-4}$ [19]. The measurements at Belle II will provide important information for the tension between the direct measurement and the Standard-Model expectation. In Fig. 4 (right), we show expected $(m_H, \tan\beta)$ region of 5σ discovery for the charged Higgs boson at Belle II with an integrated luminosity of 50 ab^{-1}, as well as the current exclusion regions at 95% C.L. The Belle II will cover large regions in the space of m_H and $\tan\beta$.

4·3. *$B \to K\pi$.* – The decays $B \to K\pi$ proceed through a tree diagram and a loop penguin diagram as depicted in Fig. 5 (left). Since the tree process is suppressed by the small CKM matrix element $|V_{ub}|$, the contribution of the loop penguin process is of similar magnitude. The interference of the two decays could lead to direct CP violation, which is equivalent to non-zero value of $A^f = [\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)]/[\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)]$ with f indicating a certain final state. As suggested in the diagrams in Fig. 5 (left), the processes for the neutral and the charged B meson decays are similar, and thus the

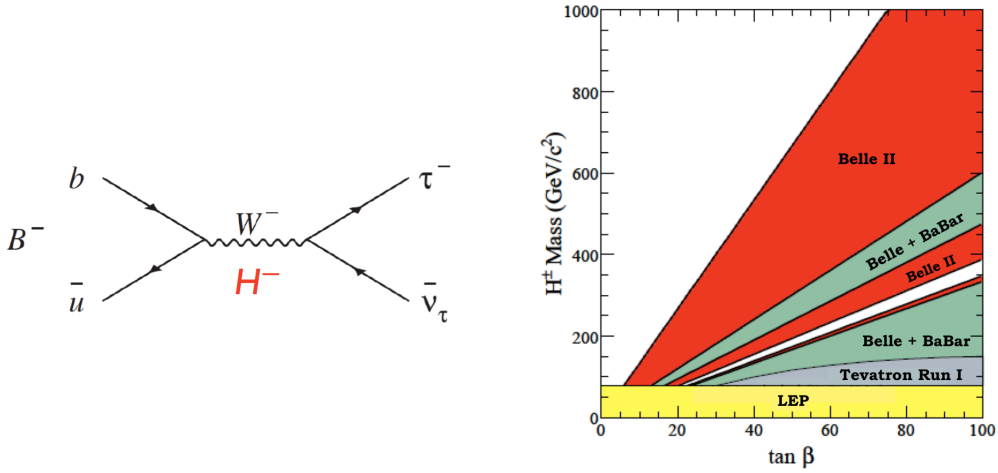

Fig. 4. – Feynman diagram for the decay $B^- \to \tau^- \bar{\nu}_\tau$ (left). 5σ-discovery region for Belle II at an integrated luminosity of 50 ab^{-1} (red) and current exclusion regions at 95% C.L. by B factories (green), Tevatron (gray), and LEP (yellow) on the plane of m_H and $\tan\beta$ (right).

difference $\Delta A = A^{K^+\pi^0} - A^{K^+\pi^-}$ should be close to zero.

The measurement by the Belle experiment has shown a significant difference $\Delta A = 0.164 \pm 0.035 \pm 0.013$ [20]. The difference could be due to the neglected diagrams contributing to the charged B meson decays only, for which the theoretical uncertainties are still large, or due to some unknown effect by the new physics. To make a test free of theoretical uncertainties, one can use a sum rule for various measurements in $B \to K\pi$ including $B \to K^0\pi^+$ and $B \to K^0\pi^0$ [21]. Fig. 5 (right) shows the accuracies expected for Belle II at an integrated luminosity of 50 ab^{-1}. The Belle II will provide a good environment even for the all neutral final state $K^0\pi^0$, which is the most critical mode for the test using the sum rule.

4˙4. *Lepton-flavor-violating* τ *decays.* – The lepton-flavor-violating decays could be induced by the oscillations of massive neutrinos. However, such processes are highly suppressed and far beyond the experimental reach. The situation is quite different if there is new physics including a particle that has mass of the order of the weak scale and couples to leptons. Example of the diagrams is shown for the decay $\tau \to \mu\gamma$ in Fig. 6 (left).

Upper limits on various lepton-flavor-violating τ decays have been obtained by the Belle experiment [22, 23, 24]. As shown for the decays $\tau \to \mu\gamma$, $\tau \to \mu\eta$, and $\tau \to \mu\mu\mu$ in Fig. 6 (right), the current limits are typically on the order of 10^{-8}. At the Belle II experiment, the anticipations for the upper limits will reach the order of 10^{-9}, by which large parameter spaces of many new physics models will be covered [25, 26, 27]. Since there are strong correlations between the expected rates of various channels, the measurements for different modes could provide important information to identify the underlying mechanism.

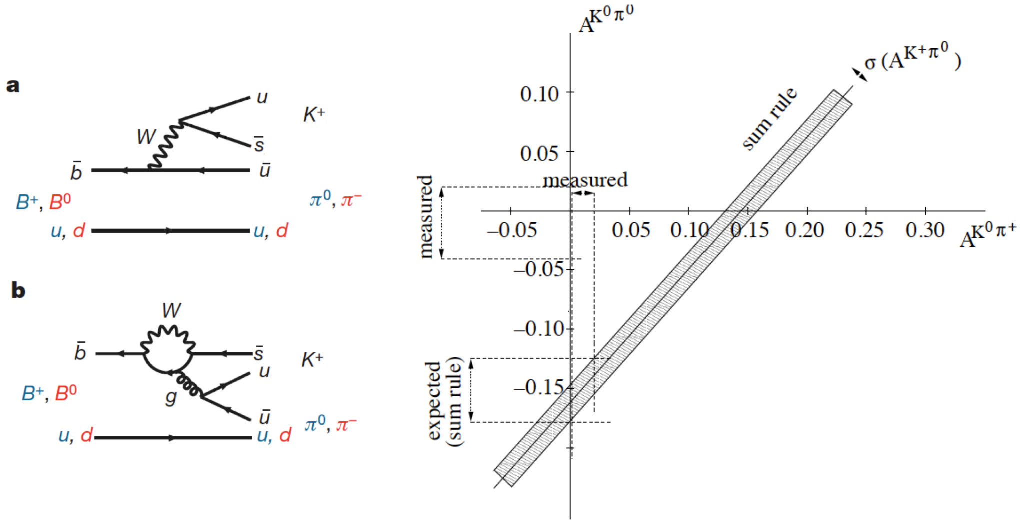

Fig. 5. – Feynman diagrams for the decays $B^+ \to K^+\pi^0$ and $B^0 \to K^+\pi^-$ (left). The sum rule for $B \to K\pi$ with the current central values of the observables and the accuracies expected for an integrated luminosity of 50 ab^{-1} (right).

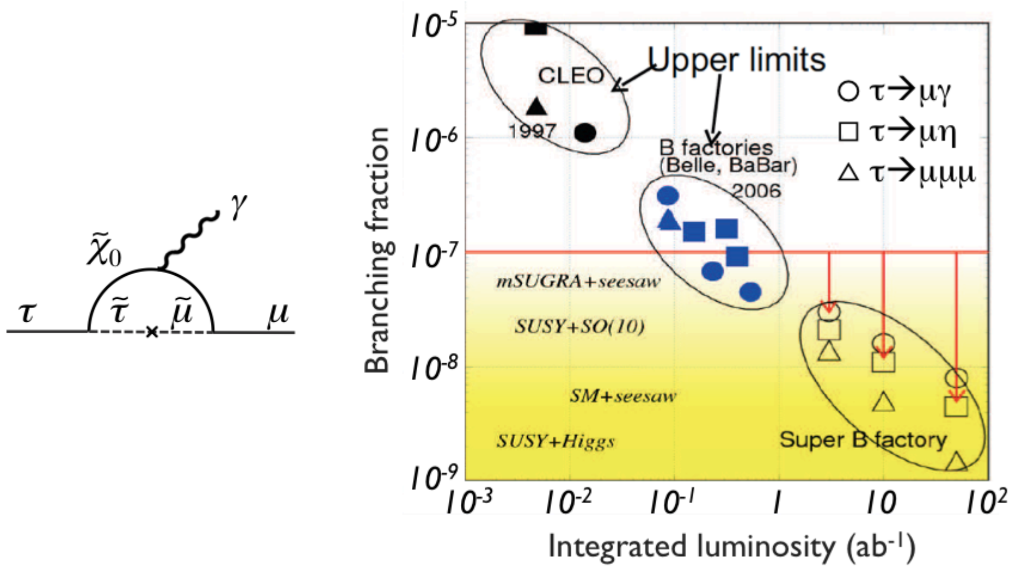

Fig. 6. – Example of the Feynman diagrams for $\tau \to \mu\gamma$ (left). History and anticipated upper limits on the branching fractions for $\tau \to \mu\gamma$, $\tau \to \mu\eta$, and $\tau \to \mu\mu\mu$ decays as a function of the integrated luminosity (right).

5. – Conclusion

At the SuperKEKB collider and the Belle II detector, we expect ~ 40 times higher luminosity and improved detection in several aspects. Of the broad physics program in the fields of heavy flavor physics, examples for $B \to X_s\gamma$, $B \to \tau\bar{\nu}$, $B \to K\pi$, and lepton-flavor-violating τ decays are shown. We will provide important information for investigating the physics beyond the Standard Model.

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